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Prof. Dr. Selahattin BARDAK

Researches and Evaluations in the Field of *MECHANICAL ENGINEERING*

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RESEARCHES AND EVALUATIONS IN THE FIELD OF MECHANICAL ENGINEERING

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gece kitaplığı

CONTENTS

CHAPTER 1

THERMAL COMFORT IN VEHICLES: MODELS, PARAMETERS, AND EMERGING TECHNOLOGIES

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1. Introduction

Thermal comfort within vehicle cabins is one of the critical aspects of modern automotive industry. Increased mobility and the widespread use of vehicles for urban commuting have resulted in extended time spent inside vehicles, making the provision of thermal comfort essential. Considering that daily commutes in cities can exceed two hours, the efficiency of cabin temperature and climate control systems has become even more crucial (Bode, Burnete, Fechete Tutunaru, & Nastase, 2023; Lajunen, Yang, & Emadi, 2020). Issues related to in-cabin thermal comfort are a significant source of post-sale customer complaints, particularly concerning the performance of Heating, Ventilation, and Air Conditioning (HVAC) systems. These complaints often involve insufficient temperature control, fan noise, and unpleasant odors. Studies have shown that vehicle owners have high expectations for HVAC systems and that issues in these systems significantly impact user satisfaction. Improving in-cabin thermal comfort has the potential to enhance driving experiences and reduce customer complaints (Diga, Severin, & Ignat, 2021).

Thermal comfort is defined by the ASHRAE 55 standard as the state of mind that expresses satisfaction with the thermal environment, such that a person would not prefer any other environment (ASHRAE, 2013). This concept is subjective and closely related to an individual's physical and mental state. Since it depends on multiple sensations and is influenced by all factors affecting the thermal conditions experienced, providing a universal definition is challenging. Given the variability in individual thermal perceptions, achieving thermal satisfaction for all individuals under the same thermal conditions is difficult (Danca et al., 2022). The Predicted Mean Vote (PMV) and the associated Predicted Percentage of Dissatisfied (PPD) indices, developed by Fanger, are the primary metrics used to measure thermal comfort (Fanger, 1980). However, evaluating thermal comfort in vehicles is significantly more complex than in buildings. The confined spaces of vehicle cabins, limited occupant mobility, and abrupt external environmental changes (e.g., variations in solar radiation angles) make predicting thermal comfort parameters more challenging.

Proper climate control in vehicles not only enhances passenger comfort but also plays a vital role in maintaining driver alertness and focus, thereby reducing the risk of traffic accidents (Norin & Wyon, 1992). However, achieving this comfort comes with significant energy costs. Increasing population and energy demand have exacerbated environmental challenges and energy crises, encouraging the adoption of electric vehicles (EVs). Thermal management systems in EVs are crucial for optimizing driving range and battery life (Haghani, Sprei, Kazemzadeh, Shahhoseini, & Aghaei, 2023; He, Jing, Zhang, Li, & Gu, 2023). Notably, HVAC energy consumption directly affects EV performance. While internal combustion engine (ICE) vehicles utilize waste heat from the engine for cabin heating, providing energy savings, EVs require additional electric heaters for this process. Under cold climate conditions, such as at -7 °C, heating systems in EVs can reduce driving range by up to 40%. Additionally, compressors used in HVAC systems can increase fuel consumption by 12–17% in smaller vehicles (Lambert & Jones, 2006). In EVs, cabin thermal management works integratively with battery and powertrain thermal management systems. This integrated structure necessitates coordination among systems to optimize energy efficiency (Lajunen et al., 2020). Therefore, designing energy-efficient HVAC systems relies on accurate measurement and optimization of thermal comfort. Advanced thermal management solutions are fundamental for reducing energy consumption and enhancing user satisfaction in EVs.

To ensure high thermal comfort, manufacturers have standardized ventilation, heating, and cooling systems in passenger cabins. These systems aim to maintain the desired indoor temperature, ensuring comfort standards are met (Sapcı & Heperkan, 2018). Additionally, tinted windows and infrared-reflective films are employed to mitigate the impact of solar radiation on cabin temperature. These specialized glass solutions block the entry of solar radiation into the cabin, minimizing temperature increases (M Özgün Korukçu & Kılıç, 2012). In smaller vehicle cabins, rapid changes in air velocity can lead to discomfort for drivers and passengers. Therefore, achieving uniform air distribution is a critical consideration in ventilation system design. Ensuring thermal comfort is not only a matter of physical ease but also impacts driving safety and performance. Inadequate thermal conditions can negatively affect driver attention and concentration, thereby increasing the risk of accidents (Mehmet Özgün Korukçu & Kılıç, 2011).

In conclusion, in-cabin thermal comfort is a key factor that directly influences passenger and driver satisfaction, driving safety, and energy efficiency. The modern automotive industry is developing innovative solutions such as advanced climate control systems, insulation materials, and infrared-reflective glass to optimize comfort. The necessity of reducing heat loads during the initial stages of vehicle design compels engineers to create more effective and energy-efficient HVAC systems. Accurate measurement and optimization of thermal comfort are vital for passenger well-being, driving safety, and energy conservation.

2. Factors Influencing Thermal Comfort Inside Vehicles

Thermal comfort in vehicles differs significantly from the conditions observed in buildings. The reasons include the compact size of vehicle cabins, limited passenger mobility, rapidly changing external environmental conditions (e.g., changes in vehicle orientation to the sun or the opening and closing of doors), complex cabin designs, and the high proportion of glass surfaces. Additionally, passengers are often seated near surfaces with temperatures differing from the interior air, and their ability to change positions within the cabin is restricted. These factors contribute to a highly non-homogeneous, transient, and asymmetric thermal environment inside vehicles (Chen et al., 2024). Moreover, HVAC systems are often inactive when there are no passengers in the vehicle or when the engine is off, leading to the occurrence of extreme microclimatic conditions (Ruzic, 2011). The amount of heat produced and transferred by the human body continuously changes, necessitating the establishment and maintenance of thermal equilibrium among the passenger, interior space, and external environment. Heat transfer between passengers and their surroundings inside a vehicle occurs through the following mechanisms (Figure 1):

- Convection: Airflows impacting the body.
- Conduction: Contact with surfaces such as seats.
- Radiation: Solar radiation and thermal radiation emitted by objects inside the cabin.
- Biological Processes: Internal body heat production, sweating, and heat transfer via respiration.

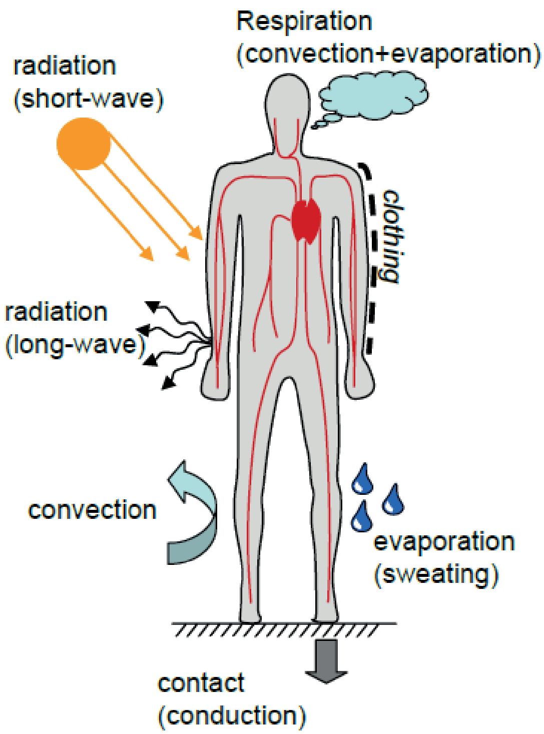


Figure 1. *Heat transfer between the human body and its surroundings (Paulke, 2008)*

Upon examining these processes, it is evident that the passenger cabin exhibits a complex and continuously changing structure. The effects can vary significantly from one individual to another, as well as across time and space.

Assessing and predicting the thermal environment inside a cabin is particularly challenging due to the variability of environmental conditions (Figure 2). Factors such as changes in solar radiation, the non-uniformity of cabin air temperature and air velocity, and fluctuations in external air temperature complicate this evaluation process.

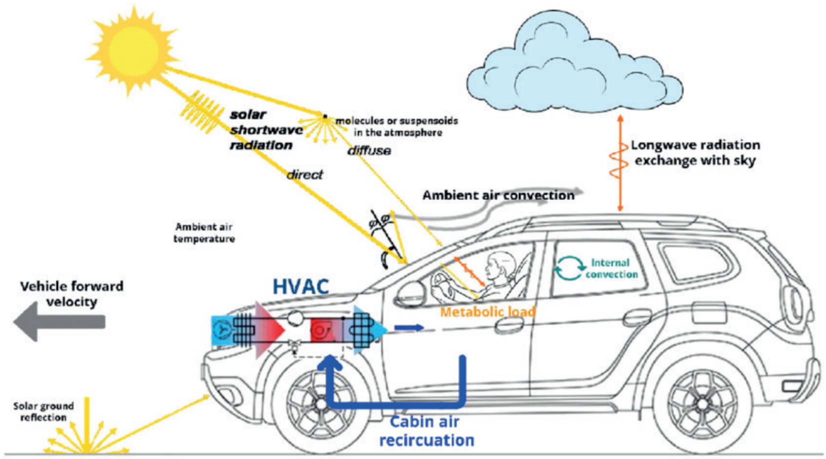


Figure 2. *Thermal effects influencing comfort in a vehicle cabin with a single-zone hvac system (Nastase et al., 2022)*

There are six main factors influencing thermal comfort, categorized into two groups (Simion, Socaciu, & Unguresan, 2016):

- Measurable Factors (Environmental): Air temperature, air velocity, mean radiant temperature, and relative humidity.
- Personal Factors (Individual): Metabolic rate (affected by activity type, age, gender, body weight, etc.) and clothing insulation.

To comprehensively analyze thermal comfort in cabins, it is essential to consider all these factors. These elements, which can vary over time or from person to person, should be evaluated through both measurable environmental parameters and individual passenger differences. This approach allows for a more accurate and detailed thermal comfort analysis within the cabin.

2.1. Air Temperature

In thermal comfort studies for vehicles, Air temperature refers to the temperature of the air in the immediate vicinity of the body, depending on location and time. Adjusting the air temperature in cabin to match seasonal conditions significantly contributes to maintaining thermal comfort. For example, during winter, an interior temperature of +22 °C is generally considered ideal, while different values are recommended for summer conditions in the literature. However, air temperature inside the vehicle is not uniform due to several factors: internal and external environmental conditions, structural characteristics of the vehicle, and the method by which the climate control system introduces conditioned air into the cabin. According to Temming, ankle-level air temperatures should be higher than those at head level (Temming, 1980). The ASHRAE Standard 55 limits this vertical temperature difference to a maximum of 3 °C, although some studies have shown that it can reach up to 6 °C (ASHRAE, 2013). Such temperature disparities, when exceeding acceptable thresholds, can negatively affect the driver's concentration and the overall comfort of passengers.

The vehicle class also significantly impacts interior temperature. Larger vehicles and models with leather upholstery exhibit different heating and cooling dynamics compared to smaller economy-class vehicles. For instance, leather-upholstered vehicles may display slower temperature distribution during heating. Air temperature metrics encompass the cabin's average temperature and standards for horizontal and vertical temperature gradients, aimed at reducing localized thermal discomfort.

Temperature measurements inside the vehicle are conducted using sensors that record values ranging between air temperature and mean radiant temperature. To minimize the influence of solar radiation, it is recommended that temperature sensors be small in size. These sensors are utilized to assess how quickly the cabin warms up or cools down in cold or hot conditions and to measure the temperature difference between head and ankle levels.

2.2. Relative Humidity

Relative humidity (φ) is determined as the ratio between the partial pressure of water vapor ($p_{w,p}$) and the saturation pressure of water vapor ($p_{w,s}$), as expressed in Equation (1) (ASHRAE, 2009).

$$\varphi = \frac{p_{w,p}}{p_{w,s}} \tag{1}$$

The saturation pressure of water vapor is calculated from Equation (2), and then partial pressure of water vapor is calculated from Equation (3), where T is temperatute and constants C_8 to C_{13} are for psychrometric relations.

$$\ln p_{w,s} = \frac{C_8}{T} + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13}\ln T \tag{2}$$

$$p_{w,p} = \frac{W\, p_a}{0.62198+W} \tag{3}$$

Inside vehicles, relative humidity is typically measured at a single point because water vapor pressure tends to distribute homogeneously throughout the cabin. The human body is sensitive to changes in air humidity, and thermal comfort is optimal when relative humidity is around 50%. However, relative humidity levels between 30% and 70% generally do not significantly affect thermal comfort. Exceeding this range can lead to passenger discomfort. When relative humidity surpasses 70%, it impedes sweat evaporation, creating a sensation of sultry air and causing issues such as condensation. This can result in technical problems like fogged windows or short circuits in electrical components. Conversely, low humidity levels create a dry sensation, potentially irritating mucous membranes, bronchial pathways, and corneas, which negatively affects both comfort and health. There is a strong correlation between relative humidity and temperature. As temperature decreases, relative humidity tends to increase. While relative humidity alone is not a critical factor, it plays a vital role in thermal comfort when evaluated alongside temperature. These two parameters directly impact the performance of in-vehicle climate control systems (Musat & Helerea, 2009). To ensure optimal in-cabin thermal comfort, relative humidity and temperature must be optimized. This is crucial for both passenger health and enhancing thermal comfort.

2.3. Mean Radiant Temperature

The Mean Radiant Temperature (MRT) is defined as the uniform surface temperature of an imaginary black enclosure where an occupant would experience the same radiant heat exchange as in the actual non-uniform environment (ASHRAE, 2013). According to ASHRAE Standard 55, MRT represents the average temperature of all objects surrounding an individual and has a direct impact on the human energy balance and heat loss. MRT is positive when the surrounding objects are warmer than the body temperature and negative when they are cooler. It is one of the most significant indicators of radiation exposure for passengers inside a vehicle. Sources of MRT include short-wave radiation from the sun and long-wave radiation emitted by vehicle interior surfaces. Factors such as material types, the orientation of surfaces to solar radiation, and the scattering of sunlight also influence the in-cabin thermal environment. To calculate MRT within the cabin, the temperatures, positions, and dimensions of the interior surfaces are taken into account. MRT can be determined using Equation (4) (Musat & Helerea, 2009).

$$\theta_m = \frac{\sum_1^n s_i \, \theta_i}{\sum_1^n s_i} \qquad (4)$$

Where; S_i represents the area of each surface relative to the occupant, θ_i is the temperature of each surface. For example, the surface temperatures of door panels, dashboard, and other cabin components are used in the calculation of MRT.

Solar radiation has the greatest impact on MRT. The glass structure of vehicles allows direct solar radiation to reach passengers, and as the vehicle moves, the angle of incoming solar radiation changes. This leads to a non-uniform distribution of MRT across different regions of the cabin. Such variability in MRT can cause localized thermal discomfort for passengers (Simion et al., 2016). During summer, when solar radiation intensity is high, the increase in MRT negatively affects thermal comfort and significantly raises the energy consumption of air conditioning systems. This highlights the importance of accounting for MRT in the design and operation of climate control systems to ensure efficient energy use and passenger comfort.

2.4. Air Velocity

Air velocity refers to the speed of air movement at a specific point, irrespective of its direction. The average air velocity is calculated for a representative passenger based on air movement at three different heights, corresponding to average air temperatures, depending on location and time. This velocity is typically averaged over a period of one to three minutes, with variations beyond three minutes considered as distinct air velocities (ASHRAE, 2013). In vehicle interiors, air velocity generally remains low, ranging between 0.1 m/s and 0.4 m/s. The maximum air velocity is determined based on convective heat exchange between the human body and the surrounding environment. The perception of airflow varies according to individual sensitivities; areas such as the head, neck, and nape are particularly sensitive to this sensation. Airflow inside the cabin typically originates from climate control systems or open windows. Air entering through an open window increases air velocity inside the vehicle, which can lead to thermal discomfort. The speed and direction of airflow directly impact passenger comfort. It is recommended that heated air be directed towards the lower body and cooler air towards the upper body (Olesen & Rosendahl, 1990). Studies indicate that higher air velocities in warm environments can enhance thermal comfort (Rohles, 1974; Scheatzle, Wu, & Yellott, 1989; Tanabe & Kimura, 1987). However, to prevent discomfort caused by airflow fluctuations, ventilation systems must distribute air uniformly throughout the cabin. Air velocity measurements are usually conducted over a period of three to five minutes to ensure a reasonable average value is obtained. These measurements are important for minimizing the impact of fluctuations in air velocity. In developing some thermal comfort models, air velocity is often neglected as it is typically low and less influential compared to other factors. The acceptable air velocity limit varies with indoor air temperature. At higher temperatures, these limits increase, allowing for improved thermal comfort. As shown in Figure 3, the relationship between air velocity and indoor air temperature reveals that higher air velocities are more acceptable under warm conditions. The sensation of airflow is most noticeable when air velocities exceed these threshold values and often impacts the nape of the neck. Additionally, the sensation of airflow is linked to the thermal state of the body (Musat & Helerea, 2009).

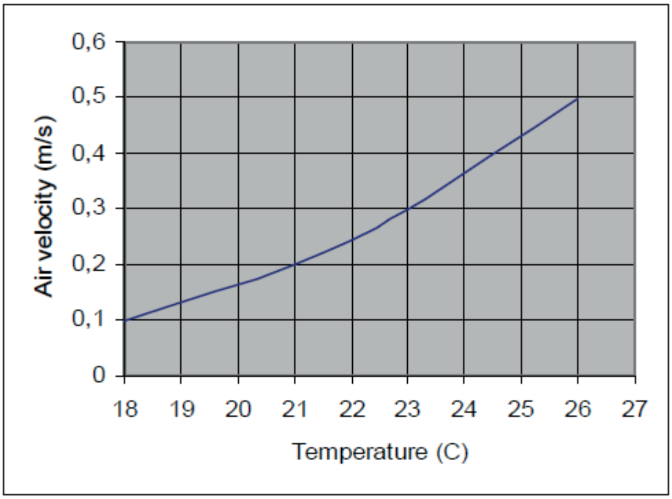


Figure 3. **The Air Flow Sensation Curve** *(Fountain & Arens, 1993)*

2.5. Metabolic Rate

Humans require energy to maintain their internal body temperature at approximately 36.5 °C and to perform various activities. This energy need is met through metabolic activities, during which heat is produced by the body. As activity levels increase, so does the heat generated (e.g., approximately 1.0 met at rest, rising to 2.0 met during physical activities). The body expels this excess heat through mechanisms such as sweating, respiration, and various heat transfer processes. The process of heat dissipation significantly impacts thermal comfort, and its effects vary according to individual activity levels and environmental conditions. Metabolic rate refers to the rate of energy expenditure by an individual during a specific activity and should be determined individually for each representative person (Table 1). Using an average metabolic rate for individuals performing different activities in the same environment is not appropriate, as it disregards significant metabolic differences between individuals. For instance, in a restaurant setting, customers may have a metabolic rate of around 1.0 met, whereas servers may have a metabolic rate closer to 2.0 met. Standard thermal comfort evaluations are not valid for individuals with high metabolic rates (e.g., above 2.0 met). These two distinct groups must be assessed separately in terms of thermal comfort conditions. Metabolic rate can be determined by selecting appropriate values from standard tables, performing interpolation or extrapolation between these values, or using engineering and physiological methods for direct measurement.

Table 1. *Estimated metabolic rate values for basic activities (A Alahmer, Omar, Mayyas, & Dongri, 2011)*

Activity	Metabolic Rate (met)	Energy Expenditure (W/m²)
Reclining	0.8 met	47 W/m²
Seated, quiet	1.0 met	58 W/m²
Filing, seated	1.2 met	70 W/m²
Light work	1.6 met	93 W/m²
Moderate work	2.0 met	117 W/m²
Heavy work	3.0 met	175 W/m²

Note: *1 met = 58 W/m² (50 kcal/m²h).*

For activities that vary over time, a time-weighted average metabolic rate can be used. However, if an activity continues for more than an hour, each activity should be treated as having a distinct metabolic rate.

Example calculation of time-weighted average metabolic rate

If a person engages in the following activities over one hour:

- 15 minutes of "Reclining" (0.8 met)
- 15 minutes of "Filing, seated" (1.2 met)
- 30 minutes of "Light work" (1.6 met)

The time-weighted average metabolic rate is calculated as:

$$(0.25\times0.8) + (0.25\times1.2) + (0.50\times1.6) = 1.3 \text{ met}$$

However, if a person engages in activities such as "Seated, quiet" for more than an hour, followed by "Filing, seated" for more than an hour, two separate metabolic rates should be calculated.

2.6. Clothing Insulation

Clothing primarily serves to protect the human body from adverse external conditions and to maintain thermal balance. Through its thermal insulation and moisture permeability properties, clothing helps regulate the heat and moisture exchange between the skin and the atmosphere (Li, 2001). The thermal insulation properties of clothing are measured in clo units, and Table 2 provides insulation values for various levels of clothing. The insulation value of clothing can decrease due to factors such as increased air velocity, displacement of air within the clothing caused by movement, and the addition of layers that resist moisture transfer. Considering that different parts of the body exhibit varying skin temperatures and that the climate within the vehicle differs significantly from the external environment, layered clothing that can be adjusted or removed facilitates achieving thermal comfort inside the vehicle.

Table 2. *Clothing levels and insulation values (A Alahmer et al., 2011)*

Description	**Thermal insulation range (clo)**
Winter outdoor clothing	2-3
Normal indoor clothing	1.2-1.5
Summer indoor clothing	0.8-1.2
Indoor Lightweight clothing	0.3-0.5

Note: *1.0 clo = 0.155* m^2K/W

3. Thermal Comfort Models and Simulations

The current standards for assessing thermal comfort include EN ISO 14505 (ISO, 2006a, 2006b, 2007), EN ISO 7730 (ISO, 2005), and ASHRAE 55 (ASHRAE, 2009). EN ISO 7730 is used to evaluate thermal comfort in buildings and is based on Fanger's PMV-PPD theory (Fanger, 1970, 1980). Similarly, ASHRAE 55 applies the PMV-PPD method or the Standard Effective Temperature (SET) method for thermal comfort evaluation in buildings. Fanger analyzed the factors influencing the heat balance of the human body and developed the PMV and PPD indices. The PMV index represents the heat flow produced and released by the human body and ranges from -3 to +3 on the ASHRAE scale (Table 3).

Table 3. *Thermal sensation scale*

Sign	**Value**	**Description**
+	3	Hot
+	2	Warm
+	1	Slightly warm
	0	Neutral
-	1	Slightly cool
-	2	Cool
-	3	Cold

The PPD index estimates the percentage of people experiencing thermal discomfort in an environment. A PPD value of 10% corresponds to a PMV range of -0.5 to +0.5 (Fanger, 1970). Even when PMV equals 0, approximately 5% of individuals may still feel discomfort. EN ISO 14505 is a standard specifically designed for evaluating thermal environments inside vehicles. Under the title "Evaluation of Thermal Environments in Vehicles," it is divided into three parts:

1. Principles and Methods for Assessment of Thermal Stress: This section outlines general guidelines and methods for evaluating thermal stress in vehicle interiors.

2. Determination of Equivalent Temperature: This part focuses on calculating the equivalent temperature, a key metric in assessing thermal comfort.

3. Evaluation of Thermal Comfort Using Human Subjects: This section involves subjective assessments through surveys and questionnaires conducted with passengers to evaluate thermal sensations and comfort levels.

The first part of the standard (ISO, 2007) references EN ISO 7730 and recommends the use of PMV and PPD indices. However, it is important to note that these indices were specifically developed for homogeneous environments in buildings and may not fully account for the non-homogeneous nature of vehicle interiors. The second part of the standard (ISO, 2006a) is based on Nilsson's Teq Index (the equivalent temperature index), which considers factors such as ambient air velocity, mean radiant temperature, air temperature, and the thermal resistance of clothing (Madsen, Olesen, & Kristensen, 1984; H. Nilsson, Holmér, Bohm, & Norén, 1997; H. O. Nilsson & Holmér, 2002). The third part (ISO, 2006b) introduces a method for subjectively assessing thermal comfort in vehicles, with the Thermal Sensation Vote (TSV) as the main index (ISO, 2007). This method records individuals' thermal sensations about an environment and uses the same scale as PMV. However, ISO 14505 is particularly sensitive to warm environments and has limitations in evaluating cold conditions (Foda, Almesri, Awbi, & Sirén, 2011).

Thermal sensation and thermal comfort are two fundamental concepts influenced by thermal stimuli affecting human perception. Thermal sensation is defined as an individual's perception of "quantitative" information, such as environmental temperature, through warm and cold receptors in the skin. Thermal comfort, on the other hand, is regarded as a combination of subjective perceptions and objective reactions to the environment. In research, thermal sensation is often used to assess thermal comfort levels. However, providing a universal definition of thermal comfort is challenging as it integrates both "objective factors," such as environmental conditions and physical parameters, and "subjective factors," such as feelings and mental states.

This complexity arises from the inseparable and complementary nature of the physical and psychological components reflecting the human condition. The physical component involves the intricate physiological mechanisms and thermoregulation systems of the human body, while the psychological component (mental state) further complicates the issue. Both components are shaped by subjective and objective factors, which can be individual or societal. Therefore, the concept of thermal comfort cannot be fully expressed through analytical equations or purely engineering approaches (Nastase et al., 2022). Various models have been developed to predict, classify, or simulate individuals' thermal comfort in indoor environments. Most of these models rely on different approaches based on the heat balance between the human body and the thermal environment and its impact on the body's thermoregulation mechanisms and mental responses (Figure 4).

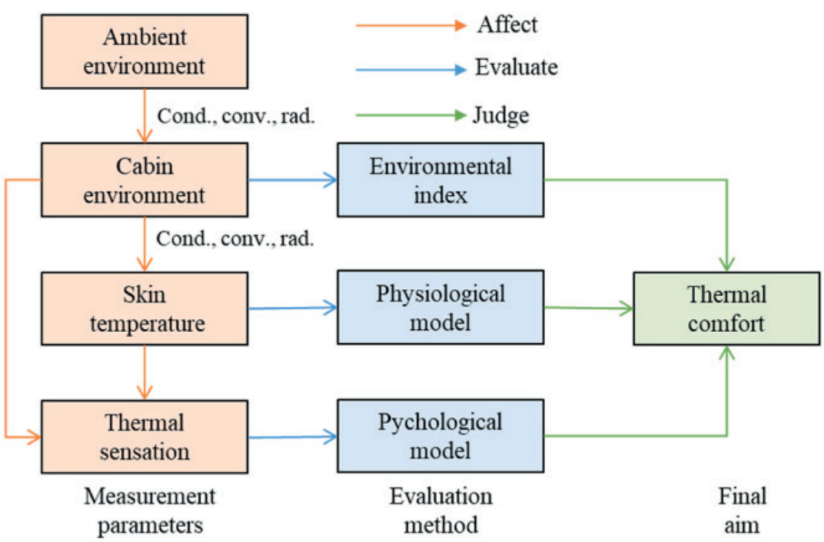


Figure 4. *Methodology for evaluating thermal comfort in vehicle cabins (Chen et al., 2024)*

Models used to evaluate in-cabin thermal comfort can be categorized into two main types: Thermal physiological models and Thermal psychological models. These models are further classified as static or dynamic, depending on their response to environmental conditions. Static models are designed to assess thermal comfort under steady-state environmental conditions, while dynamic models are better suited to respond to changing conditions. Additionally, based on the consistency of airflow and temperature distribution, these models can be categorized as homogeneous or non-homogeneous. Vehicle interiors naturally lack spatial homogeneity due to external and internal factors. However, in scenarios with minimal external fluctuations (e.g., underground parking), the environment may exhibit characteristics closer to a steady state. In such cases, the use of static models is suitable for assessing thermal comfort.

Thermal physiological models rely on the mathematical modeling of the energy balance between the human body and its surrounding environment. These models divide the human body into two main components: the tissue system and the thermoregulation system. The tissue system comprises segments such as the core, muscle, fat tissue, and skin tissue, representing the physiological and thermal properties of the body.

The thermoregulation system manages physiological responses such as vasomotor control, sweating, and shivering. These models are complemented by a clothing layer and consider factors such as body fat mass, skin surface area, gender, age, metabolic rate, type of exercise, and time of day (Ali Alahmer, Mayyas, Mayyas, Omar, & Shan, 2011). Significant advancements in physiological modeling began with Pierce's two-node human thermoregulation model (Gagge, Fobelets, & Berglund, 1986) and Stolwijk's multi-node model (Stolwijk, 1970, 1971). Pierce's model divides the body into core and skin layers, providing accurate predictions for homogeneous temperature environments. Stolwijk's model represents the body with six segments, each divided into four nodes: core, muscle, fat, and skin. Although these models were initially designed for steady-state conditions, they have been adapted to better suit non-homogeneous environments by modifying the heat transfer nodes between skin and clothing, increasing the number of nodes, and incorporating grids. The accuracy of these models has also been improved by accounting for changes in organ core temperatures. However, in the field of automotive thermal comfort, physiological models lack extensive experimental validation. Relying solely on these models can make it challenging to intuitively evaluate passenger thermal comfort. Therefore, integrating physiological model parameters with thermal psychological models is critical for real-time assessment. Incorporating changes in metabolic rate caused by environmental factors into the model can enhance prediction accuracy. An approach that combines simulations and thermal psychological models holds potential to improve the accuracy and scope of vehicle thermal comfort assessments (Chen et al., 2024).

Thermal psychological models are developed based on two main approaches: direct correlation approach and physiological response models. Direct correlation approach quantitatively expresses the relationship between environmental conditions and subjective sensations. It statistically analyzes the correlations between environmental data and human responses to derive predictive formulas. The most well-known example of this approach is the PMV model (Fanger, 1970), which is empirical. Physiological response models analyze the physiological responses of the human body to environmental conditions and their impact on thermal sensations. One notable model in this category is the UCB model (Zhang, Arens, Huizenga, & Han, 2010), which simulates physiological responses to predict comfort under varying environmental conditions.

Fanger's Comfort Equation and the derived PMV and PPD indices are the most recognized, widely used, and accepted thermal psychological models (Fanger, 1970). This model is particularly effective for static and homogeneous environments, as it indicates the degree of thermal balance deviation in the human body. Developed from controlled laboratory studies under steady thermal conditions, the PMV model uses experimental equations to describe heat exchange between the environment and the human body. While the PMV model, as modified by Gilani et al. (Gilani, Khan, & Ali, 2016), offers accurate predictions for steady and homogeneous conditions, it can result in significant errors when applied to dynamic and non-homogeneous environments such as vehicle cabins.

Fanger hypothesized that thermal comfort is achieved when there is a balance between the heat produced, consumed, and transferred to the environment by the human body. By analyzing the critical variables affecting thermal comfort and integrating them into the body's thermal balance equations (including heat transfer through radiation, convection, conduction, respiration, and sweating), Fanger developed an index capable of predicting thermal sensations under specific indoor conditions (Figure 5) (Croitoru, Nastase, Bode, Meslem, & Dogeanu, 2015).

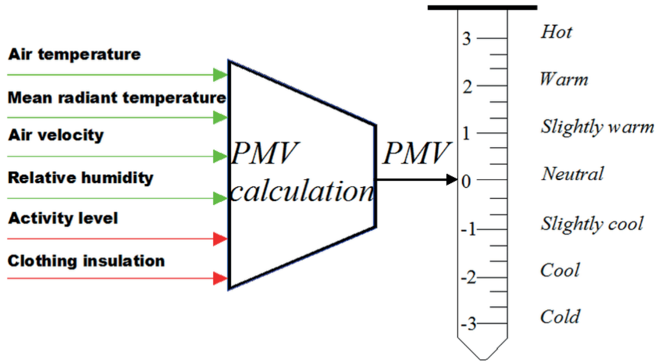


Figure 5. *PMV Calculation Framework and Value Range (Danca, Vartires, & Dogeanu, 2016)*

The PMV index provides a score corresponding to the ASHRAE thermal sensation scale and represents the average thermal sensation of a large group of people. The PMV index considers measurable parameters, such as recommended ranges for indoor temperature and humidity, that aim to satisfy at least 80% of vehicle passengers. It is determined by estimating personal factors (human activity level and clothing insulation) and measuring environmental factors (air temperature, air velocity, radiant temperature, and relative humidity). The PMV equation is expressed as follows (Equations 5–6):

$$\begin{aligned} PMV = {} & (0.303\, e^{0.036} + 0.028)\{(M-W) \\ & - 3.05[5.73 - 0.007\,(M-W) - p_a] \\ & - 0.42\,[(M-W) - 58.15] - 0.0173\, M\,(5.87 - p_a) \\ & - 0.0014\, M\,(34 - t_a) \\ & - 3.96\, 10^{-8}\, f_{cl}\, [(t_{cl} + 273)^4 - (t_{mr} + 273)^4] \\ & - f_{cl}\, h_c\, (t_{cl} - t_a)\} \end{aligned} \tag{5}$$

where,

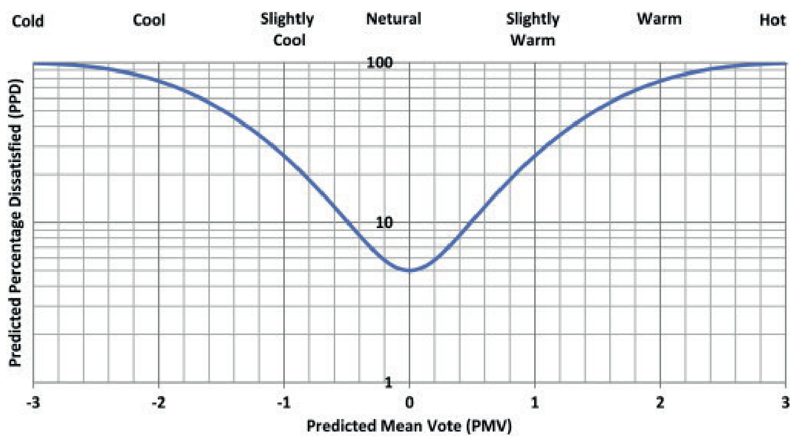
$$\begin{aligned} t_{cl} = {} & 35.7 - 0.0275\,(M-W) \\ & - I_{cl}\{(M-W) - 3.05\,[5.73 - 0.007\,(M-W) - p_a] \\ & - 0.42\,[(M-W) - 58.15] - 0.00173\, M\,(5.87 - p_a) \\ & - 0.0014\, M\,(34 - t_a)\} \end{aligned} \tag{6}$$

and f_{cl} is the clothing factor; h_c is the convective heat transfer (W/m^2 °C); I_{cl} is the thermal insulation of clothes (clo); M is the metabolic heat rate (W/m^2); p_a is the water vapor pressure (Pa); t_a is the air temperature (°C); t_{cl} is the temperature at clothes level (°C); t_{mr} is the mean radiant temperature (°C); W is the activity level (W/m²).

Based on the PMV, the PPD index was developed. PPD represents the percentage of participants experiencing thermal discomfort. The PPD index is expressed as follows (Equation 7).

$$PPD = 100 - 95\exp[-(0.03353\ PMV^4 + 0.2179\ PMV^4)] \qquad (7)$$

When the PPD value is set at 10%, the PMV range falls between -0.5 and +0.5. Even when PMV equals 0, approximately 5% of participants are still found to experience discomfort (Figure 6). This highlights the inherent variability in thermal sensation among individuals, emphasizing that complete thermal satisfaction is difficult to achieve for all occupants.



Şekil 6. Predicted dissatisfaction percentage versus mean thermal comfort vote (Ali Alahmer et al., 2011)

4. Emerging technologies and future perspectives

Advancements in technology not only enhance driving comfort and passenger satisfaction but also contribute to energy efficiency and sustainability goals. Improving thermal comfort supports health and quality of life, aligning with the objectives of well-being and sustainable living. Energy-efficient climate control systems promote the use of clean and sustainable energy, advancing the goal of accessible and clean energy.

Modeling approaches based on thermal physiology and psychology, innovative in-cabin climate control systems, and hardware solutions aimed at improving energy efficiency are critical for the future of automotive technologies.

In next-generation HVAC systems, artificial intelligence-based control algorithms and fuzzy logic approaches are increasingly employed to enhance energy efficiency and address individual thermal comfort needs. Data collected from in-cabin temperature and humidity sensors can be analyzed and optimized using methods such as artificial neural networks (ANN) (Afzal et al., 2020; Mirzabeygi & Natarajan, 2020), decision trees (DT) (Balta, Yalçın, Balta, & Özmen, 2022; Warey, Kaushik, Khalighi, Cruse, & Venkatesan, 2020), support vector machines (SVM) (Ju, Lim, & Jeon, 2022; Megri & El Naqa, 2014), and fuzzy logic models (Rajeswari Subramaniam, Cheng, & Pang, 2023; Singh & Kumar, 2024).

Fuzzy logic is a widely used approach in social sciences (Ergin, 2021; Ergin & Eker, 2019; Ergin, Feizollahi, & Kutlu, 2022; Baris Sandal & Ergin, 2023; Yağız, Sandal, Karabulut, & Salihoğlu, 2022), health sciences (B Sandal, Hacioglu, Yagiz, & Salihoglu, 2019; Baris Sandal, Hacioglu, Salihoglu, & Yagiz, 2023), and engineering (Ergin & Sandal, 2023; Barış Sandal, 2023), particularly in control applications (Hacioglu, 2015; Hacioglu & Yagiz, 2019; Ozer, Hacioglu, & Yagiz, 2016; Baris Sandal, Hacioglu, & Yagiz, 2024; Taskin, Hacioglu, & Yagiz, 2007; Yagiz, Hacioglu, & Taskin, 2008). Its flexibility in managing uncertainty and non-linear systems makes it critical in improving thermal comfort, especially in scenarios where a complete mathematical model is unavailable. These approaches provide not only effective solutions for reducing energy consumption and enhancing thermal comfort but also improve accuracy and performance in complex environmental conditions. Thus, they lay a strong foundation for the future of thermal comfort, enabling both energy efficiency optimization and tailored solutions for individual needs. This progress paves the way for adaptive and intelligent systems in vehicle thermal comfort, shedding light on the future of energy-efficient and passenger-focused HVAC technologies.

Integration of thermal comfort and air quality: The simultaneous evaluation of in-cabin thermal comfort and air quality is of critical importance for future HVAC systems. In a study by Kilic and Akyol (Kilic & Akyol, 2012), the effects of fresh air and recirculation modes on thermal comfort and air quality within vehicle cabins were examined. The study revealed that high CO_2 levels could jeopardize driving safety, highlighting the necessity for regular air renewal in the cabin. For instance, in recirculation mode, CO_2 levels exceeded 1200 ppm within 5 minutes and reached 3200 ppm within an hour. This finding underscores the need to optimize not only thermal comfort but also cabin air quality. Future systems must integrate advanced control technologies capable of reducing HVAC energy consumption while simultaneously maintaining thermal comfort and air quality. In this context, Kilic and Akyol's work suggests that innovative air distribution systems and sensor-supported approaches could play a significant role in enhancing thermal comfort and air quality.

Innovative air distribution systems: Research on the potential of three-dimensional air distribution systems for achieving thermal comfort in vehicle cabins highlights innovative approaches in this field. In an experimental study conducted by Lee (Lee, 2015), the implementation of a three-dimensional air conditioning system (3D AC) with additional ventilation units for rear-seat passengers was examined. The study demonstrated that the optimal placement of air diffusers to reduce thermal imbalances and enhance thermal comfort was behind the rear-seat passengers. This arrangement reduced temperature differences within the cabin to less than 2 °C, providing a more uniform thermal distribution between front and rear passengers. Furthermore, next-generation air distribution systems were found to achieve comfort parameters more rapidly with lower energy consumption, marking a significant advancement in in-cabin thermal management. Such systems contribute to sustainability goals by improving energy efficiency while paving the way for the development of more comfortable and adaptive solutions in the future. This progress underscores the importance of innovative air distribution technologies in advancing thermal comfort and energy-efficient HVAC solutions for vehicle interiors.

Role of MRT control: Controlling Mean Radiant Temperature (MRT) can help maintain thermal balance within the vehicle cabin, enhancing comfort and optimizing energy efficiency. Methods such as infrared reflective coatings and solar-blocking window films are highly effective in stabilizing MRT and reducing the load on HVAC systems. The impact of vehicle windows on thermal comfort and energy efficiency is substantial. Windows that reflect the infrared spectrum of sunlight can reduce interior temperatures by up to 9 °C, translating to energy savings of over 500 W for a parked vehicle. Additionally, such windows have been shown to improve the fuel economy of compact cars by approximately 0.3 km/l during operation (Farrington, Rugh, & Barber, 2000). Similarly, vehicles with silver reflective coatings can lower cabin air temperatures by 5–6 °C compared to black vehicles, reducing cooling loads by 13% (Levinson et al., 2011). These findings highlight the importance of solar radiation reflection in improving energy efficiency for both ICEs and EVs. However, studies examining the effects of solar radiation on in-cabin thermal comfort using human subjects are significantly limited compared to research on thermal comfort in buildings. This gap emphasizes the need for more comprehensive studies in automotive environments to further optimize thermal comfort and energy efficiency.

5. Conclusion and recommendations

Ensuring in-cabin thermal comfort is crucial for both individual satisfaction and energy efficiency. The factors influencing thermal comfort are interrelated and interact with one another, meaning that a change in one factor may require optimization of the others. It is important that future thermal comfort models adopt a more integrated and user-focused approach to understand the relationships among these factors.

Innovative technologies are needed to optimize the energy consumption of traditional HVAC systems. Technologies such as heat pumps and advanced air distribution systems have the potential to not only improve energy efficiency but also enhance comfort. Infrared reflective coatings can reduce solar radiation, balance indoor temperatures, and alleviate the load on climate control systems. Such technologies will contribute to sustainable transportation goals while simultaneously enhancing passenger satisfaction.

Energy efficiency has become an even greater priority in electric vehicles. Thermal management strategies should include not only solutions for the entire cabin but also more targeted approaches, such as localized heating and cooling. For example, innovative seat heating systems can reduce energy consumption while enhancing passenger comfort.

The integration of fuzzy logic and artificial intelligence-based control algorithms plays a key role in the future of in-cabin thermal comfort. These methods provide flexible solutions for adapting to complex and dynamic environmental conditions. Systems that integrate human physiological parameters with environmental factors pave the way for more adaptive and intelligent HVAC technologies.

In conclusion, future research must focus on developing more comprehensive models that encompass both dynamic and non-homogeneous in-cabin thermal environments. These models should be designed to support passenger-focused solutions while enhancing energy efficiency. Such an approach will make significant contributions to the automotive industry in line with sustainability and individual comfort objectives.

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CHAPTER 2

AN OVERVIEW OF TOPOLOGY OPTIMIZATION STUDIES FOR FIBER REINFORCED POLYMER COMPOSITES

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1. Introduction

Recently, the emergence of digitalization-oriented Industry 4.0 era, the increasing demand for multi-functional polymer-based materials as well as the advent of revolutionary additive manufacturing techniques have led to emergence of new study areas such as topology optimization. Increasing number of polymer-based materials have been introduced each year due to the unlimited possibilities proposed by these materials via several material, design, fabrication and enhancement routes. It could be also postulated that polymer-based materials, particularly composites, have been the subject of the highest number of studies in the field of engineering. Polymer-based composite materials can be categorized in various ways, including the production methods, types of reinforcing materials as well as the types of polymer matrices. Among these materials fiber reinforced polymer composites come to the forefront due to the significant improvement in mechanical properties they offer for the matrix materials in which they are incorporated. These materials have been employed for a great deal of period for structural applications and the main types of fiber reinforcements used for structural applications are carbon fiber reinforced polymer composites (CFRPs), glass fiber reinforced polymer composites, basalt fiber reinforced polymers and aramid fiber reinforced polymers (Fig.1).

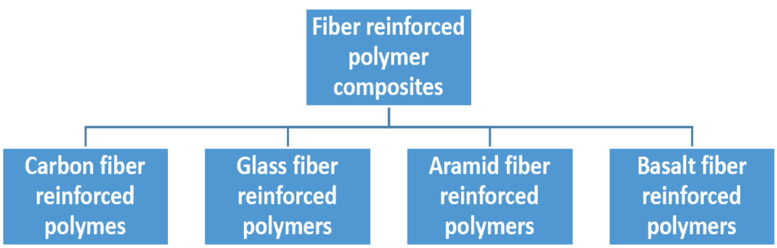

Fig. 1. *Classification of fiber reinforced composites based on the fiber types used for structural applications.*

With the advent of additive manufacturing and improvements in additive manufacturing techniques, the application areas of fiber reinforced composites have been expanded to fields other than construction such as functional engineering applications as in the cases of automotive and aerospace industries. Limitations as to the issues of environmental friendliness and recycling have brought about the employment of natural fibers as a substitution for inorganic fiber reinforcements in the fields where the attained improvements meet the structural and functional requirements. The limitations of the conventional production methods such as subtractive technologies have become disadvantageous in terms of design flexibility, acquisition of tailored material properties, minimization of raw material usage and even environmental issues for which additive manufacturing technologies offer a great deal of advantages. Since its introduction the mid-20th century, additive manufacturing or 3D printing technologies have made a great deal of process (Szederkenyi et al., 2024), such that, the materials for additive manufacturing have been expanded to other materials than polymers, including metal and cement-based materials. One of the common purposes of the abovementioned technologies is optimization of energy and material usage to meet increasing production volume demands without compromising material properties, even yielding better physical properties than the materials produced via conventional methods. Topology optimization (TO) is a powerful design method to derive optimum solution through satisfying boundary conditions in a certain domain in various areas of structural design (Shin et al., 2023; Yuhn et al., 2023). This review study aims to provide brief information related to the key subjects such as fiber reinforced polymer composites, and topology optimization. In the last section, an overview of recent research trends and studies on topology optimization studies for fiber reinforced composites will be introduced.

2. Fiber Reinforced Polymer Composites

Fiber reinforced polymer composites have been widely employed in various industries, particularly in construction industry to repair or strengthen structural components due their enhanced strength-to-weight ratio, high resistance against corrosion, and improved insulation (Nguyen et al., 2020). Aside from their relatively extended history in the field of construction, this material type has found other application areas such as defense (Fibre Reinforced Polymer Composit. in Defence App. – Kompozit Sanayicileri Derneği, n.d.), aerospace (Sreejith & Rajeev, 2021) automotive (Holbery & Houston, 2006), pipelines (Alabtah et al., 2021), etc. with the advent of new production technologies. Some of the important application areas for fiber reinforced polymer composites are shown in Fig.2. Fiber-reinforced polymer composites (FRPCs) mainly comprise of a matrix or a blend of a set of matrices preferably with high toughness, and this structural constituent is reinforced with fibers and high strength filaments, resulting with superior modulus of elasticity and tensile strength in addition to the improved design flexibility, low specific weight and high dimensional stability (Altin Karataş & Gökkaya, 2018; Poór et al., 2021). In a variety of application areas as shown in Fig. 2, these materials are subject to extreme conditions such as extremely high or low temperatures, high pressures, corrosion in marine environments, as well as ultraviolet (UV) radiation (Poór et al., 2021). Therefore, impairment and degradation in the strength of these materials under extreme conditions such as temperature and moisture have been the subject of numerous studies (K. Zhang et al., 2022). Particularly in civil engineering and pipeline industries, the deteriorations in the strength of the material under extreme conditions can be evaluated by non-destructive evaluation techniques (D. Li et al., 2021).

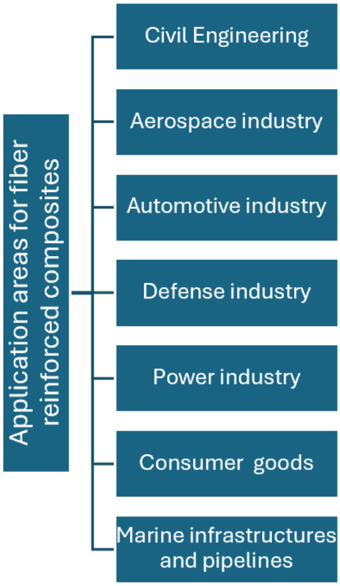

Fig. 2. *Some of the application areas for fiber reinforced polymer composites*

In the realm of fiber-reinforced composites, carbon-fiber reinforced composites find the widest usage due to the excellent mechanical and functional attributes yielded by carbon-based reinforcement materials such as carbon fibers. Carbon fiber reinforced materials rely primarily on the superior strength and stiffness provided by carbon fiber in a highly directional manner, while the matrix constituent acts as a tough binding component that holds the fibers together (D. Li et al., 2021; Melinda et al., 2023) as in the case of reinforced concrete. Due to their high resistance against extreme temperatures, superior strength and light weight, carbon fiber reinforced materials find wide usage in high-end applications such as aerospace, defense, automotive and consumer goods industries (Ahmad et al., 2020; Zheng et al., 2022). Fiber orientation (Fu & Lauke, 1996) and interfacial bonding (Bhuvaneswari et al., 2024) have been among the important issues to enhance the propertied of carbon fiber reinforced polymers. In the case of automotive industry, carbon fiber reinforced thermoplastics (CFRTP) are reported to be preferred over carbon fiber reinforced plastics (CFRP) which involve a thermosetting polymer as the matrix constituent as opposed to CFRTPs that involves a thermoplastic matrix. Reportedly, the fabrication route of CFRPs that require a chemical reaction to take place result in extended production cycle times as opposed to CFRTPs that require nearly a minute for the molding process to take place (Fujita & Nagano, 2017). In such applications, a controllable fiber orientation is crucial to acquire the designed properties (Fujita & Nagano, 2017). Fujita and Nagano (2017) proposed a method to assess the fiber orientation of FRCs in sheet form by exploiting thermal diffusivity (Fujita & Nagano, 2017). The distribution of fiber orientations within carbon fiber reinforced plastic composites has been evaluated via various non-destructive methods. For instance, Sugimoto et al. (2022) assessed the fiber orientation distribution of CFs within CFRPs using small angle X-ray scattering (SAXS) method. The authors postulate that, their method is also suitable for evaluation of the fiber distribution for organic fibers due to its reliance on scattering from elongated voids in carbon fibers (Sugimoto et al., 2022). Conventionally manufactured carbon fiber reinforced polymer composites comprise of laminates with single CF orientation, whereas composite laminates comprise of multiple CF layers having identical or varying orientations ((PDF) Effect of Fibre Orientation on Mechanical Properties of Carbon Fibre Composites, n.d.) In another research on evaluation of fiber orientation in CFRPs, Wiegel et al. (2023) proposed an algorithm for rapid assessment of in-plane fiber orientation by exploiting light microscopy images (Wiegel et al., 2023). The authors suggest that their method can be employed on large areas of interest owing to the low computation time and it required no preliminary information before the analysis (Wiegel et al., 2023). Reportedly, composite laminates are sensitive to structural failures arising from the directions of the applied load, which brings about the necessity to evaluate the change of mechanical properties for varying fiber orientations ((PDF) Effect of Fibre Orientation on Mechanical Properties of Carbon Fibre Composites, n.d.). Hence, simulation studies predicting the various attributes for different fiber orientations have also been conducted beside benefiting from the abovementioned non-destructive evaluation techniques ((PDF) Effect of Fibre Orientation on Mechanical Properties of Carbon Fibre Composites, n.d.). Aside from conventional fabrication of CFRPs with single or composite laminate structures, CFRPs can also be additively manufactured using specific 3D printing technologies. Majority of the studies on additively manufactured CFRPs also focus on quantification of fiber orientation and their distribution within the composite. Nargis and Jack (2023) attempted to quantify fiber orientation in additively manufactured carbon fiber reinforced acrylonitrile butadiene styrene (ABS) pellets using scanning electron microscopy (SEM) images and the method of ellipses (MoE) (Nargis & Jack, 2023). In another research, Parmiggiani et al. (2021) evaluated the impact of fiber orientation on the flexural and tensile behavior of thermoplastic polymers reinforced with continuous carbon fibers (CCFs) fabricated via fused filament fabrication (FFF) 3D printing technique. They compared the results with those of the samples reinforced with chopped carbon fibers to report the cons and pros of varying fiber orientation designs (Parmiggiani et al. 2021). One of the main advantages of additive manufacturing over conventional methods for CFRP manufacturing is the capability to control fiber orientation during the fabrication stage. In one of these attempts Zhang and Wang (2024) proposed magnetic field controlled (MFC) method for controlling fiber orientation during the 3D printing of nickel coated carbon fiber reinforced polymer composites via fused filament fabrication route (H. Zhang & Wang, 2024). Reportedly, by use of MFC method, the research managed to effectively improve the tensile strength and Young's modulus of the samples through controlling fiber alignment in CFRP samples (H. Zhang & Wang, 2024).

Fiber reinforced polymers are also the subject of numerous studies on enhancement of interfacial bonding between the matrix and the fiber constituent. Cheon et al. (2021) attempted to improve the bonding force at the polymethacrylimide (PMI) foam-carbon fiber interfaces in CFRP sandwich composite structures by producing holes having constant volume on PMI foam surface (Cheon et al., 2021). Li et al. (2021) conducted research on improvement of interfacial bonding between CFs condition under cryogenic conditions and epoxy resin. Reportedly, the authors employed a multiple stage cryogenic approach for optimization of the interfacial shear strength between the matrix and reinforcing components of the composite and achieved nearly 27% increase in the strength values (W. Li et al., 2021). As inferred by the above literature overview, majority of the studies related to FRPs involve carbon fiber reinforced composites CFRP and most of them focus on improvement of the overall material properties either by controlling fiber orientation or by improving interfacial bonding force.

3. Topology Optimization

In the simplest terms, topology optimization is a mathematical and computational design process to automatically optimize material layout in a specific design domain for a given set of assumptions, in which the main goal is to optimize the component performance and efficiency in terms of dimensional and functional considerations by building a mathematical model and evaluating the effect of factors such as loading and boundary conditions in addition to material properties an constraints (What Is Topology Optimization? | How-to Guide | NTop | NTop, n.d.; Wu et al., 2021). In broader terms, the formulation of a structural design problem can be achieved via optimization of the material distribution in a discretized domain of design (Bendsøe, 1989; Wu et al., 2021). The fact that topologically optimized layout is not restricted with the original topology paves the way for enhanced structural performance over conventional designs, hence, the technique has found a wide application area in key industries involving automotive, architecture, aerospace and healthcare (Wu et al., 2021). Key applications of topology optimization in diverse fields can be categorized into four groups as shown in Fig. 3.

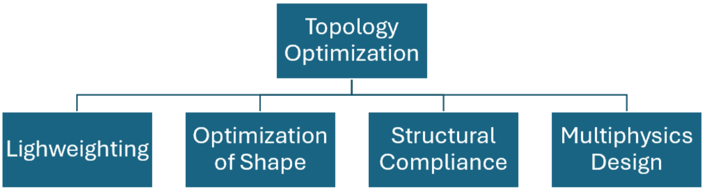

Fig. 3. *Applications of topology optimization*

In lightweighting applications, the main purpose is to gain the best strength-to weight ratio by minimizing (Hu et al., 2024). Shape optimization applications is related to creation of geometries based on a given set of constraints (Allaire et al., 2021). Structural compliance is more about evaluation of the effect of external forces and the geometry's response to these forces (Ooms et al., 2023), whereas multi-physics design is a process of inclusion of various physical phenomena to attain the optimal design based on these physical considerations (Maute, 2014; Simplest Topology Optimization Guide: Application, Advantages & More, n.d.). In the last three decades, numerous topology optimization techniques have been introduced by researchers. Among these the most popular ones were the level set method (LSM), evolutionary structural optimization (ESO) and density-based method (ZHU et al., 2021). Although the above-mentioned techniques have some advantages, the most popular one has become the solid isotropic material with penalization (SIMP) introduced by Bendsøe and Kikuchi (Bendsøe & Kikuchi, 1988) which has been commercially employed via computer aided engineering (CAE) software. Level set method utilizes Hamilton-Jacobi equation along with shape sensitivity analysis (Yulin & Xiaoming, 2004) whereas ESO relies upon the principle that the optimum structure could be achieved by gradual removal of excessive material from the domain of interest (Tanskanen, 2002). SIMP method, on the other hand, operates through keeping the FE (finite element) discretization fixed, after which each element is linked with a density function (Siva Rama Krishna et al., 2017). The complex geometrical characteristics of topologically optimized solutions mostly restrict the compatibility of this numerical technique to additive manufacturing methods.

4. Topology Optimization Studies for Fiber Reinforced Composites

Given the enormous extent of the subject, both in theoretical and experimental sides, it can be stated that, a vast number of studies have been introduced on the topology optimization of fiber reinforced composites, and a great deal more is likely on the way. The advent of Industry 4.0 and the improvements in additive manufacturing technologies have opened unlimited possibilities for researchers to control and optimize material properties during the manufacturing stage. Various ways of categorizing the studies can be offered under this subject. One way is to categorize based on the manufacturing technology such as molding or additive manufacturing. Another way is to categorize based on the type or form of reinforcing material. In the current overview of the recent research trends, the studies will be categorized as studies related to short (or chopped) fibers and those about continuous carbon fibers, since the principle of fabrication slightly differs for these materials.

4.1 Topology Optimization Studies for Short Fiber Reinforced Composites

Short fiber reinforced composites generally consist of a thermoplastic resin or polymer and various types of organic or inorganic chopped fibers, the majority of which are CFs. Inclusion of short fibers into thermoplastics enhances the materials mechanical performance particularly for applications where a high strength/weight ratio is required. An advantage of short fiber reinforced composites is the easier and more cost/effective fabrication route as compared to manufacturing of continuous carbon fiber reinforced composites which require specific modifications on the manufacturing equipment. Such advantages make these types of composites an important choice for most applications where the provided mechanical properties meet the requirements. Short fiber reinforced composites' mechanical properties depend primarily on fiber orientation (FOD) and fiber length distribution (FLD) (Fu & Lauke, 1996; Zhou et al., 2018). The strength of composites that involve short fiber reinforcements has a direct correlation with the mean fiber length and inverse correlation with the mean value of the angle between loading direction and fiber axis, also referred to as fiber orientation angle (Fu & Lauke, 1996). In the literature the studies may cover the use of both additive manufacturing methods and molding techniques.

Kurkin et al. (2024) recently introduced a methodology to topologically optimize polymer structures reinforced with short fibers by considering the anisotropy (E. Kurkin et al., 2024). The authors underline the importance of specific stiffness and strength in high-tech industries such as automotive and aerospace industries where weight reduction is essential. Their methodology involved establishing a dependence or correlation between the stiffness matrix and fiber orientation tensor, acquisition of fiber orientation tensor through performing fabrication simulations, to constitute a metric to evaluate short fiber reinforced polymer structures in terms of material usage and shape, and to realize the verification of the constituted technique via experiments (E. Kurkin et al., 2024). As a conclusion, the instances where predetermined anisotropy was considered resulted with increases in stiffness owing to the fiber orientation (E. Kurkin et al., 2024). In another work of Kurkin et al. (2021), the authors introduced the technique to consider material anisotropy for topology optimization of short fiber reinforced composite structures and emphasized that this approach can yield considerable change in the structure's topology as it could be possible to enhance the stiffness of bracket parts in aerospace industry made of short carbon fiber reinforced polymers (E. I. Kurkin et al., 2021).

Ospald and Herzog (2018) performed a topology optimization study on short fiber reinforced composites manufactured via injection molding. In their research the authors attempted to substitute costly fiber orientation (FO) simulations with the solution of an eikonal equation to find the principal fiber orientation (Ospald & Herzog, 2017). As a conclusion of the study where they first modelled the material, stated the elasticity and optimization problems, and then introduced the numerical results, they concluded that, parts made of short carbon fiber reinforced polymers should be produced thicker in areas where fiber orientation is uncertain, and thinner in areas with optimum fiber orientation (Ospald & Herzog, 2017).

Almeida Jr. et al. (2023) proposed a method for concurrently assessing fiber orientation and topology optimization for additively manufactured fiber reinforced composites (Almeida et al., 2023). The novel approach they propose is reported to be capable of optimizing fiber angle and topology for minimization of the structure's compliance. The authors underline the fact that, in the last three decades, the number of topology optimization studies have reached to a saturation due to the extent of the knowledge on isotropic metallic materials and the manufacturing techniques compatible with complex metallic shape designs (Almeida et al., 2023). They also emphasize that, the increased use of CFRPs in aerospace and automotive industries has paved the way for increasing number of studies accounting for the anisotropic nature of these materials (Almeida et al., 2023). They accordingly proposed a robust methodology to concurrently optimize both the topology and the fiber angle for additively manufactured composites and concluded that, concurrent control of fiber angle in 3D-printed samples yields the optimum stiffness values among all other scenarios (Almeida et al., 2023).

Islam and Liu (2024) carried out research on topology optimization of fiber reinforced and additively manufactured materials characterized with discrete fiber orientations and proposed a method utilizing a penalized normal distribution (PND) function to control fiber orientation based on discrete predefined angles (Islam & Liu, 2024). They state that, fibers are usually steered in printing domain, often with previously determined discrete angles, which brings about the necessity to consider the manufacturing constraints along with structure and orientation optimization (Islam & Liu, 2024). Reportedly, their numerical models prove the advantage of concurrent use of discrete angle optimization with the optimization of the structure, as the structural topology is optimized by considering 3D printing constraints (Islam & Liu, 2024).

4.2 Topology Optimization Studies for Continuous Fiber Reinforced Composites

Continuous fibers differ from chopped or short fibers in a couple of ways. Reinforcing fibers may be deemed continuous at a point where their mechanical attributes no longer correlate with the length of the fiber (Green, 2012). The highest strength can be obtained from continuous fibers when they are positioned unidirectionally, however, the direction perpendicular to the fiber orientation shows low strength (Green, 2012). When a comparison is to be made between continuous and short fibers, it can be stated that, the use of continuous fibers result with higher stiffness and higher strength of the overall composite structure (Green, 2012). The disadvantage of continuous fiber composites when compared with short fiber reinforced composites is their lower moldability and the limited ability to be mixed with other reinforcing gradients such as micro and nano-dimensioned fillers (Chung, 2016). As a conclusion it can be stated that, continuous fiber reinforced composites are more suitable for highly demanding structural applications, whereas short fiber carbon reinforced composites are more suitable for functional applications with less demanding structural requirements such as electromagnetic interference (EMI) shielding or the casing of an electronic component (Chung, 2016). Reportedly, the mechanical performance of continuous fiber reinforced composites vary with the level and nature of the fiber, its aspect ratio, fiber dispersion, orientation and the overall anisotropy in the final component, treatments to improve interfacial bonding between the fiber and the matrix, as well as the real fiber length in the final part (Green, 2012; Introduction to Continuous Fiber Composites: Future of High-Performance Materials, n.d.). An overview of the studies on the topology optimization of continuous fiber composites is provided below.

Luo et al. (2023) introduced a novel design approach for spatial optimization of fiber reinforced composites via iso-surface control of 3D printing constraints (Luo et al., 2023). The authors based their research on the optimization of fiber volume fraction, local fiber orientation and utilization of a density-based approach for topology optimization to achieve an optimal design. The authors underline the fact that, in 3D printing of fiber reinforced composites, the orientations of fibers are controlled by the printing head which follow deposition instructions and directions, hence steering the printing head to achieve the control of fiber orientation has been an effective technique to draw on full potential of anisotropic properties (Luo et al., 2023). They introduced a numerical model of a cantilever beam to demonstrate the efficiency of the proposed approach and concluded that, the proposed approach yielded well control of manufacturability and fiber volume fraction although the compliance significantly increased in the case of manufacturing constraints (Luo et al., 2023).

In recent research on topology optimization of continuous-fiber reinforced composites, Luo et al. (2024) introduced an approach considering the manufacturability and buckling resistance (Luo et al., 2024). The authors emphasize that buckling in structures may be inevitable under compressive loads due to the geometrical inconsistencies, member's slender structure and other material properties. Considering this, they attempted to combine fiber orientation optimization and topology optimization to optimize the buckling resistance of additively manufactured short-fiber reinforced polymer parts (Luo et al., 2024). In their novel approach they included linear buckling analysis and underlined the advantage of using continuous fibers to reinforce polymer structures (Luo et al., 2024).

Guo et al. (2024) carried out topology optimization studies on continuous fiber reinforced composites by utilizing Shepard interpolation coupled with design variable reduction (Guo & Zhou, 2024). Their optimization framework was intended for truss-like materials reinforced with continuous fibers, and reportedly, by utilizing the Shepard interpolation approach, they managed to interpolate the fiber morphology for a specific computational point via scattering design variables in a circular domain (Guo & Zhou, 2024). They demonstrated the efficiency and applicability of the proposed approach by numerous numerical instances in their research (Guo & Zhou, 2024).

Li et al. (2021) performed research on how to conduct a full-scale topology optimization for continuous fiber reinforced composites by addressing the restrictions for topology optimization studies such as discontinuous fibers, reduced design of freedom, complex fiber orientation optimization routes as well as the separation of length scale (H. Li et al., 2021). They accordingly built their methodology upon a framework on density-based topology optimization of a bi-material element and treated the reinforcing and matrix materials in a uniform FE model devoid of scale separation. They validated the efficiency of the proposed approach via design procedure and error simulation analyses (H. Li et al., 2021).

Boddeti et al. (2020) introduced a work on the optimal design and fabrication of continuous fiber reinforced composites with variable stiffness (Boddeti et al., 2020). The authors underline the importance of high-end manufacturing methods such as additive manufacturing as they enable the design and manufacturing of materials with complex geometries and multiscale material properties. Their methodology involves enabling the spatial variation of stiffness for laminated continuous carbon fiber composites, thus they adopted the multiscale topology optimization, voxel-based jetting and an algorithm based on mesh parametrization for this purpose. They validated the simulations by experimenting on two planar structures (Boddeti et al., 2020).

5. Conclusion

The present study is intended to provide a brief overview of the recent research on topology optimization of short and continuous fiber reinforced composites produced either via conventional manufacturing methods such as injection molding, or additive manufacturing methods which provide a broader control of parameters such as fiber orientation, thus realizing more efficient optimizations. The findings of the studies performed in this field show that, the progress achieved in the field of fiber reinforced composites equally rely on the numerical and experimental efforts to improve the interfacial bonding between the reinforcing and structural constituents of the composites as well as optimization of the fiber orientation distributions within the structure. With increased replacement of structural materials with fiber reinforced polymer materials in the key industries, the focus on this subject is likely to increase as well, warranting more research efforts to improve the mentioned attributes.

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CHAPTER 3

TRIBOLOGICAL PROPERTIES OF POLYMER COMPOSITES: A REVIEW

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1. Introduction

Polymers and polymer-based composites and nanocomposites have been attracting increasing interest from academic and industrial domains, due to the endless possibilities they offer in terms of enhancement of structural and functional properties in several applications. Each year, polymer-based materials have been replacing their metal-based counterparts in increasing number of applications due to the advantages such as strength-weight ratio, design flexibility, cost efficiency, ease of manufacturing as well as acquisition of tailored properties. The significance of polymers has been even bolstered by emergence of additive manufacturing technologies in Industry 4.0 era. The primary routes to improve the properties of polymer materials are fabrication of polymer blends from different polymers and fabrication of polymer composites via incorporation of reinforcing materials of several types and in several forms. Polymer based materials are classified into three main groups, namely thermoplastics, thermosets and elastomers. The main types of polymers and forms of materials used as reinforcements are shown in Fig. 1.

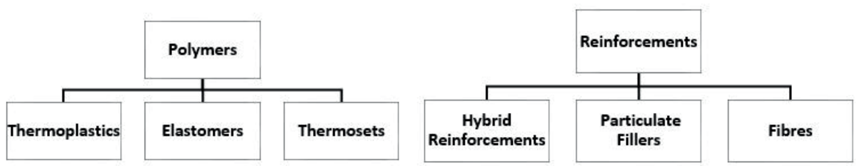

Fig. 1 *Classification of polymers and reinforcing materials.*

Extensive efforts in scientific and academic domains to minimize material loss by controlling friction and wear have been extended to polymers for a long time now, since polymers and polymer-based materials have been used as bearing and slider materials (Bartenev, n.d.). Moreover, polymer composites with self-lubricating capabilities have paved the way for new possibilities in applications where the use of lubricants is not suitable (Fusaro, 1990). In this regard, polymers and polymer-based materials have been the subject of a vast number of studies which mainly address the following issues: the routes in fabrication and material design specifically adopted for reducing friction and wear, as well as investigation of the synergistic effect of different polymer matrices and reinforcements used to fabricate polymer composites and nanocomposites. The conventional applications for polymer-based tribo-components involve include various sliding elements in automotive components, textile machine components and other applications where polymer-based bearings and bushings are used (Friedrich, 2018). The subjects associated with tribology of polymer-based materials also involve enhancement of other material properties such as electrical and thermal conductivity (Bartoli et al., 2022), mechanical resistance against extreme conditions such as high temperature (Chang et al., 2007) and cryogenic environments (S. Chen et al., 2023), optimization of the various parameters of composite fabrication techniques such as compounding, compression molding, extrusion and additive manufacturing, as well as optimization of fabrication parameters via algorithms and prediction of wear behavior via data processing and training (G. Cheng, Xiang, et al., 2023). In this regard, this review study on enhancement of tribological properties of polymer-based materials initially aims to provide the readers with fundamental information on structural and physical properties of polymer-based materials, friction and wear of polymer-based materials, and finally recent research trends on tribological properties of polymer-based materials.

2. Structural and Physical Characteristics of Polymers

Organic polymer structures can be defined as large molecules, or macromolecules, that can also be described as chains of regularly repeating structural units, "monomers" (Guerra, 1989). The complicated interrelation between the structure and physical properties of polymer structures is the key subject that researchers aim to understand to design new polymeric materials (Veksli et al., 2000) such as smart polymers (Mu & Ebara, 2020), shape memory polymers (Dayyoub et al., 2022), biocompatible polymers (Arif et al., 2019), electro-optical polymers (Ullah et al., 2021) self-lubricating polymers (Aderikha & Krasnov, 2013), etc. Polymers basically exist in four states, crystalline state and the three amorphous states namely, rubbery, glassy and viscous flow (Jena et al., n.d.). Polymers' physical states are governed by their specific thermos-mechanical curves, indicating their mechanical and structural attributes at different temperatures. A general thermo-mechanical curve for polymers is provided in Fig. 2. Below the glass transition temperature T_g polymer materials deform as a "low-molecular-weight-glass", and above this temperature, the materials' capability to exhibit reversible strain increases dramatically, thus exhibiting the rubbery state until the flow temperature (T_f), after which the material is in a highly viscous liquid state (Bartenev, n.d.). Polymers that exist in highly crystalline state at room temperature constitute a class of engineering plastics that have found wide usage in industrial applications. This type of polymers is also referred to as semi-crystalline polymers, since a fully crystalline state is impossible to achieve with common processing routes (S. Z. D. Cheng & Jin, 2002). These polymer structures can be more precisely defined as polymers with highly or adequately regular crystalline chain structures (Gedde, 1999). These materials involve an amorphous and a crystalline phase, and the degree of the crystallinity of the structure is evaluated based on the latter. These materials involve voluminously produced polymers such as nylons, polyesters, polyethylene and polypropylene. Polymers referred to as glass polymers are amorphous polymers that practically exist in glassy state at room temperature or under their glass transition temperature, and these are characterized by a highly stiff non-crystalline structure (Jansen, 2015). This polymer class involves polycarbonate (PC), polyamide (PA), polyimide (PI), polyvinylidene fluoride (PVDF), polysulfone (PSU), etc. (Mannan et al., 2020). Rubbery polymers also exhibit an amorphous structure as glassy polymers, however this structure is not frozen as in the case of glassy polymers, since these materials are practically above their glass transition temperature at room temperature (Ludovice, 1999). This polymer type has natural and synthetic types and is characterized with the capability to deform under lower loads, quickly regaining its original shape once the load is withdrawn. These materials have particular importance in the automotive industry as raw materials for tires. Physical states of polymeric materials are shown in Fig. 3.

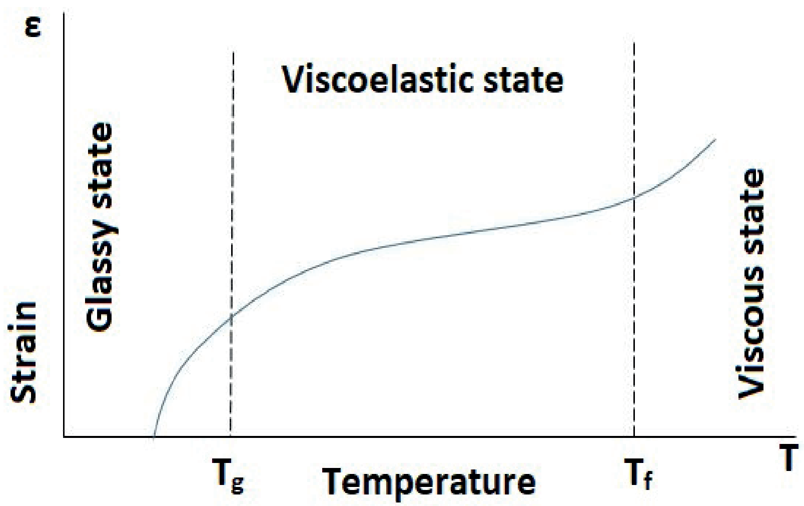

Fig. 2 *General thermo-mechanical curve for polymers.*

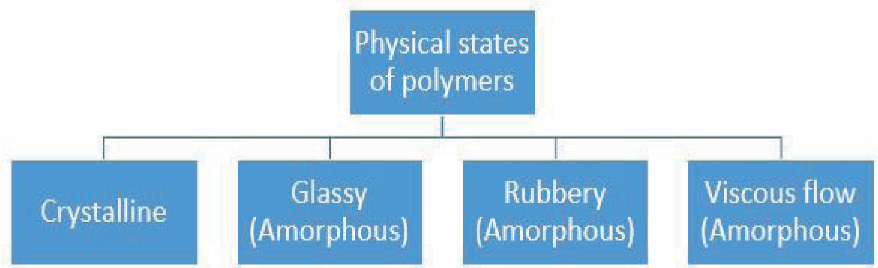

Fig. 3 *Physical states of polymers.*

Polymers are also categorized as thermoplastics, thermosets and elastomers. These classes differ from each other mainly by their processing and recycling capability, such that, due to the weak non-covalent bonds of linear chains within the thermoplastics, they can experience phase transitions and operate in a wide range of temperatures without decomposing. The cross-linked structure of thermosets with covalent bonds on the other hand keep them in solid phase until the polymer chains finally decompose (Abdelbary, 2014). The advantages of thermoplastic materials involve excellent ductility, ease of processing and recycling, whereas thermosets exhibit superior solvent resistance, thermal stability and rigidity in return (Madhav et al., 2019). Elastomers are natural or synthetic rubber-like polymeric materials that stretch twice their original length under the room temperature with the capability to return to its approximate original length in a certain time as the force is withdrawn (Rosato et al., 2004).

3. Friction and Wear of Polymers

As a common phenomenon in industry and casual life, friction can be characterized by the processes that arise on the surface layers of bodies in contact moving in relative motion (Myshkin et al., 2005). Friction, for most of the materials including polymers can be modelled using two primary components which are considered to have no interdependence, and these are deformation and adhesion. In this regard, the subjects that should be covered to fully understand friction can be listed as: a) type and strength of interfacial bonds; b) the shearing and rupturing of counter-surface materials in the vicinity of the contact region, and c) the real contact area (Myshkin et al., 2005). Adhesion can be defined as the attraction phenomenon between particles and surfaces which result with their contact. The adhesion process has a significant role in terms of friction and wear. Aside from the tribological aspect, adhesion is also crucial for many other applications such as cold welding of metals, adhesives and biomedical applications. The degree of deformation on polymer surfaces has significant effect on the characteristics of polymer joints that are in relative motion, thus, the tribological behavior of polymers depends largely on this property (Nazarenko et al., 1967). The adhesion constituent of the friction phenomenon is dependent on the adhesive junctions that emerge in the real contact area between the mating surfaces, whereas the deformation constituent of friction model arises from the polymer's resistance against the ploughing effect of the harder counter-body's asperities (Myshkin et al., 2005). During the relative motion of two surfaces in contact, the adhesion of the asperities of counter-bodies in addition to other interactions act as sources of frictional force. The real contact region that occurs between the moving counter-bodies is a significantly small portion of the nominal contact region (Jiang et al., 2017). The information of nominal contact area can be useful for evaluating the friction-induced contact temperature; however, it is the total of asperity contacts comprising a small portion of the nominal area that carries the load applied (Kalin & Vižintin, 2000). In a friction model, information related to deformation, distribution of pressure, contact stresses as well as the area of contact can be obtained using the Hertz theory ("Fundamentals of Contact Mechanics and Friction," 2014).

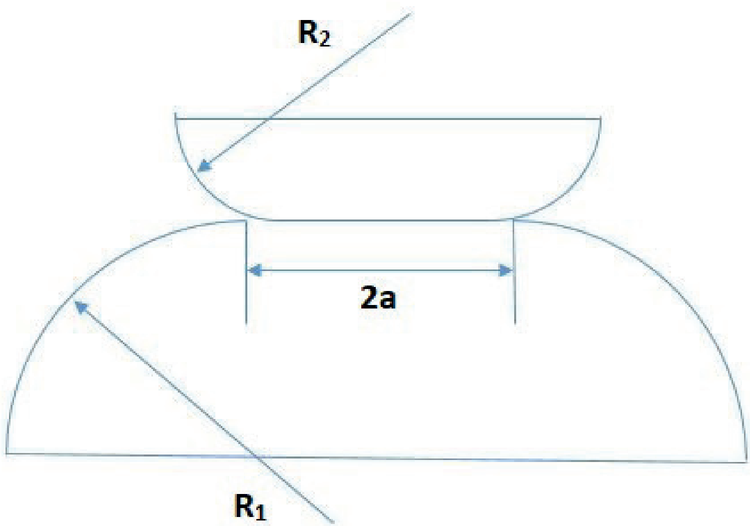

Fig. 4. *Two spheres in contact under load*

When the contact spheres of two different materials with radii R_1 and R_2 upon loading shown in Fig. 4 are assumed, the effective or reduced elastic modulus "E*" can be calculated as follows, where E_1, E_2, v_1 and v_2 are the young's moduli and Poisson's ratios for the counter-bodies, respectively.

$$\frac{1}{E^*} = \left[\frac{(1-\nu_1^2)}{E_1} + \frac{(1-\nu_2^2)}{E_2}\right] \quad (1)$$

Accordingly, the contact radius *a* can be calculated as follows; where P is the normal load, R is the radius of curvature of the contact region calculated from R_1 and R_2 ($\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$):

$$a = \frac{3RP^{\frac{1}{3}}}{4E^*} \quad (2)$$

As in the case of relative motion of other materials, the friction and wear of polymer materials vary depending on various factors such as load, sliding speed, ambient temperature, etc.

4. Recent Research Trends on Tribological Behaviors of Polymer Composites

The tribological properties of polymer-based materials have been the subject of various research studies. The studies either specifically concentrate on the friction and wear properties of polymer blends, composites and nanocomposites, or the tribological aspects are integrated in a broader scope such as the studies involving electrical (Nowacki et al., 2024), thermal (Rasul et al., 2022), flame-retardancy (You et al., 2019), and mechanical (Sharma & Kumar, 2020) studies. There is also an increasing trend in the tribological behavior of additively manufactured polymers and polymer-based composites. In this review study, the studies on tribological properties of polymer-based materials have been addressed under specific sections, although the extent of these sections may overlap in some cases.

The subject of polymer nanocomposites is an extensive domain in the field of polymer studies and involves numerous types of additives, matrices, production routes, etc. Most of the studies on polymer nanocomposites involve reinforcement of polymer matrices or blends with carbon-based fillers and these studies mainly focus on the enhancement of thermal, electrical and tribological properties of polymer-based materials. Some of the recent research and their findings are provided in this section.

Cheng et al. (2023) conducted molecular dynamic simulation-based research to evaluate the tribological mechanisms of a polymer interface at low temperatures (G. Cheng, Chen, et al., 2023). The authors underline the importance of the tribological degradation of polymers under polymer-metal contact at low temperatures for several industries including aerospace, automotive and biomedicine (G. Cheng, Chen, et al., 2023). In the research, the authors compared the macro and micro tribological evolution processes of polychlorotrifluoroethylene (PCTFE) and fluorinated ethylene propylene copolymer (FEP) for different operational conditions including low temperature and they theoretically supported their evaluation with molecular dynamics simulation. Reportedly, molecular dynamics simulation studies aided in evaluation of mechanisms underlying microscopic interaction, as well as the evolution of temperature for the interface of polymer-metal pairs. The authors also emphasize that, tribological performance should not be considered as an inherent material property but it should be rather regarded as a system behavior acting under the effect of various factors (G. Cheng, Chen, et al., 2023).

Uyor et al. (2019) performed research reporting enhanced mechanical and tribological performance of multifunctional polymer nanocomposites intended for various engineering applications (Uyor et al., 2019). The authors point to the significance of surface modification of materials as this route help in their protection against frictional and corrosive harsh conditions without altering the overall bulk characteristics of the target material for intended use. In this regard the authors reinforced the poly(vinylidene fluoride) with titanium di-oxide and surface modified graphene nano-fillers to investigate the mechanical and tribological enhancements of the matrix. They reported a 76.5 % drop in worn volume, also 186.5 % and 52 % improvement in the modulus of elasticity and tensile strength of the neat blend upon filler addition. They attribute the significant improvement in the mechanical and tribological properties to the surface modification of nano-fillers which led to improved dispersion of nanofillers within the matrix (Uyor et al., 2019). Most of the studies on mechanical and tribological enhancement via addition of polymer nanofillers report similar results on the importance of achievement of an enhanced dispersion of fillers in acquisition of enhanced physical and functional properties.

In another research on the effect of nanofiller addition on the tribological properties of various polymers, Karteri et al. (2023) evaluated the effect of graphene nano-platelet (GNP) addition on the friction and wear behavior of polypropylene (PP)-acrylonitrile butadiene styrene (ABS) blends (Karteri et al., 2023). Reportedly, PP-ABS-GNP samples were fabricated by extrusion and injection molding methods where the blend matrices were reinforced with GNP nano-filler with weight rations varying between 3 wt. % and 11 wt. %. In their research, the authors emphasis the importance of the use of polymeric materials in various industries such as automotive and aviation against conditions where tribo-systems occur. Reportedly, PP and ABS as important engineering thermoplastics have found wide application in the automotive industry including interior doors, seat back and various other automotive components. Their blend with PP also has high potential for use in these industries, as the drawbacks of one polymer constituent can be compensated by integration of the other polymer into the system. In this research, the incorporation of GNPs into the polymer blend is believed to improve the tribological performance of the blends owing to the fillers' self-lubricating capabilities as well as the high aspect ratio which is regarded as a highly advantageous attribute in terms of mechanical properties (J. Chen et al., 2019). Indeed, the findings of this study revealed significant reductions in both coefficient of friction (COF) and specific wear rate (SWR) values up to an optimum weight fraction of 3 wt. % after which agglomeration-induced impairment of dispersion is reported. Reportedly, the thermal camera measurements also revealed that the thermal stability provided by GNP addition seems to have contributed the enhancement of the tribological performance of the polymer-based samples (Karteri et al., 2023).

Ferreira et al. (2018) produced polymer nanocomposite samples of high-molecular-weight polyethylene (HMWPE) and their blends with ultra-high-molecular-weight polyethylene (UHMWPE) (80/20 wt.%) reinforced with trace amount of (lower than 0.1 wt.%) multilayer graphene oxide (mGO) nanofiller with a twin-screw extruder to evaluate the effect of nanofiller addition on the tribological properties of the single and double matrix polymers (Ferreira et al., 2021). Reportedly, the viscous behavior of both polymers resulted in high levels of agglomeration of the nanofillers within the matrices, whereas both the mechanical and tribological properties of the filled samples proved to be better than the neat samples. The authors explain such improvement despite the adverse effect of agglomeration to a super-lubricating characteristic of the agglomerates of multilayer graphene oxide particles. Another contributing effect of mGOs was reported to be their well-exfoliation which led the authors to postulate that, agglomeration can act in favor of mechanical and tribological properties as opposed to most studies reporting the negative effect of agglomeration (Ferreira et al., 2021).

Roy et al. (2020) evaluated the friction and wear characteristics of polyimide (PI) coatings reinforced with carbon nanotubes (CNTs) at room and high temperature conditions (Roy et al., 2020). They also emphasized that the self-lubrication capability of polymer coatings characterized by enhanced wear resistance have led to the replacement of conventional lubricants with these materials which is deemed as an important measure against environmental pollution (Roy et al., 2020). Reportedly, polytetrafluoroethylene (PTFE) has been widely preferred as a self-lubricant material as coating material for rolling components as in the case of printing, textile, tobacco and sports applications. However, the authors underline the wear resistance of this material against wear and its inapplicability under high temperatures, thus suggesting the use of polyimides (P) for the same purpose. In this regard the authors incorporated CNT fillers into PI matrix to obtain PI/CNT composites with improved thermal, mechanical and tribological attributes. They accordingly reported important enhancements in the microhardness, thermal stability, and tribological performance of the samples reinforced with CNT nanofillers. They attributed such enhancements in the investigated characteristics to formation of organic-inorganic microstructures that reduce the thermolysis phenomenon in the produced coatings while improving their mechanical properties (Roy et al., 2020).

Hussein et al. (2018) fabricated epoxy resin (EPRY) based nanocomposites reinforced with mixed GNP and multiwalled carbon nanotube (MWCNT) nano-fillers via ultrasonic aided dissolution casting method to observe microstructural and thermal attitudes (Hussein et al., 2018). They characterized the following samples via Fourier transform infrared spectroscopy (FT-IR), transmission electron microscopy (TEM) and field emission scanning microscopy (FESEM). They accordingly reported that the introduced nanofiller fractions led to marked improvements in thermal, coating and conducting characteristics of the non-filled EPYR coating (Hussein et al., 2018).

Some researchers' approach involves the application of nanofillers and natural fillers in micro or macro dimensions in a hybrid fashion to reinforce polymer-based materials, by which the advantageous attributes of nano and macro-dimensional fillers are intended to be drawn on. In one of these attempts Kishore et al. (2021) conducted research to evaluate the tribological properties of epoxy polymers reinforced with jute and basalt fibers in addition to nano-graphene as the nanofiller reinforcement (Kishore et al., 2021). Reportedly, the authors motivation was conducting research using graphene-based fillers since most similar works was based on graphite-based fillers, in addition to the use of a hybrid approach for the use of natural fibers and nano-fillers as reinforcement material for fillers. As a conclusion, the authors reported marked reductions in coefficients of frictions and wear rates and related the improved wear resistance of graphene-reinforced hybrid composite to the lubrication characteristic of this filler (Kishore et al., 2021).

It can be concluded based on the above literature review that, most of the concern in the studies related to reinforcement of polymers with various nanofillers is to attain maximum lubricating, thermal, electrical and other attributes of nanofiller particles without compromising the mechanical properties of polymer matrices that is likely to occur after certain weight fractions due to agglomeration of these particles.

It can be observed from the extent of the studies on incorporation of nanofillers in polymer-based materials that, such research studies rely rather on experimental findings with a deeper focus on microstructural changes and property alterations via microstructural, thermodynamical, thermal, electrical and other characterization techniques. On the other hand, research on polymer composites reinforced with fibers seem to cover a broader number of studies using theoretical approaches to predict and optimize the various physical and tribological properties obtained via incorporation of fillers.

In one of the recent studies, Birleanu et al. (2024) investigated the tribological performance of polymer composites reinforced with glass fibers against chrome alloy steel and they conducted their research with ELECTRE decision making method (Birleanu et al., 2023). In this research the mechanical response of a fiber-reinforced polymer composite is correlated with the modulus and the strength of the used fiber reinforcement, the chemical stability and the strength of the matrix, as well as the extent of bonding between the interface of the matrix and the fiber which is believed to play a major role in the transfer of stresses arising within the structure (Birleanu et al., 2023). They also reported that one of the main application areas of fiber-reinforced polymers is brake components in trains and automobiles in the transportation and automotive sector where tribological concerns need to be taken seriously. In this regard, they produced glass-fiber (GF) reinforced polymer composites, performed ball-on-disc experiments to acquire the friction and wear data, and then analyzed the results using a decision-making method called ELECTRE, abbreviation for elimination and choice translating reality. After the conducted characterization and experimental studies, the authors concluded that, addition of glass fiber reinforcements did not have a considerable effect on the tribological behavior of the matrix material (Birleanu et al., 2023).

Another research on hybrid use of fiber components with nano-fillers was performed by Chen et al. (2023) on evaluation of tribological response of carbon-fiber-reinforced-polymers (CFRPs) further reinforced with highly oriented graphite nanoplatelets (GNPs) (Y. Chen et al., 2023). The researchers prepared CFRPs by epoxide resin (EP) as the polymer matrix, carbon fiber sheets (CFS) as the fiber component and GNPs via compression molding technique, which is a widely employed technique to produce CFRPs.

Li et al. (2022) evaluated the tribological and mechanical properties of composite polyetheretherketone (PEEK) coatings produced via thermal spraying and reinforced with carbon fibers (Li et al., 2022). Carbon fiber reinforcement materials can be roughly categorized as short fibers and continuous fibers and the composites reinforced with these materials differ in terms of fabrication routes. In the study performed by Li et al. (2022), the researchers used two types of short carbon fibers (CFs) that differ in dimension as 300-mesh and 600-mesh and these were incorporated in PEEK coatings by weight fractions of 10 and 30 wt. %. Reportedly, increasing the CF content resulted in higher porosity for the produced samples. Moreover, inclusion of CFs within the polymer structure is reported to result in a limited thermal degradation for the polymer in addition to a lower degree of crystallinity (Li et al., 2022). Overall, the best option in terms of nanoindentation and tribological response is reported to be 10 wt. % CF addition with 1.31-fold higher hardness as compared to the neat PEEK samples. CFs with 600-mesh size were reported to perform better in terms of tribological performance, which was attributed to the higher degree of graphitization (Li et al., 2022).

One of the biggest impacts of the advent of Industry 4.0 era has been the application of additive manufacturing methods, which has been initiated for polymer-based materials and expanded its application area with metal-based materials and even cement-based materials in the construction sector. Application of additive manufacturing method for polymer-based materials and their composites have paved the way for countless new possibilities in the research domain of polymer-based materials. The biggest advantage of additive manufacturing over the other conventional methods is the design flexibility, which enables the production of complex materials, hence the emergence of new optimization areas such as topology optimization. Moreover, the control and monitoring of the production process has been facilitated with additive manufacturing via digitization and direct transition from design to production, hence a higher extent of data analysis and utilization also emerged as another advantage. With additive manufacturing, the production of composites that have numerous challenges and high costs have become more flexible and easier as in the case of the production of continuous fiber reinforced materials. For such materials, issues such as fiber orientation has crucial impacts in terms of the overall strength of the produced material, and with additive manufacturing, the desired fiber orientation is enabled with high accuracy. The main disadvantage of additively manufactured composites, compared to their conventionally produced counterparts is the weaker interfacial bonding between the reinforcing and structural materials which arises from some of the limited processing parameters compared to the other methods such as compression molding and extrusion, thus the focus in additive manufacturing-based studies is to improve the interfacial bonding between the structural and the reinforcing constituents. Research on the properties of additively manufactured polymer composites also involve tribological studies and some of the recent research on the subject are summarized below.

Balan and Raj (2024) studied the tribological response of functional coated and fiber reinforced 3D printed polymer composites and in their research, they used the fusion deposition modeling additive manufacturing process followed by thermal spray and spin coating for deposition of hafnium carbides onto the surface of 3D printed samples (Balan & Aravind Raj, 2024). This hybrid approach combining the additive manufacturing process with coating routes is reported to yield improved tribological performance for CF reinforced polylactic acid (PLA-CF) samples in addition to higher resistance against thermal degradation compared to the uncoated composite samples (Balan & Aravind Raj, 2024).

Batista et al. (2023) used fused filament fabrication (FFF) method to produce additively manufactured polymer composites (Batista et al., 2023). As also stated by the authors, FFF is the most widely adopted technique to fabricate 3D printed materials primarily using thermoplastic materials such as nylon (Polyamide), acrylonitrile butadiene styrene (ABS), thermoplastic polyurethane (TPU), polylactic acid (PLA) and polyethylene terephthalate glycol (PETG) (Batista et al., 2023). In their research the authors evaluated the mechanical and tribological performance of additively manufactured CF-reinforced PETG samples. As a result of the performed tests, the CF reinforced PETG turned out to exhibit lower tensile strength compared to the neat samples, whereas it outperformed the neat sample in terms of compressive strength. In terms of tribological performance PETG-CF samples turned out to exhibit higher coefficients of friction compared to the neat PETG samples (Batista et al., 2023).

In terms of the used fibers, fiber reinforced polymer composites can be roughly categorized as those reinforced with inorganic fibers such as carbon, glass, etc., and those reinforced with organic fibers, also referred to as natural fibers, which can be obtained from nature instead of using chemical routes. Natural fibers are also characterized with notable mechanical properties and draw interest from the researchers due to the advantageous properties such as cost efficiency, biodegradability, recycling as well as environmental considerations.

In one of these studies Erdoğdu and Temiz (2022) studied the friction and wear response of natural fiber reinforced polyurea composites also reinforced with nanofillers (Erdoğdu & Temiz, 2023). The authors attempted to address hydrophilicity the poor (UV) resistance of natural fiber reinforced polymer composites and for this purpose they introduced new composite types. In this regard, they produced polyaspartic polyurea based composites produced via vacuum assisted resin transfer molding (VARTM) method and reinforced with graphene nanoplatelets (GNPs) and natural jute fibers. They performed high temperature pin-on-disc wear tests. Reportedly, the wear and friction response of the produced sample varied with varying nano-filler type, whereas increasing load and temperature increased the SWR. Moreover, the incorporation of nanofillers led to formation of instable COF curves (Erdoğdu & Temiz, 2023).

Another research on the use of natural fibers was carried out by Singh et al. (2023), where the authors evaluated the impact of subjective and objective weighing methods to optimize the tribological properties of natural fiber reinforced composites used for brake friction. According to the authors, incorporation of varying amounts of fillers had very diverse effects on the tribological response of the produced composites, which made it challenging to determine the best fabrication parameters. In this regard they applied EDAS-MADM (evaluation based on the distance from the average solution-multi attribute decision making) and incorporated different subjective and objective weighting methods into EDAS. In conclusion they found out that, the best tribological performance was exhibited by the composite with 5 wt. % ramie fiber (Singh et al., 2023).

5. Conclusion

The studies on improvement of tribological properties of polymer composites cover an extensive set of sub-fields which can be categorized based on several criteria, such as the type of fibers used and the type of the fabrication method. This review study aimed to provide a brief overview of the recent studies on each of these subjects, such as the composites reinforced with inorganic fibers such as glass fibers or short carbon fibers, natural fibers, nano-fillers such as graphite and graphene nano-platelets or multi-walled carbon nanotubes, and those manufactured via compression molding or additive manufacturing. The brief overview of the performed studies on the tribological properties of polymer composites show that, the unlimited possibilities to enhance the several properties of polymer-based materials via various reinforcements, matrix materials and fabrication routes pave the way for increasing number of future works.

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