EVOLUTION OF THERMAL COMFORT IN AIRCRAFT CABINS: A LITERATURE REVIEW

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ABSTRACT

The passenger thermal comfort in aircraft interiors is one of the most important aspects to consider in the general Environmental Control System (ECS) design. Given the large number of variables that can affect the thermal load, the study of heat, ventilation and air conditioning may be extremely complex. Although the main factors directly related to thermal comfort may be environmental factors, such as air speed, seat arrangement and type of ventilation used, the human factors are also strongly related to thermal sensation. Therefore, the psychological and physiological aspects have been measured with different methodologies and approaches. Furthermore, a study of aircraft Heat, Ventilation and Air Conditioning (HVAC) was performed, aiming to clarify the impact of ECS design on thermal comfort. The study also explored different approaches to investigating ventilation behavior, pollutant and CO2 dynamics, and innovative systems designed to maintain low weight, high efficiency, and a thermally comfortable environment. Therefore, analyzing existing methods and systems, as well as identifying improvements and future trends in this research area, it is possible to provide an overview and insights into studying thermal comfort.

NOMENCLATURE

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CENMEC	Colegiado de Engenharia Mecânica
CFD	Computational Fluid Dynamics
CHDG	Chlorhexidine digluconate
ECS	Environmental Control System
FTF	Flight Test Facility
HEPA	High-Efficiency Particulate Air
HVAC	Heating, Ventilation, and Air Conditioning
IMI	Interferometric Mie Imaging
KD	Kalman Decomposition
LDA	Linear Discriminant Analysis
MBSE	Model-Based System Engineering
MRSA	Multiple-resistant Staphylococcus aureus
PIV	Particle Image Velocimetry
PLIF	Planar Laser-Induced Fluorescence
PMV	Predicted Mean Vote
RANS	Reynolds-Averaged Navier-Stokes
RNG	Renormalization Group
SARS CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2
VPTV	Volumetric Particle Tracking Velocimetry

1. INTRODUCTION

Human comfort is one of the most important aspects to consider in a wide range of environments and applications such as product design. Although human thermoregulation may involve many aspects, such as physiological, psychological and environmental, thermal comfort is a field of study widely explored to deliver better conditions in different environments. Also, according to Özdamar; Umarogullari (2018), the factors that most influence thermal comfort are related to relative humidity, air flow rate and radiant temperature. In general, ASHRAE (2001) extensively explores and documents thermal comfort parameters in its handbook.

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Further, when exploring thermal comfort in aircraft cabins, some well-established methodologies are used for investigation. According to Pang et al. (2014), the well-known method to estimate thermal comfort is Predicted Mean Vote (PMV). However, other innovative methodologies are also applied, such as use of mannequins in full scale aircraft cabins, and measurements were performed to investigate thermal behavior in different locations. On other hand, Kok et al. (2006) explored the numerical approach, where they used CFD tools to investigate thermal comfort in a sectional aircraft cabin as a fluid domain. In this line of exploration, it's common to encounter other approaches to study thermal comfort, for instance, Flight Test Facility (FTF), where tests are performed in real cabins under low pressure conditions.

Moreover, thermal comfort parameters in aircraft cabins are directly linked to the Heating, Ventilation, and Air Conditioning (HVAC) systems. In aircraft, these systems typically use bleed air from the engines or electric compressors to control cabin temperature and ventilation. The ASHRAE Handbook – Fundamentals (2019) examines the environmental control of HVAC systems, highlighting key design parameters and airflow patterns within the cabin.

In this study, we aim to investigate the fundamental concepts of aircraft thermal comfort and its evolution over time. Furthermore, we analyze the historical improvements of HVAC systems in aircraft cabins, examining the evolution of applied methods and different approaches to measuring thermal comfort. Therefore, this study provides a general overview of the factors affecting thermal comfort and how HVAC systems are used to regulate it.

2. THERMAL COMFORT: DEFINITION AND CONCEPTS

According to GARCIA SOUTO (2012), human thermal comfort can be defined in several ways. In her thesis, she defines thermal comfort as the comfort a person experiences under environmental conditions. However, it can also be described as a neutral state in which people do not wish to feel cooler or hotter. Although thermal comfort studies have a wide number of factors that may affect human well-being, there are some well established methodologies to measure it in different environments. Further, Hoof (2010) in his review research defines thermal comfort as the state of mind that expresses satisfaction with the thermal sensation.

In an aircraft cabin, thermal comfort is also directly influenced by environmental and human factors. Fan; Zhou (2019) investigated the main factors influencing thermal comfort in aircraft interiors, identifying low relative humidity, mean radiant temperature, and colored light as key environmental factors, while metabolism and gender are the primary human factors.

3. METHODS TO MEASURE THERMAL COMFORT

3.1 Predicted Mean Vote (PMV)

The first and most widely used methodology for measuring thermal comfort is Predicted Mean Vote (PMV). To perform these calculations, PMV considers six main parameters, including metabolic rate, clothing insulation, air temperature, mean radiant temperature, air velocity, and humidity and evaluates these parameters on a scale of -3 (cold) and +3 for (hot) (KU et al., 2015).

Table 1. PMV thermal sensation scale (adapted from Ku et al. (2015)).

PMV	Sensation
3	Hot
2	Warm
1	Slightly warm
0	neutral
-1	Slightly cold
-2	Cool
-3	Cold

In general, the PMV method is based on public feedback from the thermal sensation scale, allowing the study of the six parameters to influence the comfort of various environments. However, according to Yau (2012), the PMV method could be a mistake when applied globally, and this is mainly due the expectations of comfort temperature is very individual in different environments. Further, Wagner et al. (2007) confirm that adaptive prediction models are more efficient at prediction of thermal sensation and comfort than the models with fixed limits on indoor temperature in cases where transient temperature are considered.

3.2 Gagge's Model

In this empirical model, A.P. Gagge, J.A.J. Stolwijk, and Nishi (1972) developed a model that emphasizes human variables Further, to perform the calculations, the parameters considered in the calculations are internal body temperature, skin temperature, vasoconstriction and vasodilation, sweating, and skin surface.

In this model, each mode of human heat loss is considered in order to calculate a more accurate empirical model.

3.3 Experimental Investigation

In aircraft cabin environments, experimental setups using models or full scale testing is common. Tejsen et al. (2007) conducted a test in a full scale section of an aircraft cabin, using a 21-seat configuration in their experiment. In this experiment, the PMV questionnaire was first conducted to different parts of the body, evaluating the acceptable PMV scale values for each part. Following this, the experiment was conducted under three different exposure conditions

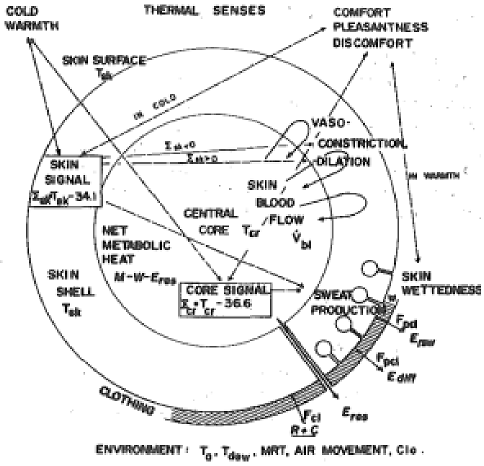

Figure 1. Concentric shell model of heat transfer mechanics of the human body. (Gagge, A.P.; Stolwijk, J.A.J.; Nishi, T. (1972))

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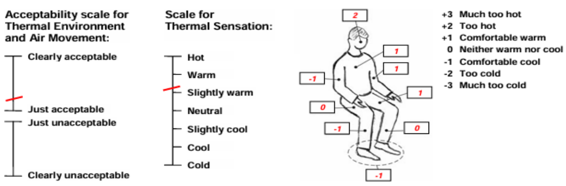

Figure 2. Three different ranges of thermal sensation for testing and the body acceptable PMV values in different parts of the body. (Tejsen et al., 2007)

In this type of approach, it's fundamental to consider the heat transfer phenomena in order to set up the human conditions in mannequin skin. In their study Tanabe et al. (1994) define the process to set up the mannequin conditions with different approaches, where the human heat losses are calculated based on empirical equations of heat transfer and concepts of ASHRAE (2001).

In their experimental investigation, Winzen, Albers, and Marggraf-Micheel (2013) used the arrangement of colored lights in the cabin to observe their impact on thermal comfort. In this study, they observed the psychological impact of colored lights on thermal comfort and well-being, concluding that yellow lights resulted in a perception of being slightly warmer, while blue lights were perceived as rather cold.

3.4 Numerical Simulations Approach

The Computational Fluid Dynamics (CFD) approach is also widely used in the study of flow circulation and the design of aircraft environments for thermal comfort. Due to the ease of physical domain representation, as well as the time and cost efficiency of this type of analysis, the use of CFD tools is increasing considerably, from the design stage to thermal management.

Rommelfanger et al. (2021) investigate the influence on skin temperature when analyzed with different turbulent closure models and even with empirical calculations. For the bodies used in the simulation, they modeled a mannequin and used the values described in standard ISO 14505-2 as boundary conditions. In their studies, the models for analyzing skin temperature were defined by equivalent temperature and a numerical fluid dynamics model, with the latter focusing on different turbulence closure models such as laminar, k-, k-, and k- SST.

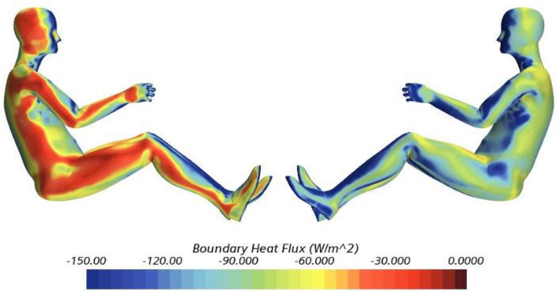

Figure 2. Output heat flux from CFD analysis of thermal response to a flow. (Rommelfanger et al. (2021))

In a similar application, Aboosaidi, Warfield, and Choudhury (1991) performed CFD simulations in three different setups. The simulations were conducted to investigate the flow, velocity fields, and temperatures using different CFD tools, such as FLUENT and BINS3D.

Mboreha et al. (2021) studied six different personalized ventilation systems and performed CFD simulations to analyze the velocity field, air temperature, and relative humidity, comparing the results with experimental data. You et al. (2019) improved the CFD-based approach using the Wells-Riley equation to investigate different ventilation systems, studying the dynamics of contaminants while maintaining thermal comfort in aircraft interiors. Fu and Zhao (2025) analyzed the weak optical influence of glass on overall thermal comfort, as well as the trivial impact of glass heat load on the temperature field inside the cabin. ZHANG and CHEN (2007), in their study on disease propagation in cabins, also used the CFD approach to investigate air circulation and concluded that a mixing air distribution provides the highest air velocity, the most uniform temperature, and CO2 concentration, all of which affect thermal comfort.

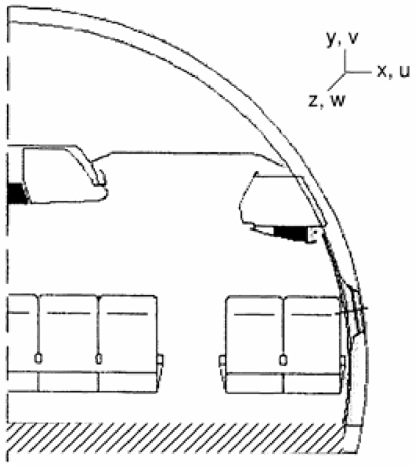

Figure 3. Cabin model used to simulate the airflow in aircraft interior. (Aboosaidi, Warfield, and Choudhury (1991))

Therefore, CFD analysis of heat transfer behavior, flow circulation, and arrangement in specific environments, such as aircraft interiors, proves to be an extremely efficient tool for studying thermal comfort.

3.5 HVAC Systems in Aircrafts

Aircraft HVAC systems, also known as Environmental Control Systems (ECS) in the aviation industry, face some challenges. In addition to managing high temperatures and humidity on the ground, they must regulate extremely cold, dry air and hazardous elevated ozone levels at cruising altitudes, all while maintaining a comfortable and habitable cabin environment for passengers and crew.

Moreover, like all aircraft components, onboard systems must minimize their weight contribution to the aircraft's total mass while adhering to stringent design requirements. These systems must be compact for easy inspection, highly reliable to meet aviation safety standards - the foremost priority in the industry - and robust enough to withstand vibratory stresses, maneuver loads, and potential failure scenarios.

Figure 4 illustrates the airflow path within a typical aircraft cabin air-conditioning system. The process begins with engine bleed air, which is then channeled to the air cycle machine for temperature and pressure regulation. After conditioning, the air is delivered to the distribution manifold and subsequently supplied to the cabin via supply nozzles. A portion of the cabin air is continuously recirculated through return air grilles, mixing with fresh intake air for reprocessing. System pressure is maintained by controlled venting of excess air through the outflow valve.

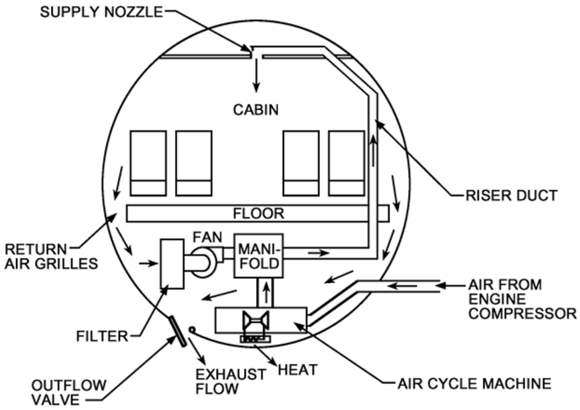

Figure 4. Cabin airflow with bleed air system representation (ASHRAE (2019))

3.6 Thermodynamic Overview

Unlike building HVAC systems, automotive air conditioning, and domestic/commercial refrigeration systems, which typically operate on the reverse Rankine cycle, aircraft environmental control systems utilize the reverse Brayton cycle for thermal management. According to Merzvinkas et al. (2020), the most common simple air cycle system, based on engine bleed air supply, is essentially a reverse Brayton open cycle, consisting of a high-pressure air source, a heat exchanger, a fan to increase cooling air flow through the heat exchanger, and a high-speed turbine.

3.7 Environmental Control Systems Impact In Thermal Comfort

Using the Model-Based System Engineering (MBSE) approach, IQBAL, BAIG, and ULLAH (2024) modeled the entire Environmental Control System (ECS) with Simulink and Simscape. In their work, the ECS was divided into six subsystems: bypass flow, catalytic converter, controllers, outflow, engine bleed air, thermal and moisture loads, and trim airflow. On the other hand, aiming to localize and control the main sources of irreversibilities in the ECS, Gandolfi et al. (2007) used exergy analysis, providing a complete evaluation and upgrading the internal cabin environmental thermal control efficiency.

Similarly, to investigate the efficiency of the ECS, Zhao et al. (2009) performed experiments analyzing the bootstrap air cycle and high-pressure water separation. In their experiment, parameters influencing the system's efficiency were observed, such as variations in outlet pressure, turbine efficiency, and rotational speed with operating conditions. In general, they concluded that investigating off-design performance and dynamic response must be considered to maintain reliability and efficiency, thus ensuring a comfortable cabin interior.

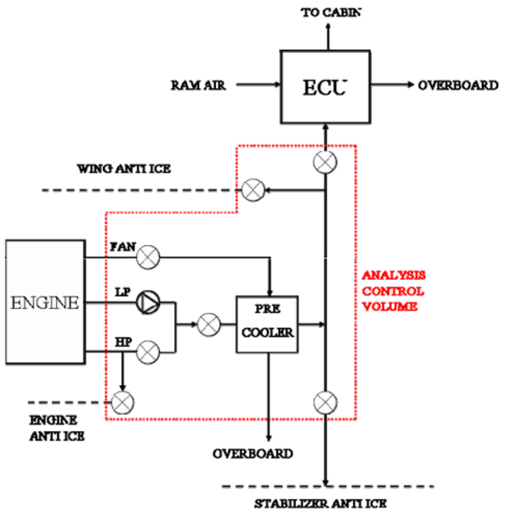

Figure 5. Conventional architecture of integrated pneumatic systems. (Gandolfi et al. (2007))

In his work, Smith (2021) describes a model for the ideal case of heat transfer that occurs during time-averaged flight, where major heat losses occur from the aircraft skin. He also explores how internal heat losses may affect the overall HVAC design.

Pérez-Grande; Leo (2002) consider the minimum entropy generation and minimum weight as the two main optimization criteria for finned cross-flow heat exchangers. In this work, they explore the commercial aircraft demand of low weight systems to provide an optimized configuration of ECS, maintaining the general heat exchange efficiency.

In his thesis, Alkhadashi (2022) applied Linear Discriminant Analysis (LDA) and Kalman Decomposition (KD) to study parameters that may or may not be controllable and observable, aiming to maintain system efficiency and occupant comfort.

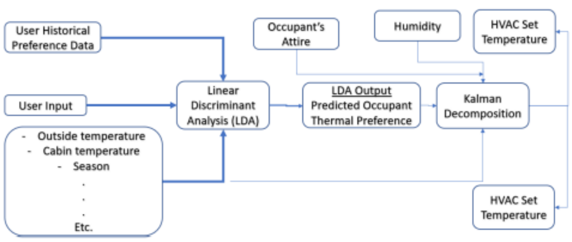

Figure 6. LDA/KD control system to manage HVAC. (Alkhadashi (2022))

On the other hand, also in his master's thesis, Bueno (2021) addresses the HVAC system design and simulation using numerical methods and model-based systems engineering, making assumptions and applying linearizations to simplify the problem, especially for product development. He also considers the impact of thermal sources and power supply in different situations to control thermal comfort in the environment

3.8 Air Quality Management And Techniques

Aircraft interior air quality management is a crucial factor. The concentration of pollutants, CO2, and its influence on thermal comfort depend on how the air is managed.

Grady et al. (2013), who aimed to investigate the CO2 concentration in the cabin, defined the thermal inputs and proposed the fractional air recirculation system. Furthermore, their study demonstrates the impact of fractional air recirculation on CO2 and water vapor concentration in cabin interiors.

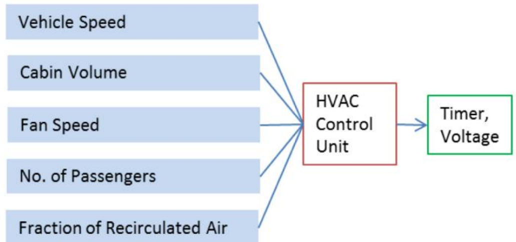

Figure 7. Control logic schematic to control the air quality through HVAC control unit. (Grady et al. (2013))

Elmaghraby; Chiang; Aliabadi (2017) explored a wide range of techniques to manage the cabin air quality. Among the techniques addressed, it is fair to highlight the main and most used such as Particle Image Velocimetry (PIV), Volumetric Particle Tracking Velocimetry (VPTV), Planar Laser-Induced Fluorescence (PLIF), Flow Visualisation as well as other techniques explored in this study. Then, there's a lot of techniques to guarantee and maintain the air quality as well as thermal comfort in the interior cabin.

Aiming to improve the air quality supply, ZÍTEK et al. (2010) performed CFD simulations of his personalized concept of ventilation. Before performing the simulation, they conducted an experiment using helium bubbles and SAFEX fog to observe the flow movement which are two variations of PIV. As a result, it was possible to study the cabin air quality and thermal comfort.

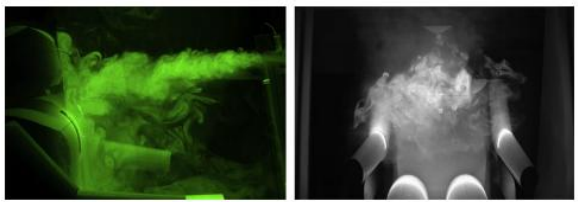

Figure 8. Use of SAFEX fog to visualize the flow of a personalized ventilation system. (Zítek et al. (2010))

Using a hybrid experimental-numerical approach to measure the temperature and velocity fields in an internal aircraft mockup experiment, ZHANG et al. (2009) used ultrasonic and omni-directional anemometers. Furthermore, to observe the gaseous contaminant behavior, they chose the photo-acoustic multi-gas analyzer method. Also, after performing the experiments, they used the values and flow behavior to validate the RANS analysis using the RNG k-turbulence model.

With a fully experimental setup, Poussou et al. (2010) performed an internal cabin experiment using Particle Image Velocimetry to study contaminant propagation through a moving body and then validated the CFD analysis with these data. Similarly, SZE TO et al. (2009) conducted a cabin mock-up experiment, using the PIV approach for airflow and Interferometric Mie Imaging (IMI) combined with an aerosol spectrometer for aerosol analysis, to investigate the dispersion and deposition of expiratory aerosols in order to study disease propagation in aircraft cabin interiors.

Therefore, today, the number of methods to investigate cabin airflow, the concentration of air pollutants and CO2, as well as the impact of HVAC system configuration on thermal comfort, is substantial. Furthermore, these phenomena can be investigated with a reasonable safety margin using numerical approaches such as CFD simulations. However, the most reliable methods for investigation are still experiments performed in mock-ups.

With this information - such as flow parameters, pollutant concentration, and specific areas affecting passengers - systems engineers can design and maintain the internal cabin for optimal comfort and air quality.

4. INNOVATION AND FUTURE TRENDS

4.1 Personalized Ventilation Systems

Innovations in aircraft air distribution systems continue to advance within the aviation sector. System redesign presents an effective innovation approach, as it enhances efficiency using existing technologies rather than requiring new developments. PANG et al. (2013) proposed an adjustable inlet design that adapts to the seated height of passengers. This cabin air inlet configuration demonstrates improved fresh air utilization efficiency and enhanced air quality. Simulation studies further indicate potential energy savings through optimized fresh air delivery, minimizing waste while maintaining thermal comfort.

The improved air distribution system shows promising potential to simultaneously meet multiple critical requirements: maintaining healthy airflow patterns, ensuring good air quality, and reducing energy consumption. However, practical implementation in civil aircraft necessitates careful consideration of structural design constraints and optimal pipeline layout. Additionally, increased fresh air circulation may reduce airborne disease transmission risks, a consideration that has gained significant importance following the COVID-19 pandemic.

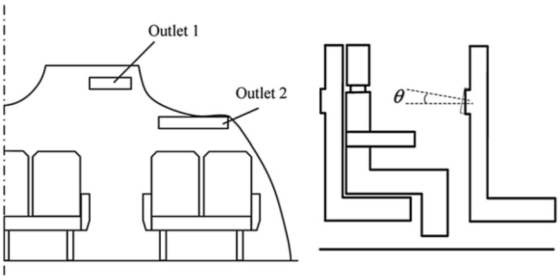

Figure 9. Outlet positions and air supply angle (PANG et al. (2013))

An alternative configuration proposed by ZHANG; LI; WANG (2012) integrates under-aisle air supply, also proposed by ZHANG; YIN; WANG (2009), with personalized ventilation through seat armrest-mounted terminals.

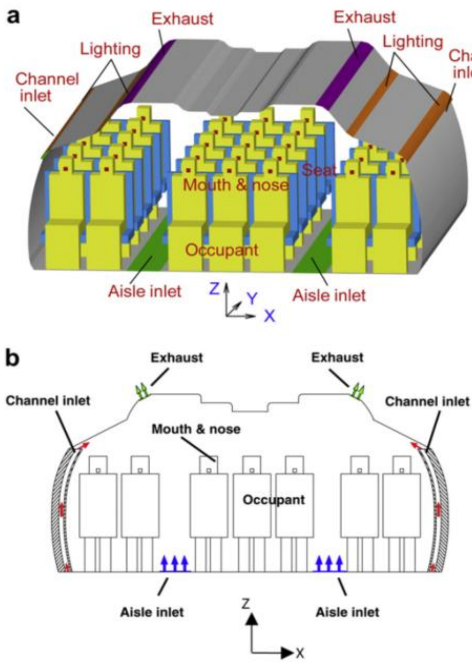

Figure 10. (a) The new under-aisle air distribution system, (b) schematics of the air supply scheme (sectional view). (ZHANG; YIN; WANG (2009))

The hybrid approach offers enhanced contaminant control by delivering conditioned outside air directly to passenger breathing zones. The system design features air terminal devices embedded within both armrests, maintaining the same fundamental principle of targeted airflow delivery while improving distribution efficiency.

Another area that has been extensively researched due to the pandemic was this bias in filtering the air that is recirculated in aircraft. Due to the need to contain SARS CoV-2, High-Efficiency Particulate Air (HEPA) filters for recirculated air in environmental control systems (ECS) began to be used. A study was carried out on the feasibility of using HEPA filters with nanofiber media instead of glass fiber media. According to ZHANG et al. (2022), the use of nanofiber media instead of glass fiber media can reduce the pressure drop by 66.4%–94.3% and significantly increase the quality factor by analysis of literature data. In addition to being more efficient, nanofibers are an environmentally friendly filter material unlike glass fiber.

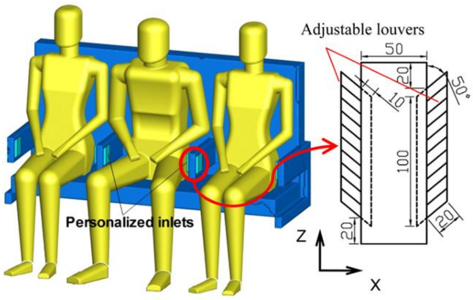

Figure 11. Enlarged view of the personal air supply louvers embedded within chair armrests (mm). (ZHANG; LI; WANG (2012))

A complementary research direction involves the application of chlorhexidine digluconate (CHDG) as a biocide within aircraft environmental control systems. This approach extends beyond particulate filtration to actively eliminate microorganisms, thereby preventing pathogen recirculation through the cabin air supply.

According to WATSON et al. (2022), the antimicrobial filters studied in his work are shown to kill pathogens, such as Candida albicans, Escherichia coli and MRSA in under 15 min and to destroy SARS-CoV-2 viral particles in under 30 s following contact with the filter. It was also demonstrated that the treatment has no detrimental effect on rate of air-flow or fiber size of the filter, while also showing excellent antimicrobial efficacy against gram-positive and gram-negative bacteria, fungi and viruses.

5. CONCLUSION

Thermal comfort in aircraft cabins is a critical factor in environmental control system (ECS) design, requiring a balance between human factors, energy efficiency, and technological innovation. This review examined physiological and psychological aspects, such as clothing, gender, and metabolic rates and, at same time, environmental factors to understand their influence on passenger thermal sensation. To assess these factors, various methodologies, including numerical, analytical, and experimental approaches, were explored, enabling a considerable analysis of cabin thermal conditions.

A key focus was the evaluation of current ECS technologies, particularly the widely used bleed-air system, which utilizes engine-extracted air for cabin conditioning. The primary challenges in this system include optimizing weight, cost, and energy efficiency while maintaining passenger comfort. Furthermore, aircraft manufacturers are investing significantly in model-based engineering, simulations, and mockup testing to enhance ECS performance, focusing the sector's compromise to advancing cabin environmental quality.

Moreover, emerging trends promise further improvements in passenger well-being. AI-driven thermal comfort control, for instance, could dynamically adjust cabin conditions based on human and environmental inputs. Innovations in ventilation, such as HEPA filters, carbon nanofiber materials (replacing traditional glass fibers), and personalized airflow systems, aim to enhance air quality while minimizing energy consumption. These advancements show the potential for innovative, healthier, and more efficient cabin environments.

In summary, this review provides a comprehensive overview of thermal comfort considerations in aviation, emphasizing how ECS design directly impacts passenger well-being. Future developments in smart systems, advanced materials, and personalized ventilation will likely improve cabin comfort, ensuring a more sustainable and pleasant travel experience.

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