

Systems for precision control of microclimate in world rail transport: Technological structure and intelligent management

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ABSTRACT

The issue of ensuring a suitable microclimate in railway carriages and analyses of the key parameters determining the quality of the environment in the carriages – temperature, relative humidity, air flow rate, carbon dioxide (CO₂) levels are considered in the publication. The detailed hierarchy of systems is described, including a real-time data sensor network, centralized logic control controllers and actuators (frequency-controlled compressors, heating modules and recirculation valves). Special attention is paid to the transition to intelligent management technologies. Mechanisms for automated optimization of energy consumption through adaptive control algorithms and remote monitoring have been considered. On the importance of preventive diagnostics and the implementation of environmentally friendly refrigerants as key trends for achieving sustainable and energy- efficient railway transport, and recommendations are made regarding the implementation of these systems in practice and their importance for safety and energy efficiency in transport conclusions has been formulated.

KEYWORDS

HVAC systems, Automated control, Energy efficiency, Microclimate, Railway safety, Railway transport, Sensor networks.

1. INTRODUCTION

In modern railway transport, ensuring an optimal microclimate is a critical factor for passenger comfort, equipment safety and energy efficiency. This article examines the technological structure of the new generation of HVAC (heating, ventilation and air conditioning) systems integrated into rolling stock around the world. The subject of analysis is the transition to intelligent control through artificial intelligence (AI), the use of environmentally friendly refrigerants and strategies for optimizing energy consumption.

Global urbanization and the drive to decarbonize transport are making railways the preferred mode of mass transportation. However, high-speed trains and urban metros face the challenge of maintaining constant air parameters under extreme external conditions and fluctuating passenger traffic. Traditional air conditioning systems no longer meet modern sustainability standards, which necessitates the implementation of precise and intelligent control technologies. The development of modern climate control systems is essential to enhance passenger comfort and energy efficiency in rail transport. The integration of advanced predictive analytics and artificial intelligence into climate control systems can further improve both passenger comfort and energy efficiency. For example, the use of real-time weather data and occupancy patterns allows for dynamic adjustments in heating, ventilation and air conditioning (HVAC) systems, ensuring optimal conditions regardless of external fluctuations. Furthermore, the implementation of smart grid technology can facilitate better energy management, reducing operating costs while maintaining high levels of comfort in train compartments. As the demand for sustainable transport solutions grows, these innovations not only promise to enhance the travel experience, but also align with wider environmental goals, highlighting the importance of smart systems in the future of rail transport. Importance of microclimate in rail transport.

As the rail industry continues to evolve, the importance of climate management extends beyond passenger comfort to maintaining safety and operational efficiency. For example, fluctuations in temperature and humidity can lead to skewed oscillations or equipment failures, posing a risk to both infrastructure and passengers. This integration of predictive analytics with real-time monitoring systems can not only improve the passenger experience, but also proactively address

potential hazards, ensuring the reliability of rail services. Furthermore, the adoption of advanced climate control technologies, such as those that use artificial neural networks to optimally manage HVAC, can be significant in mitigating energy consumption while maintaining required comfort levels. This holistic approach highlights the need for a comprehensive strategy that prioritizes both environmental sustainability and operational resilience in relation to climate variability.

2. TECHNOLOGICAL STRUCTURE OF MODERN HVAC SYSTEMS

The rail industry prioritizes passenger comfort, and it is crucial to consider the psychological effects of microclimate conditions on passengers. Studies have shown that factors such as temperature, humidity and air quality can significantly enhance passengers' mood and satisfaction, which in turn influences their overall experience and the likelihood of them choosing rail over other modes of transport. By implementing advanced air quality monitoring systems that assess not only temperature but also particles and allergens, rail operators can create a more pleasant environment that affects relaxation and well-being. Furthermore, integrating user feedback mechanisms could allow for real-time adjustments based on passenger preferences, further improving the travel experience while ensuring that energy consumption remains efficient and sustainable. This multifaceted approach not only addresses immediate comfort issues but also long-term citizen loyalty among passengers, ultimately resulting in the growth of the rail sector amidst increasing competition.

Conventional HVAC systems often treat temperature control as the primary objective, but thermal comfort is a more complex, subjective concept influenced by multiple factors. Temperature, air velocity, humidity and infrared radiation are key parameters that determine the heat exchange between a person and the environment. The study proposes a logic controller (FLC) that uses the Predicted Mean Voice (PMV) index to control indoor temperature. The PMV index aims to achieve a neutral thermal sensation ($PMV = 0$) with a low percentage of dissatisfied persons (PPD).

FLC is well suited for thermal comfort control as it can deal with the ambiguity and subjectivity inherent in thermal sensation by treating comfort ranges. The FLC adjusts the air temperature setpoint based on the estimated PMV level and the required comfort range, taking into account various contributing comfort variables.

PMV Index and Control Actions in a Logic Controller in Railway Transport

The Predicted Mean Voice (PMV) index plays a central role in determining the control actions of a Logic Controller (FLC) for thermal comfort management. The FLC uses the PMV to estimate the thermal sensation in the rooms and subsequently adjust the heating, ventilation and air conditioning (HVAC) system to maintain comfort and optimize energy consumption.

PMV Assessment and Comparison

FLC continuously assesses the PMV level, which is an index of thermal sensation that predicts the average thermal sensation rating on a standard scale for a large group of people. This assessment is based on environmental variables such as room air temperature, relative humidity, average radiant temperature and air velocity, together with human factors such as activity level and thermal resistance of clothing.

The calculated PMV level is then compared to the required comfort range. The goal is to achieve a neutral thermal sensation, typically when the PMV is equal to zero, with a low percentage of dissatisfied persons (PPD). For example, a PPD of 5% is assessed when the PMV is zero and the target indoor temperature is set relative to this point.

Determination of control actions

Based on the comparison between the estimated PMV and the desired comfort range, FLC determines the required control. If the PMV level falls outside the comfort range, the controller provides the air temperature setpoint that the HVAC system should use to create indoor thermal comfort.

The FLC processes clear inputs, such as the PMV value, through a fuzzy interface, converting them into linguistic variables (e.g., "COLD", "COOL", "NEUT", "WARM", "HOT") using membership functions.

Fuzzy control rules, which are conditional statements, then define the relationship between these linguistic input variables and the corresponding output control actions. These rules are often derived from experiential knowledge or models of plant behavior. For example, a rule might state: "If PMV is "COLD", then V_p is "FO" (where V_p is the output variable and FO is a fuzzy output set).

The inference engine applies these rules to derive a fuzzy output, which is then converted into a clear control signal (e.g. for a heating valve) through a process of fuzzification, typically using the center of gravity (COG) method. This clear signal dictates the actual setting of the HVAC system.

Advantages of PMV-based FLC

The use of PMV within FLC allows for a more nuanced and robust control strategy compared to traditional temperature PID controllers. It addresses the subjective and vague nature of thermal comfort by treating comfort ranges as fuzzy variables.

This approach allows the controller to maintain excellent tracking of the comfort reference state and achieve significant energy savings (e.g. 20% reduction in energy consumption over a typical 7-day winter period). FLC also demonstrates greater robustness and general applicability across different building types, without requiring specific re-tuning for each application, unlike PID controllers. In essence, the PMV index acts as a basic feedback for the FLC, guiding the system to make intelligent, comfort-driven adjustments to the indoor environment, thereby increasing occupant satisfaction and energy efficiency. Improving microclimate systems in rail transport is key to ensuring safety, comfort and energy efficiency.

The architecture of microclimate systems in the rail sector consists of three main levels:

- Actuators: Inverter-controlled compressors, multi-speed fans and electronic thermostatic valves (RTVs) that allow smooth power regulation.
- Sensor network: Sensors for measuring temperature, relative humidity, carbon dioxide (CO₂) levels and pressure sensors (critical when passing through high-speed tunnels).
- Control module: Local controllers (PLCs) integrated into the overall train control system (TCMS – Train Control and Management System).

3. REGULATORY FRAMEWORK AND INTERNATIONAL STANDARDS

The design, testing and operation of HVAC systems in global rail transport are subject to strict international standards that guarantee safety and thermodynamic comfort:

- EN 14750:2024 [1]: Basic European standard defining the parameters of thermal comfort (temperature, humidity, air flow velocity) and the methods for their testing in urban and regional rolling stock.
- EN 13129 [2]: Standard for mainline and high-speed trains regulating the air comfort in passenger compartments under extreme external conditions.
- UIC 553 / UIC 553-1 [3]: Code of the International Union of Railways defining ventilation rates and ventilation programs for passenger carriages.
- ISO 19659 [4]: A series of international standards for railway applications unifying the terminology and requirements for energy efficiency of HVAC installations.
- Regulation (EU) 517/2014 [5]: Regulatory act stimulating the phase-out of fluorinated greenhouse gases (HFCs) and the transition to natural agents (R744).

4. INTELLIGENT CONTROL AND ALGORITHMS

The key to precise microclimate is software logic. Static settings are replaced by adaptive algorithms:

- Occupancy-based Control: Using data from CCTV cameras or weight sensors on the carriages, the system calculates the exact number of passengers. Ventilation dynamically adjusts the flow of fresh air based on CO₂ levels, preventing air stagnation and saving energy when the carriage is half-empty.
- Predictive Control: Intelligent systems use GPS data and weather forecasts. If the train is approaching a tunnel or an area with extreme temperatures, the HVAC system adjusts parameters in advance to compensate for sudden changes in pressure and heat load.
- Machine Learning and Diagnostics (CBM): By collecting data in cloud structures, predictive maintenance algorithms are applied, which reduces breakdowns along the way.

5. REFRIGERANT BENCHMARKING / ENERGY EFFICIENCY BENCHMARKING

An important structural component in modern transport is the transition to environmentally friendly fluids under the pressure of regulatory frameworks [5]. Instead of traditional freons, world leaders in the industry are implementing natural refrigerants such as carbon dioxide (R744), whose global warming potential (GWP) is equal to 1 [6]. Table 1 provides a comparative technical and environmental analysis of the most widely used fluids.

Comparison 1: Global Warming Factor (GWP) of Refrigerants

The transition to R744 (CO₂) eliminates the risk of greenhouse gas emissions from possible leaks from air conditioning installations during their life cycle.

Table 1: Comparison of technical and environmental parameters of refrigerants.

Refrigerant	Fluid type	GWP potential	Working pressure	Ecological status
R407C	Synthetic (HFC)	1774	Low / Medium	In process of replacement
R134a	Synthetic (HFC)	1430	Low	Limited by regulations
R513A	Synthetic blend	631	Average	Transitional solution
R744	Natural fluid	1	Natural fluid	Sustainable / Future standard [6]

Comparison 2: Annual energy consumption by control type

Traditional systems operate on the "On/Off" principle or maintain constant flow rates. The implementation of inverter precise control and management based on occupancy (number of passengers and CO₂ levels) dramatically optimizes consumption.

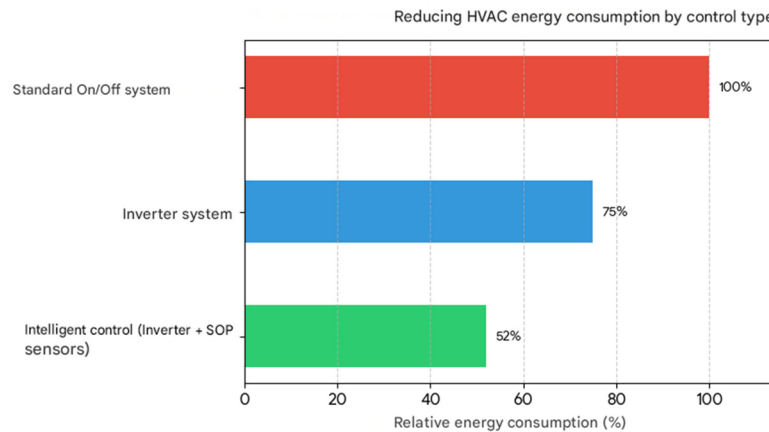


Figure 1:

Comparison 3: Coefficient of Performance (COP) in heat pump mode

At low outdoor temperatures, heat pump systems with R744 show significant superiority in heating mode over conventional combustion or electric heaters, saving up to 78% energy in winter conditions.

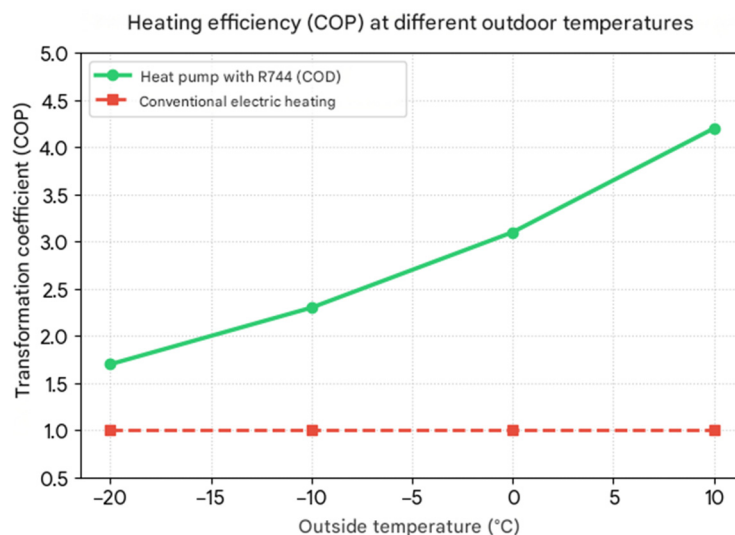


Figure 2:

6. ENERGY EFFICIENCY AND HEAT PUMP TECHNOLOGIES

HVAC systems are among the largest consumers of electricity in a train (up to 30% of the total auxiliary power). Modern configurations use reversible heat pumps with R744, which provide both cooling in summer and efficient heating in winter. They show high Coefficient of Performance (COP) at negative temperatures and utilize waste heat from traction inverters, saving up to 30% of the total energy compared to conventional on/off systems [6].

7. CONCLUSION

The transformation of rail climate systems is moving from purely mechanical solutions to software-defined, environmentally friendly and intelligent ecosystems. The implementation of precise control not only ensures first-class passenger comfort, but also drastically reduces the carbon footprint and operating costs of the rail sector globally.

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