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Holistic Evaluation of Electric Vehicle Efficiency: Benchmark Study of R-474A, R-1234yf, and R-744 using Digital Twin Simulation

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The global automotive industry is undergoing a foundational paradigm shift toward complete electrification, driven by increasingly stringent emissions regulations and the urgent societal imperative to decarbonize the transportation sector. Despite rapid, successive advancements in battery cell chemistry, energy density, and high-voltage drivetrain efficiency, mainstream consumer adoption remains heavily impeded by range anxiety, which affects approximately a third of consumers worldwide across key global markets. In traditional internal combustion engine vehicles, cabin heating is achieved simply and effectively by harvesting abundant waste heat rejected from the engine block. In stark contrast, highly efficient battery-electric vehicles (BEVs) generate minimal waste heat under normal operating conditions, necessitating active thermal management systems to intentionally condition both the passenger cabin and the high-voltage battery pack. Relying on traditional electrical resistance heaters during extreme ambient temperature conditions can drain battery energy at an alarming rate, severely curtailing the vehicle's effective driving range by as much as half. Consequently, the deployment of advanced, reversible vapor-compression heat pump systems has become an absolute necessity. The thermodynamic efficiency and operational envelope of these heat pumps are inextricably linked to the specific thermophysical properties of the circulating refrigerant. Historically, the industry transitioned to R-1234yf to comply with environmental mandates, but its relatively high boiling point severely limits heat-pumping capacity at low ambient temperatures, causing dramatic capacity fade. Alternatively, the natural refrigerant R-744 (carbon dioxide) exhibits exceptional heating capabilities at deep sub-zero temperatures but suffers from severe efficiency degradation in cooling modes at elevated temperatures and requires highly complex, heavy, high-pressure architectures.

To bridge this profound performance gap, this study comprehensively benchmarks R-474A, a next-generation, ultra-low Global Warming Potential (GWP) refrigerant blend designed specifically to address the unique constraints of modern electric vehicles. R-474A is a zeotropic mixture composed of 77 percent R-1234yf and 23 percent R-1132(E), a novel molecule that acts as a powerful thermodynamic booster. By depressing the boiling point to -43.4°C and maintaining a robust critical temperature of 87.8°C, R-474A achieves a 40 percent higher volumetric capacity than baseline R-1234yf systems while operating within standard, manageable pressure tolerances. To accurately capture the dynamic interplay between the refrigerant circuit, the ambient environment, the passenger cabin, and the high-voltage powertrain, a comprehensive digital twin environment of a standard BEV platform was utilized. High-fidelity simulations were conducted across a wide spectrum of global climate conditions, encompassing standardized transient driving cycles and aggressive thermal loads ranging from -30°C to 43°C.

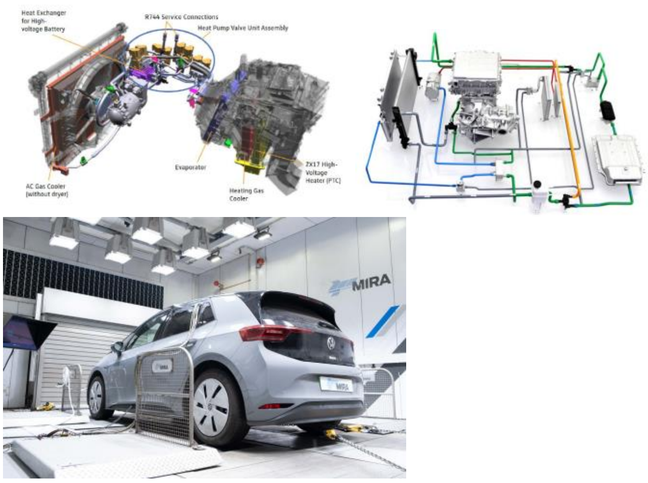

Fig.1 Base systems for R-1234yf, R-474A, and R-744 virtually implemented in digital twin of VW ID.3 vehicle

The simulative benchmarking conclusively demonstrates the overall thermodynamic superiority of R-474A. Under high ambient cooling conditions of 35°C, R-474A achieved a Coefficient of Performance (COP) of 3.27, comprehensively outperforming both R-1234yf and transcritical R-744 systems while requiring significantly less compressor energy. During mild and severe winter dynamics, R-474A maintained highly adequate suction pressures and excellent vapor density. At extreme lows of -30°C, where legacy R-1234yf systems experienced total capacity fade and reverted to highly inefficient resistance heating, R-474A continued to scavenge ambient heat effectively. It delivered a functional COP of 1.35 and matched the rapid time-to-comfort curve of specialized high-pressure R-744 systems. Furthermore, because the peak discharge pressures of R-474A operate within a marginal delta of existing R-1234yf profiles, the refrigerant can be adopted as a near drop-in replacement. This transition requires only sophisticated software calibration and control logic updates rather than systemic hardware overhauls, presenting a highly balanced, cost-effective, and commercially viable solution to mitigate range anxiety while accelerating the trajectory toward sustainable mobility.