Master of Science – Mechanical Engineering

Numerical Analysis of Leakage Scenarios in R290-Operated HVAC Systems

CFD-based investigation of flammable gas dispersion in railway air-conditioning units under critical operating conditions

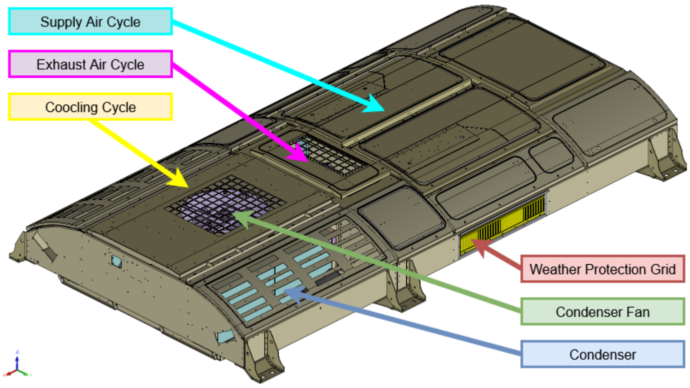

Figure 1: 3D-CAD of HVAC-Unit 2 positioned on the train roof

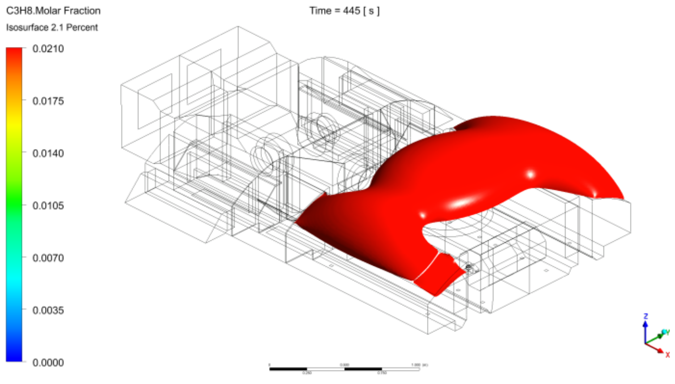

Figure 2: R290 leakage under standstill condition with isosurface at the lower flammability limit

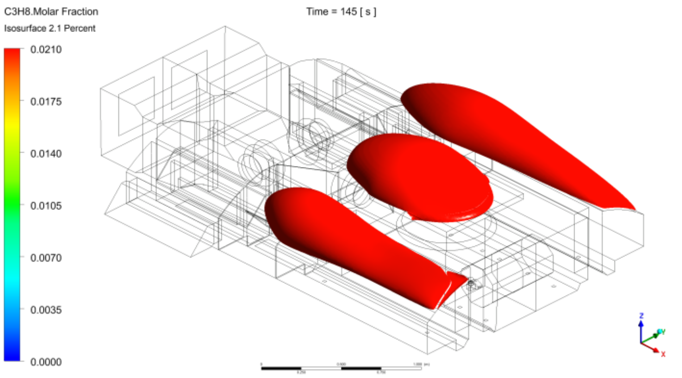

Figure 3: R290 leakage with worst-case ambient airflow with isosurface at the lower flammability limit

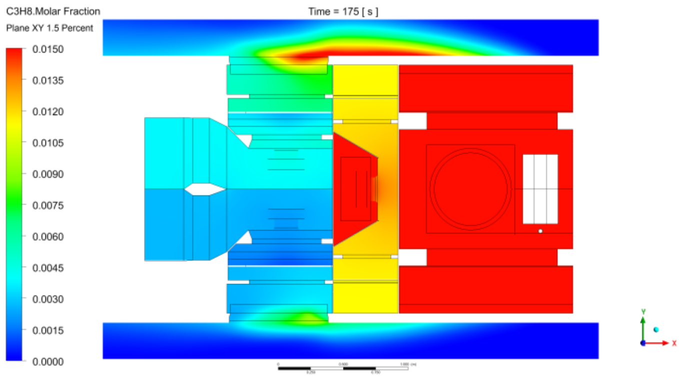

Figure 4: Top view of the worst-case R290 leakage scenario

Problem Statement

The increasing use of natural refrigerants such as propane (R290) in heating, ventilation and air conditioning (HVAC) systems poses a particular challenge from a safety perspective. While R290 offers excellent thermodynamic properties and a low global warming potential, it is also highly flammable. In the event of a leakage in railway vehicle air-conditioning units, critical concentrations may therefore develop in the surrounding environment or even within the fresh-air cycle. This is especially relevant since large groups of passengers are transported in confined spaces, and even small amounts above the lower flammability limit (2.1 vol.,%) present significant hazards. To date, however, comprehensive numerical studies analyzing the formation and dispersion of such leakages under realistic operating conditions are lacking. This highlights the need to develop appropriate simulation methods, validate them against measurement data, and systematically investigate safety-relevant scenarios.

Solution Concept

A validated CFD model was developed to analyze R290 leakages in railway HVAC units. By combining steady-state and transient simulations, both density-driven dispersion and ventilation effects were captured with high accuracy. Critical leakage scenarios were systematically assessed to derive safety-relevant insights and provide a reliable basis for risk assessment.

Results

For HVAC-Unit 1, without ventilation the R290 leakage accumulated inside the cooling cycle and gradually spread to the surroundings. Large flammable zones above 2.1 vol.% formed, and a stable layer of gas settled close to the ground, persisting throughout the simulation. In the worst-case scenario of HVAC-Unit 1, a weak opposing airflow transported a mixture above the lower flammability limit directly toward the fresh-air intake. This led to concentrations above the Immediately Dangerous to Life or Health (IDLH) limit of 0.21 vol.% inside the supply air cycle, exceeding 0.425 vol.%, indicating a realistic pathway for hazardous gas to enter the passenger compartment.

HVAC-Unit 2 exhibited comparable risks under its worst-case scenario. With the condenser fans switched off and low ambient airflow directed toward the fresh-air intake, R290 was able to bypass diffusion and accumulate near the intake. As a result, concentrations above safety-relevant thresholds were entrained into the fresh-air cycle, underlining that both devices can reach critical states under unfavorable but conceivable operating conditions

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