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Analysis of Humidity Response Characteristics and Ventilation-Based Moisture Control Strategies for Railway Containers in Hot and Humid Environments

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Abstract: This study examines moisture accumulation and the limits of ventilation-based moisture control in railway containers exposed to hot and humid conditions. It reanalyzes reported heat and moisture transfer simulations for a 20-foot container; no new simulations are performed. Under the baseline condition, the reported humidity increment rose from 0.64% to approximately 1.29% and then changed little. Moisture retention was concentrated near the floor and in regions of weak air movement. Under the extreme condition, the increment reached approximately 5.84% at 3 h and 6.9%–7.0% later in the simulation. Opening the front end face reduced heat accumulation, but lowered the peak humidity increment by only approximately 0.2 percentage points. This contrast shows why cooling performance alone is insufficient to assess moisture control. Ventilation decisions should compare the humidity ratios of the inside and outside air and assess wall temperature against the local dew point. Adjustable openings, moisture-resistant packaging, desiccants, and, where needed, independent dehumidification are proposed as complementary measures. These recommendations are qualitative and remain subject to the source model's boundary conditions and the definition of its humidity indicator.

Keywords: Railway container; hot and humid environments; humidity response; natural ventilation; moisture control.

1. Introduction

Railway containers may encounter high temperatures, humid air, rainfall, and large daily temperature changes during cross-regional transport. Moisture can enter with ambient air or be released by cargo and packaging. Temperature differences within the container then affect relative humidity and the likelihood of condensation. Condensation becomes possible when a local surface cools to or below the dew point of the adjacent air. The resulting moisture can weaken cardboard, promote corrosion, or damage moisture-sensitive goods. Research on refrigerated and maritime containers has examined these connections between heat transfer, moisture transport, packaging behavior, and cargo protection [1–4].

The available literature covers several related but distinct problems. Container studies address humidity control [2], moisture adsorption by corrugated cartons [3], and condensation during marine transport [4]. Research on refrigerated containers also considers evaporator frosting [5] and refrigeration capacity control [6]. In China, early investigations described internal temperature and humidity under hot and humid conditions and in southeastern coastal regions [7–8]. A test rig with adjustable temperature, humidity, and air velocity was also developed to reproduce refrigerated transport conditions [9]. These studies provide context for container moisture management, but their operating conditions differ from those of conventional railway containers. In particular, the moisture-removal benefit of exchanging air with an already humid environment requires closer examination.

Here, reported results from a multiphysics simulation of a 20-foot container are reanalyzed to examine the progression of the humidity indicator, local moisture retention, and the response to ventilation. The analysis does not introduce new numerical simulations or reconstruct unavailable time-series data. Its purpose is to distinguish the reported thermal benefit of ventilation from its more limited effect on humidity, and to identify the conditions that should guide practical moisture-control decisions.

2. Data Sources and Analytical Methods

2.1. Data Sources

The source study used COMSOL Multiphysics 6.4 to model heat and moisture transfer between the steel walls and the humid air in a 20-foot container. Solar radiation, external convective heat transfer, conduction through the walls, and moisture transport in the air were included. The reported analysis covered a 12 h period of diurnal temperature and humidity variation. Ventilation through openings was examined at a relative external airflow velocity of approximately 37 m/s. This airflow condition is important: the ventilation results should not be generalized to a stationary container in still air or to buoyancy-driven flow alone. The present analysis uses the reported values at identifiable times, descriptions of spatial distributions, and the available ventilation comparisons (Table 1). Missing portions of the continuous humidity record are neither interpolated nor recalculated.

Table 1. Scope of the source data used in the humidity response analysis

Item	Baseline hot and humid condition	Extreme hot and humid condition	Purpose in this study
Time scale	Diurnal variation over 12 h	Diurnal variation over 12 h	Compare the progression of the humidity indicator
Main boundary conditions	High temperature and humidity, solar radiation, and external airflow	Higher ambient temperature and humidity	Examine the response to more severe external conditions
Key outputs	Humidity increment rises from 0.64% to approximately 1.29%	Approximately 5.84% at 3 h; 6.9%–7.0% in the later stage	Compare reported levels and late-stage behavior
Ventilation results	Humidity comparison for front-end ventilation	Comparison under the same hot and humid boundary conditions	Assess the limits of ventilation-based moisture control

2.2. Analytical Approach

The analysis first compares the reported humidity response under baseline and extreme boundary conditions, then considers where moisture is retained and how ventilation changes that response. The source term "humidity increment" and its numerical values are retained throughout. They are not relabeled as relative humidity, humidity ratio, or water-vapor mass. This distinction limits interpretation: a change in the reported indicator alone does not establish how much water entered or left the container. Humidity ratio, water-vapor partial pressure, and dew point are used separately to discuss ventilation and condensation. The proposed control measures follow from that physical interpretation; they are not additional simulation results.

3. Humidity Response Characteristics in Hot and Humid Environments

3.1. Water Vapor Accumulation under the Baseline Condition

In the baseline case, the humidity increment increased from 0.64% to approximately 1.29%, after which the reported value became relatively stable. The response therefore developed over time rather than appearing immediately after exposure to the external conditions. A nearly constant indicator in the later stage should not, by itself, be taken as proof of complete moisture equilibrium. The source model also placed moisture-retention regions near the container floor and in areas of weak airflow. Restricted local exchange and uneven temperatures offer plausible explanations for this pattern. These locations merit attention even when a container-wide humidity measure appears stable (Table 2).

Table 2. Comparison of humidity responses under baseline and extreme hot and humid conditions

Condition	Key period	Humidity increment	Moisture-control implication
Baseline hot and humid condition	0–12 h of the diurnal cycle	Rises from 0.64% to approximately 1.29%, then becomes relatively stable	Check local stagnation regions despite a stable late-stage indicator
Extreme hot and humid condition	At 3 h and during the later stage	Approximately 5.84% at 3 h; 6.9%–7.0% later	Higher reported increments warrant closer assessment of moisture exposure

3.2. Amplified Accumulation under Extreme Hot and Humid Conditions

The extreme hot and humid case produced a much larger response: the humidity increment reached approximately 5.84% at 3 h and 6.9%–7.0% in the later stage. The peak internal temperature was 40.5°C. These results show that the reported humidity indicator is sensitive to the more severe boundary conditions. They do not, however, isolate the contributions of higher temperature and greater ambient moisture content. Temperature changes affect saturation vapor pressure and relative humidity, whereas moisture exchange changes the water-vapor content of the air. Their effects should not be conflated. For cargo protection, the higher reported increment warrants closer attention to moisture exposure and to condensation if local surfaces subsequently cool to the dew point.

Figure 1 compares the representative late-stage values: approximately 1.29% in the baseline case and approximately 7.0% in the extreme case. The latter represents the reported range of 6.9%–7.0%. The bars summarize two different sets of boundary conditions, not repeated measurements under an identical environment. They are intended to show the contrast in the reported indicator, rather than a calculated ratio of water accumulation or a continuous time history.

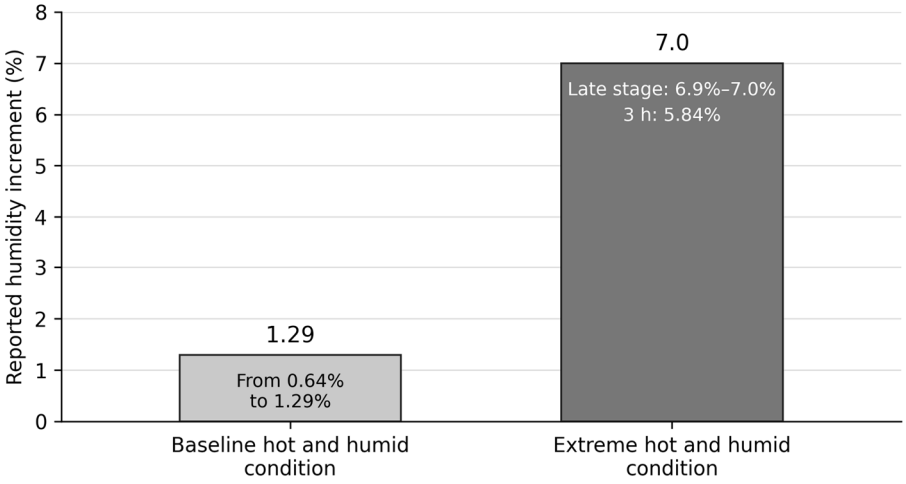


Figure 1. Reported humidity increments under baseline and extreme hot and humid conditions

4. Effects of Ventilation on Humidity and Its Applicability Limits

4.1. Extent of Humidity Improvement through Front End Face Ventilation

Opening the front end face substantially reduced the peak internal temperature in the source study, but the peak humidity increment fell by only approximately 0.2 percentage points. The thermal and humidity responses therefore differed in magnitude under the specified conditions. A small inside–outside humidity-ratio difference would be consistent with this limited drying effect, because replacing internal air with air of similar moisture content removes little water vapor. The available comparison does not establish that difference quantitatively, so it should be treated as a physical explanation rather than a separately measured result. Nor can the change in humidity increment be converted directly into a moisture-removal rate. The evidence supports a narrower conclusion: effective cooling through the openings did not guarantee a comparable reduction in the reported humidity indicator.

4.2. Conditions for Effective Ventilation-Based Moisture Control

Relative humidity alone is not a sufficient basis for deciding when to ventilate, because it varies with temperature as well as water-vapor content. For moisture removal, the relevant comparison is the humidity ratio of the outside air with that of the air being exhausted. Lower outside humidity ratio provides a drying potential; higher outside humidity ratio can introduce moisture. The temperature comparison answers a separate question. Cooler, drier outside air may support both cooling and drying, whereas warmer but drier air may offer drying at the cost of heat gain. Cooler, moister air presents the opposite trade-off: it may reduce air temperature while increasing the moisture load. Surface temperature must also be checked against the dew point of the adjacent air, since a favorable bulk-air comparison does not exclude local condensation. Figure 2 summarizes these qualitative operating conditions; it is not a validated control map.

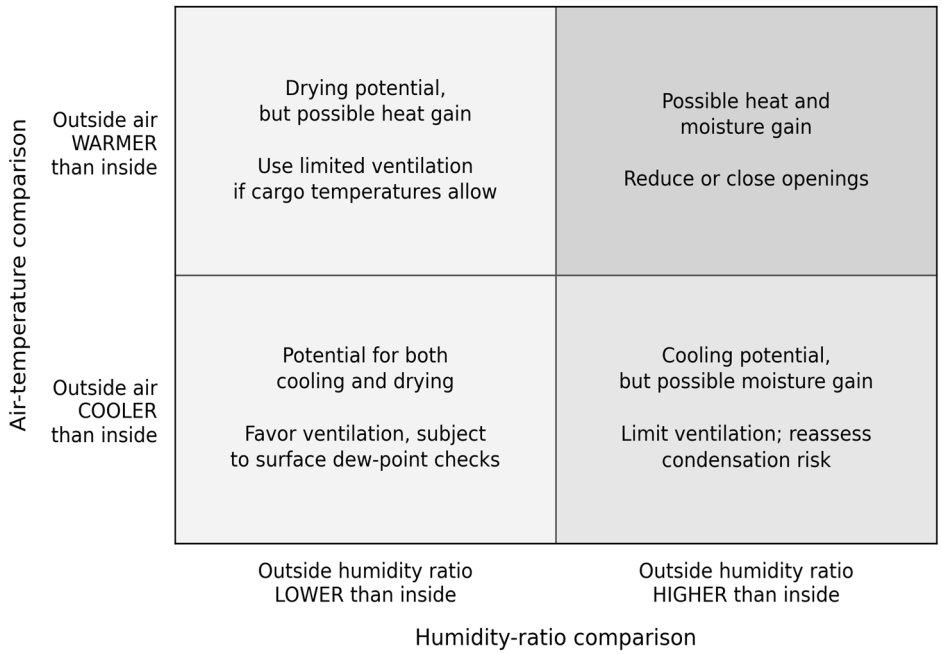


Figure 2. Qualitative ventilation choices based on outside–inside temperature and humidity-ratio comparisons. Local dew-point and surface-temperature checks are required in all four cases.

For a train crossing climatic zones, these comparisons need to be revisited as outside conditions change. Keeping the vents permanently open would ignore changes in both the direction of moisture exchange and the thermal effect of ventilation.

5. Coordinated Control Strategies for Moisture Protection and Ventilation

5.1. Ventilation Pathways with Adjustable Openings

Adjustable side and roof openings offer a way to respond to these changing conditions. Side openings can admit lateral airflow, while roof openings may provide an outlet for warm, humid air near the top of the container. Their actual roles depend on the pressure and airflow distribution; adding an opening does not ensure that a stagnant region will be flushed. Temperature and humidity measurements inside and outside the container should therefore inform operation. When the outside air has a lower humidity ratio and the thermal effect is acceptable, side openings can be used first and roof openings added as needed. When outside air would add moisture, windward and roof openings should be restricted or closed, subject to the cargo's thermal requirements. Rainfall provides an additional reason to close exposed openings. If surfaces are approaching the local dew point, vent positions should be reassessed using both moisture and temperature conditions rather than air temperature alone. These are proposed operating principles, not a tested opening sequence.

5.2. Supplementary Moisture Protection Measures

Ventilation should be supplemented where cargo or packaging can absorb moisture, or where the outside air offers little drying potential. Moisture-resistant films and liners can limit exposure, while desiccants provide a separate means of taking up water vapor. Independent dehumidification may be needed when ventilation and passive protection cannot maintain the required cargo conditions. Table 3 groups these options by operating situation. Selection should be supported by temperature and humidity monitoring, rather than by opening size alone. The source results do not quantify the performance of these supplementary measures, so no removal capacity or universally safe operating threshold is assigned here.

Table 3. Proposed combinations of ventilation and supplementary moisture protection

Environmental or transport condition	Ventilation recommendation	Supplementary measures
Outside air is cooler and has a lower humidity ratio than inside air	Open side vents moderately; use roof vents as needed	Monitor inside and outside temperature, relative humidity, and dew point
Outside air is cooler but has a high moisture content	Use limited ventilation for cooling only after checking the humidity-ratio difference	Use moisture-resistant packaging and desiccants; do not assume cooling also removes moisture
High ambient temperature and humidity	Limit direct ventilation if outside air would add heat or moisture	Improve sealing and use independent dehumidification where necessary
Heavy rainfall, blowing sand, or foggy, humid conditions	Close exposed ventilation openings	Check seals, drainage, and waterproofing
Hygroscopic cargo on long journeys	Adjust vents using humidity-ratio comparisons and dew-point checks	Use desiccants, moisture-resistant films, or moisture-barrier liners

6. Conclusions

(1) In the reported simulations, front-end ventilation reduced heat accumulation but lowered the peak humidity increment by only approximately 0.2 percentage points. The baseline increment rose from 0.64% to approximately 1.29%, whereas the extreme case reached 6.9%–7.0% later in the simulation. These results support separate assessments of thermal relief and moisture control. Their scope remains the reported humidity indicator and the source model's boundary conditions, including the approximately 37 m/s relative airflow used for ventilation.

(2) Ventilation decisions should compare the humidity ratios of inside and outside air and evaluate local surface temperatures against the relevant dew point. Adjustable openings can then be combined with moisture-resistant packaging, desiccants, and independent dehumidification where needed. The proposed strategy is qualitative. Its operating thresholds and effectiveness require validation for the cargo, container configuration, and transport conditions concerned.

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