Assessment of Indoor Relative Humidity Variations on the Energy Use and Thermal Performance of Supermarkets' Refrigerated Display Cases

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ABSTRACT

Each year supermarkets consume about 55 billion kWh of the United States' electrical energy. Refrigeration and air conditioning can contribute up to 75% of this usage. A large portion of this energy is utilized to satisfy the cooling load of refrigerated display cases. Furthermore, the cooling load of display cases is strongly dependent on the store's relative humidity. While transferring the moisture load from refrigerated fixtures to the air conditioning system can save energy, the additional energy cost of dehumidification must be closely evaluated. A reliable approach to quantifying the adverse impact of the relative humidity on the energy use of the refrigerated display cases can assist supermarket operators in performing such evaluations. Additionally, it can provide a robust premise to better evaluate the impact of energy efficiency opportunities on the defrost and anti-condensate energy and demand savings.

This paper presents the results of laboratory testing of four different display cases commonly found in supermarkets, under various indoor conditions. Tests specifically focused on evaluating the impact of indoor relative humidity reductions on the cooling load and refrigeration energy use of display cases. Due to the variation of electricity rates across the nation and different costs of dehumidification options, the economic analysis of the trade-off between refrigeration savings and air conditioning penalties in achieving lower indoor humidity was left outside the scope of this project.

The results showed open vertical case coil loads were considerably more vulnerable to changes in indoor humidity than coffin and reach-in fixtures, since infiltration constituted about 80% of the total cooling load of open vertical cases. Lowering the relative humidity from 55% to 35% reduced the latent load and compressor kW demand of the open vertical dairy case by 74.0% and 19.6%, respectively. It also reduced the defrost duration by 40.0%.

Introduction

This project investigated the effects of decreasing indoor ambient relative humidity on the performance and energy use of four different types of refrigerated display cases. The four tested cases represent fixtures commonly found in supermarkets for storage and merchandising of medium and low temperature products. The test results established a correlation between decreasing indoor relative humidity and the following key parameters:

- Mass of frost formed on the evaporator coil

- Defrost cycle length and power
- Anti-sweat heater power
- Discharge air velocity
- Product temperature
- Compressor power
- Display case cooling load
- Refrigerant mass flow rate
- Discharge air temperature
- Frost formation pattern and uniformity
- Reach-in case door fog refresh rate

The performance of these fixtures was evaluated under equal indoor conditions. Southern California Edison's (SCE's) Refrigeration Technology and Test Center (RTTC) was utilized to conduct various tests in the project. The controlled environment chamber of the RTTC was maintained at a fixed dry bulb temperature of 75°F, while its relative humidity was changed from 55% to 35% -- in 5% increments -- for all tests. The results of this study indicate a direct correlation between the indoor relative humidity and:

1. The weight of moisture removed from the air during the process of refrigeration
2. The fog removal time on freezer glass case doors with equal anti-sweat heater power (refresh rate)

Test Scenarios

Each display case was tested under five scenarios as shown in Table 1.

Table 1. Test Runs

Test Scenario	Room Condition (Dry Bulb Temp. / Relative Humidity)
1	75°F / 35%
2	75°F / 40%
3	75°F / 45%
4	75°F / 50%
5	75°F / 55%

The main control parameter for all test scenarios was the suction pressure based on manufacturer's specifications. Additionally, other parameters such as saturated evaporator and discharge air temperatures were monitored closely. For each fixture, the target suction pressure (as defined by the manufacturer) was maintained constant while the relative humidity inside the controlled environment room varied. All of the tests were conducted with a constant room temperature set at 75°F dry bulb while the relative humidity was varied in 5% increments, from 55% to 35%.

Test Design and Setup

The most important goal of this project was to capture the effects of indoor relative humidity on the power and energy use of four different types of refrigerated display cases. A specification summary of these fixtures is given in Table 2. These four tested display cases' classifications represent the largest categories of fixtures found in a typical supermarket.

Table 2. Specification Summary of Tested Fixtures

DISPLAY CASE TYPE	MAKE	MODEL	APPLICATION	DISCHARGE AIR TEMP. (DEG. F)	CAP.	LENGTH	HEIGHT W/O WHEELS
OPEN - 2 SHELF FRONT LOADING	*HUSSMANN*	IMPACT M3 w/ E-Coil	MEAT (M.T.)	28	1,120 Btu/hr-ft	8FT	73 15/16"
OPEN -5 SHELF FRONT LOADING	*TYLER*	L6DL8 ADVANTAGE	DAIRY/DELI (M.T.)	N/A	1,492 Btu/-hr-ft	8FT	79"
NARROW ISLAND COFFIN	*HILL PHOENIX*	ONIZ(F)	FROZEN FOOD	-12	369 Btu/-hr-ft	8FT	34 31/32"
GLASS DOOR REACH IN	*HILL PHOENIX*	ORZ(F)	FROZEN FOOD	-8	1,400 Btu/-hr-door	**3 DOOR** (90")	81 5/8"

All fixtures, with the exception of the coffin case, were tested with their shelf lights on. The refrigeration system was charged with a hydroflurocarbon refrigerant (R-404A). The refrigeration system's controller maintained a fixed saturated condensing temperature of 95°F ($\pm$ 0.5°F) for all tests. For each group of 5 test scenarios, the suction pressure was maintained at a fixed setting according to the case manufacturer's specifications throughout the entire test. This approach reasonably captured the effects of relative humidity variations on product temperature as well as system energy use. The product temperatures were monitored at the top shelf front right corner, top shelf rear center, bottom shelf front left corner, and bottom shelf front center.

The American Society of Heating, Refrigerating and Air-conditioning Engineers' (ASHRAE) standard 72-83 dictates that in the testing of display cases, the "food product zones shall be filled with test packages and dummy products" to simulate the presence of food product in the cases. According to ASHRAE standard 72-83, section 7.2.1, food products are composed of 80% to 90% water, fibrous materials, and salt. Plastic containers completely filled with a sponge material that is soaked in a brine solution of salt and water were used to simulate the product during the tests. These test packages, or product simulators, were placed in the locations where product temperature maintenance was most critical. The spaces in the test fixture where temperature measurement was not required were stocked with dummy products to add mass and stabilize the temperature in the case.

The effects of shopper traffic were also simulated on the open and reach-in fixtures. For the reach-in display case, each of the three glass doors was opened manually in sequence using a pulley system for 16 seconds, every four minutes, during 8 hours of a 24-hour test. For the vertical cases, a low-speed, oscillating, propeller-type fan blew air perpendicularly into their air curtain planes. The same fan agitated the horizontal air curtain of the coffin case by blowing air into it at a 45°angle.

A timer was used to turn on the fan for one minute, and turn it off for one minute and 50 seconds. Each test scenario was conducted for a period of 24 hours. Prior to each test, the controlled environment room and the refrigeration system underwent 8 hours of equalization interval to establish steady-state conditions.

Instrumentation

Prior to the test, all temperature and pressure instruments were calibrated. With the objective of minimizing instrument error and maintaining a high level of repeatability and accuracy in the data, careful attention was paid to the design of the monitoring system. The instrumentation system has special grade type-T thermocouples accurate to $\pm$ 0.1°C, precision 100Ω platinum resistance temperature device inputs accurate to $\pm$ 0.01°C, analog inputs from pressure transducers, dew point sensors, flow meters, and CT-transducers. An RS-232 link communicated instantaneous values of all data points every ten seconds. The dew point sensors located inside the frozen food narrow island coffin case and frozen food reach-in case malfunctioned during the test. Their failure was caused by low operating temperatures of the frozen food cases, which were below sensor tolerance levels. Several alternative approaches were attempted in order to utilize the sensors, but they all failed eventually. After these failures, it was concluded that new dew point sensors with lower temperature tolerance were needed to capture the humidity variation inside the freezer fixtures. It was finally decided to continue the test without this information, due to the high cost of the sensors and the relatively long lead time required to obtain them.

The capturing of the fog refresh rates on glass doors was achieved by the use of an analog video camera system. The camera's lens was placed at approximately 5 feet away from the glass doors, zooming at a 25" x 20" area at the center of the middle door. The video camera system recorded the entire test scenarios of the reach-in freezer. The camera system was equipped with an 8mm lens on a single charged couple device and a VHS Sanyo 40-hour time-lapse tape recorder that allowed the estimation of fog recovery duration.

Every ten seconds, the data acquisition system sampled the scanned data and created time-stamped two-minute averages. The two-minute data were then saved to a file that was closed at the end of each 24-hour period. Edison engineers reviewed the initial data on site at the RTTC to ensure the key control parameters were within acceptable ranges. In the event that any of the control parameters fell outside acceptable limits, the problem was flagged. In such cases, test runs were repeated until correction of the problem. Once the data passed the initial screening process, they were downloaded remotely to SCE's Irwindale office for further screening and processing.

The weight of condensate during each test scenario and for each display case was measured using a high precision digital scale with $\pm$ 0.1 gram accuracy. The data acquisition system received the exact condensate weight measurements from the digital scale every two minutes. Therefore, it became possible to closely monitor and distinguish between the moisture removal from the air during refrigeration cycle and defrost periods. At the end of each test period, the condensate data were also aggregated into hourly and daily values.

Controlled Environment Room Condition

The display cases were tested in the controlled environment room of the RTTC. The controlled environment room is an isolated thermal zone served by independent cooling, heating and humidification systems. This allowed simulation of various indoor conditions of a supermarket. The sensible cooling load representing people and other heat gain sources was provided by a constant volume direct expansion system reclaiming the waste refrigeration heat via a six-row coil. Auxiliary electric heaters located down-stream of the heat reclaim coils provided additional heating when required. While the air was conditioned to a desired thermostatic set point, an advanced ultrasonic humidification unit introduced precise amounts of moisture to the air surrounding the display cases, representing the latent load due to outside air and people.

Three rectangular laminar diffusers supplied approximately 1,100 cubic feet per minute of air into the room. The intensity of ambient lighting in the controlled environment room, as measured from the center of the test fixture opening at a distance of 1 foot from the air curtain, was 115 foot-candles. This complied with ASHRAE standard 72-83, which requires the lighting intensity not to be less than 75 foot-candles at this location.

Discussion of Results

Figure 1 shows the weight of moisture in the form of condensate collected at the end of each test. Clearly, open vertical meat and dairy fixtures demonstrated more vulnerability to humidity variations, and removed more moisture from the air than the coffin and reach-in units. In other words, the mass of condensate collected at the end of each test indicated that frost formation on the evaporator coil of all fixtures increased as relative humidity inside the controlled environment room was raised (Figure 1). The increase in frost accumulation on the evaporator coil, and resultant increase in condensate weight, was greatest for open vertical cases. The lowering of indoor humidity from 55% to 35% reduced the weight of condensate collected from the meat and dairy cases by 61.7% and 73.2%, respectively.

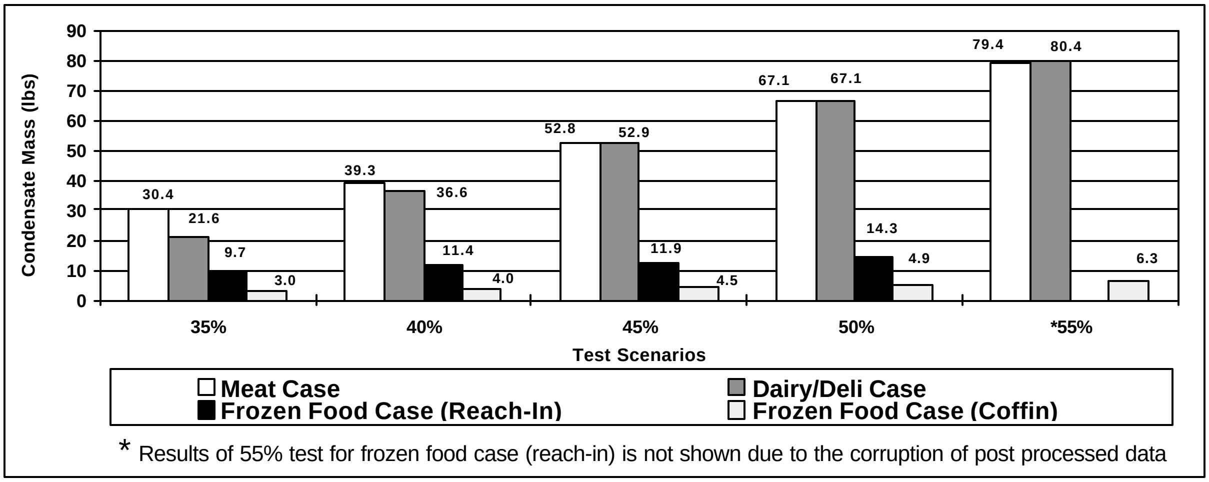


Figure 1. Comparison of Total Collected Condensate vs. Relative Humidity (All Four Tested Display Cases)

The cooling load of open vertical meat and dairy/deli fixtures proved to be more sensitive to the humidity fluctuations than coffin and reach-in units. Coupling the experimental data with heat transfer and thermodynamic equations, provided a sound approach for determining the individual cooling load components for all the fixtures. The cooling load analyses of three of the fixtures confirmed that infiltration makes up roughly 80% of the open vertical cases' load. The role of infiltration relatively diminishes for the coffin case while radiation takes over (Figure 2). The extreme vulnerability of open vertical cases' performance and energy use to indoor humidity variations is mainly due to their large infiltration loads.

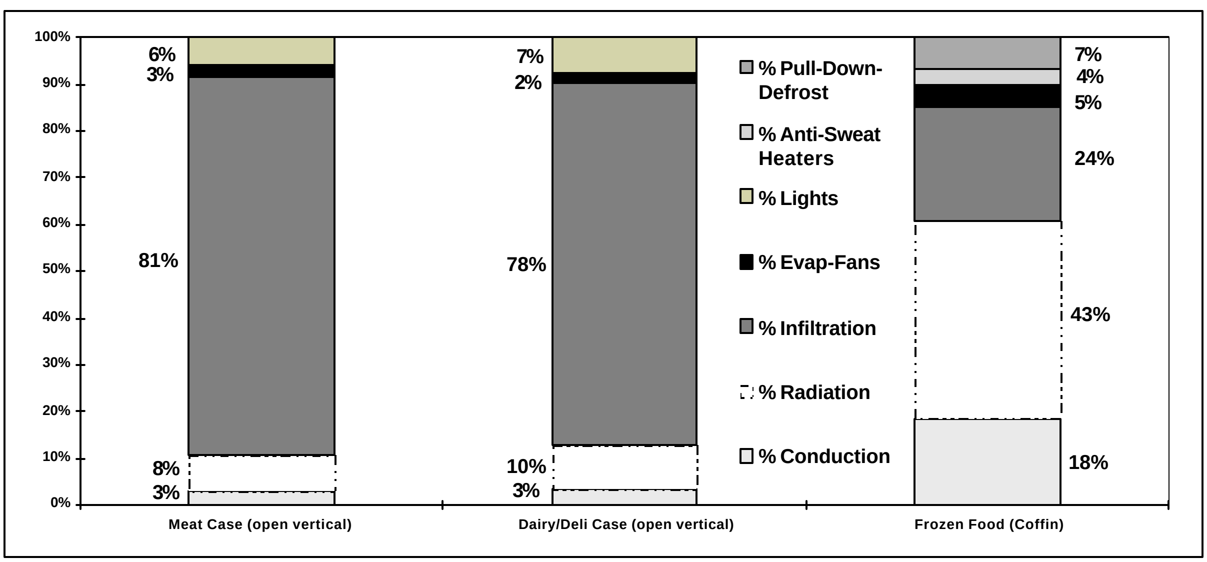
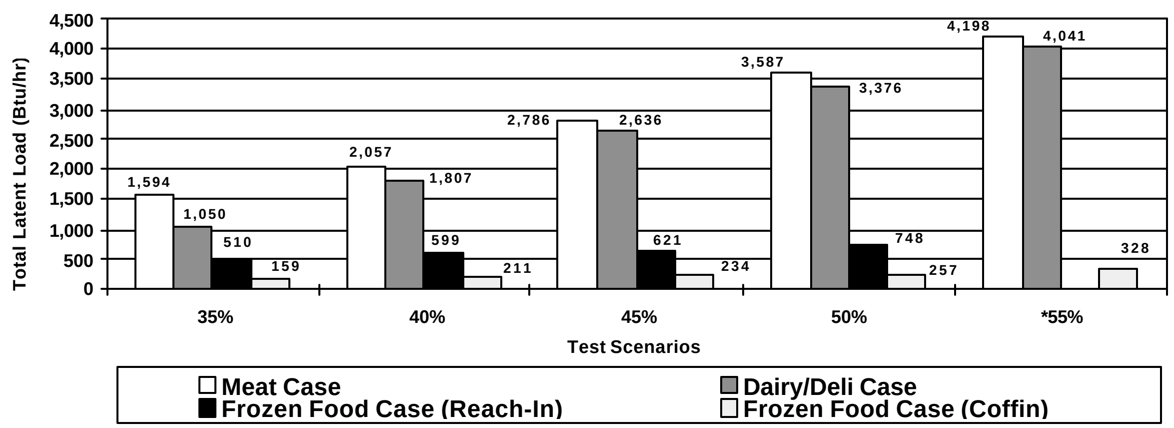


Figure 2. Refrigeration Load Percentage Breakdown for Meat, Dairy/Deli and Frozen Food (Coffin) at 75°F Dry Bulb and 55% Relative Humidity

The decrease in indoor relative humidity had an immediate impact on the latent load of all fixtures. As shown in Figure 2, the infiltration accounts for approximately 80% of the cooling load of open vertical cases. This factor brought about a considerable latent load penalty for open vertical display cases (Figure 3). The growth in mass of condensate at higher indoor relative humidity levels is a clear indication of the increase in refrigeration systems' latent load. Lowering the indoor humidity from 55% to 35% resulted in 62.0% and 74.0% reduction in latent loads of the meat and dairy cases, respectively.



* Results of 55% test for frozen food case (reach-in) is not shown due to the corruption of post processed data

Figure 3. Comparison of Total Latent Load vs. Relative Humidity (All Four Tested Display Cases)

The effect of decreasing latent load, as a result of lowering indoor humidity, was reflected directly on the power consumption of the test compressor (Figure 4).[1] As expected, open vertical meat and dairy cases showed the highest increase in their compressor power demand as indoor relative humidity increased. Lowering of relative humidity from 55% to 35% for these two fixtures resulted in 17.7% and 19.6% reduction in compressor power, respectively.

[1] The test compressor and its rack system were not designed specifically for the subject casework and therefore will have certain inefficiencies that would appear in actual system design. Therefore, refrigerant cooling load is a preferred measure of system performance.

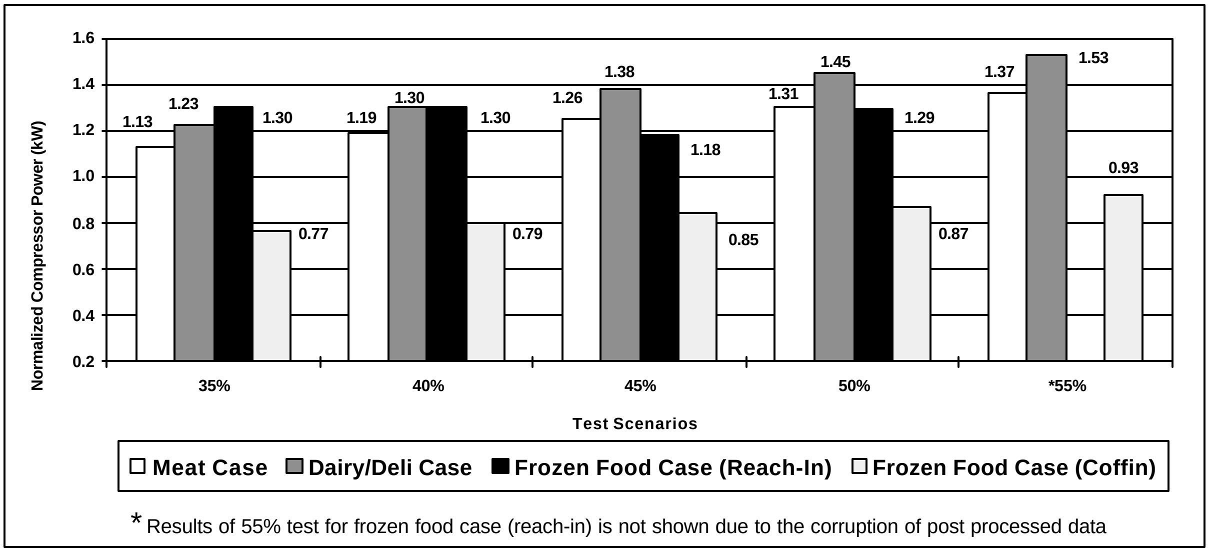


Figure 4. Comparison of Normalized Compressor Power Consumption vs. Relative Humidity (All Four Tested Display Cases)

Figure 5 shows that lowering of relative humidity from 55% to 35% for the open vertical meat and dairy cases resulted in 20.7% and 20.8% reduction in the total cooling loads, respectively.

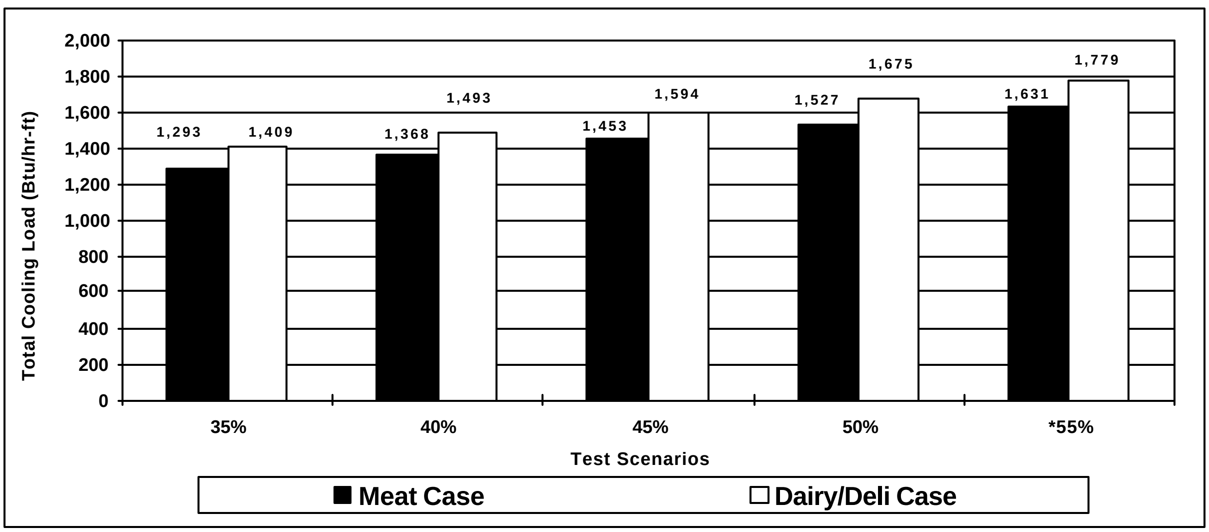


Figure 5. Comparison of Total Cooling Load vs. Relative Humidity (Meat and Dairy/Deli Cases)

Results of testing the four different refrigerated display case types under various indoor relative humidity conditions clearly indicate that the energy use of these cases is dependent on humidity. Except for some anomalies observed in the results of low temperature fixtures tests, all other tests showed an increase in compressor energy use as indoor relative humidity increased

(Figure 6). Compressor energy use of open vertical fixtures seemed more vulnerable to humidity variation than the reach-in and coffin units. The inconsistencies in reach-in display case test results were consequence of human errors introduced in the test during door opening and closing sessions. The increase in compressor energy demand of all tested fixtures under more humid conditions was a direct result of the evaporator heat transfer and rise in air pressure drop across the coil.

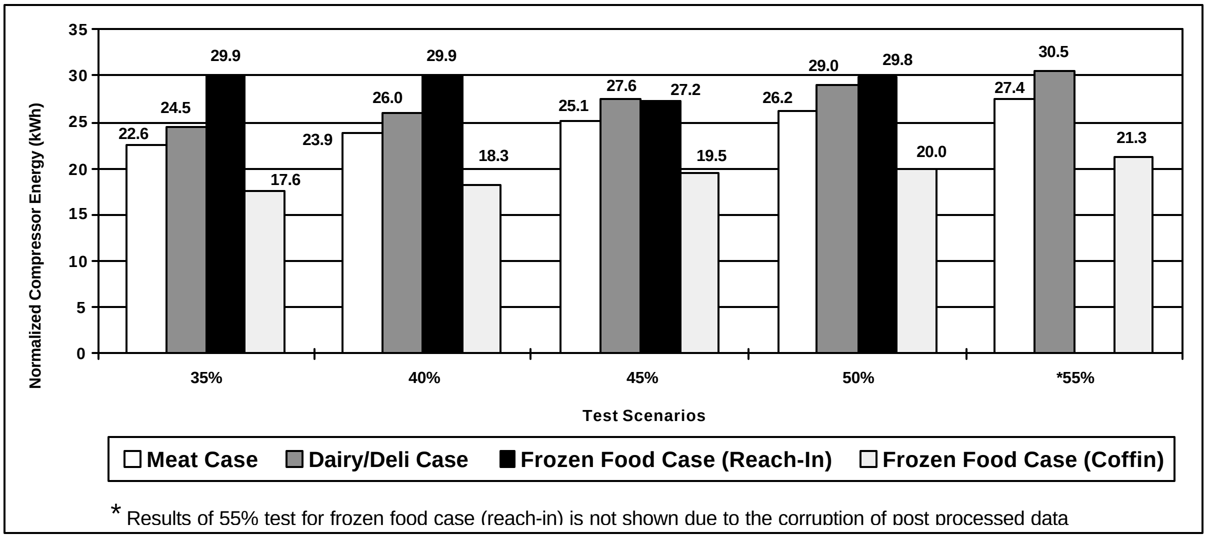


Figure 6. Comparison of Normalized Compressor Energy Consumption vs. Relative Humidity (All Four Tested Display Cases)

The thermal performance and energy use of the low temperature reach-in case was severely impacted by the door opening frequencies and their intervals. Coupled with their electric defrost and anti-sweat heaters, the reach-in case had the highest total system energy use during the 24 hour test period. Figure 7 reconfirms that, of the four display cases tested, the total system energy use of open vertical meat and dairy/deli fixtures was most vulnerable to relative humidity changes. The growth in total system energy use of open vertical cases is dictated by the increase in compressor power use under more humid conditions. The total system energy use results depicted in Figure 7 include compressor, fixture lights, evaporator fan motors, electric defrost, and anti-sweat heaters. The condenser energy use was not included in these results.

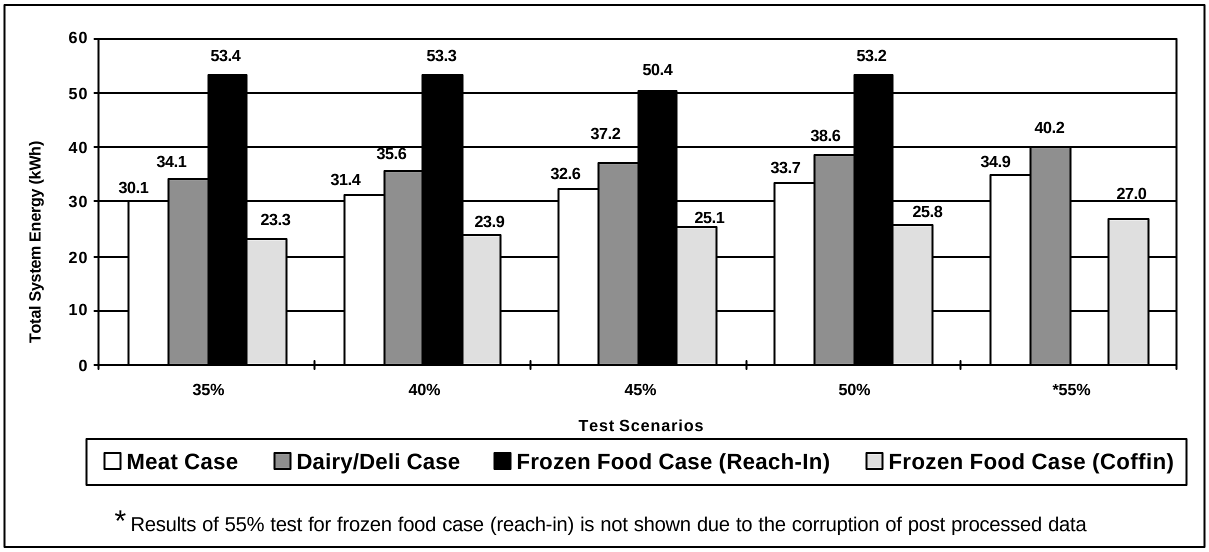
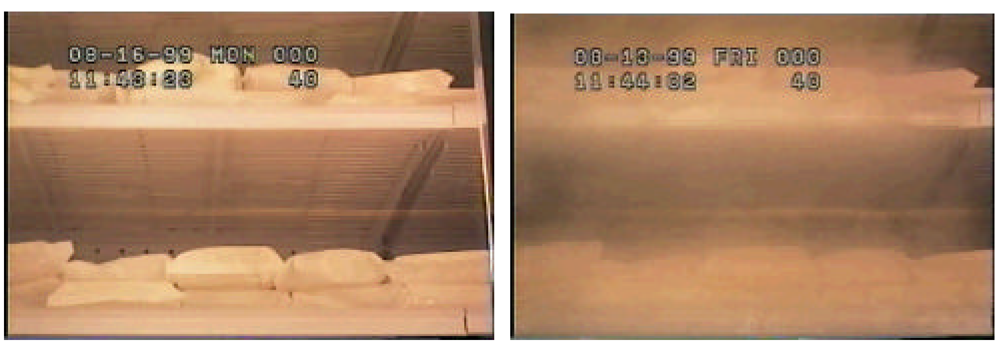


Figure 7. Comparison of Total System Energy Consumption vs. Relative Humidity (All Four Tested Display Cases)

The fogging effect on the reach-in display case under different indoor relative humidities was evaluated. Fogging of the reach-in glass doors has an adverse impact on the merchandising capability of the display case, and its quick recovery may require additional power consumption by the anti-sweat heater. Figures 8 (a) and (b) clearly illustrate the visual effect of fogging before and after the middle glass door was opened in the test environment of 75°F dry bulb and 50% relative humidity.



(a) (b)

Figure 8. Comparison of Visibility Due to Fogging Effect on the Middle Glass Doors for 75°F Dry Bulb and 50% Relative Humidity Test Scenario

It then became one of the objectives of this investigation to determine the potential impact of reduced indoor relative humidity on the length of time required to clear the fogging. Additionally, a sensitivity test was conducted to determine the fog clearance time required for the fixture at lowest indoor relative humidity of 35% while the anti-sweat heater was turned off.

Quantification of the impact of reduced indoor relative humidity on the length of time required for the fogging to be cleared was determined using a time calibrated analog video camera. Figure 9 compares the fog recovery time requirements under various indoor relative humidity conditions. Clearly, the fog recovery time increased as a function of indoor relative humidity. Lowering the relative humidity from 50% to 35% resulted in 69.2% reduction in fog recovery time. Additionally, operating the fixture at 35% relative humidity with anti-sweat heaters off yielded equivalent results to running the display case with anti-sweat heaters on, under indoor relative humidity conditions between 45% and 50%.

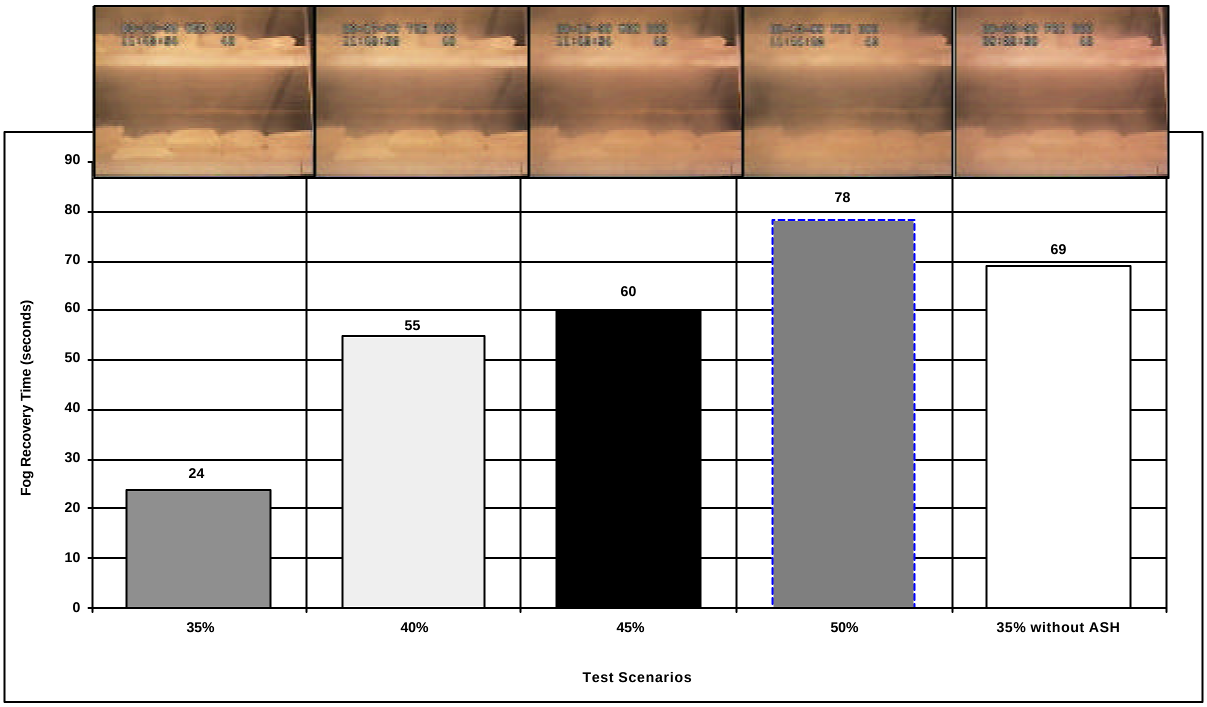


Figure 9. Fog Recovery Time and Actual Fog Image on Middle Glass Door for Each Test Scenario

Conclusions and Recommendations

The results of this study indicate that there is a direct relation between the indoor relative humidity and the weight of moisture removed from the air during the process of refrigeration. Clearly, open vertical meat and dairy fixtures demonstrated more vulnerability to humidity variations, and removed more moisture from the air than the coffin and reach-in units. Decreasing indoor relative humidity had an immediate impact on the latent load of all fixtures. Since infiltration accounted for approximately 80% of the cooling load of open vertical cases, decreasing relative humidity caused a significant latent load reduction for these fixtures. The effect of latent load reduction, as a result of lowering indoor humidity, was reflected directly on the evaporator coil load and consequently the power consumption of the test compressor. As expected, open vertical meat and dairy case showed the largest reduction in evaporator coil load and, subsequently, in test compressor power demand as indoor relative humidity fell.

This study also provides important quantification of the impact of reduced indoor relative humidity on the length of time required for the reach-in freezer glass door fogging to be cleared. Clearly, the fog recovery time increased as a function of indoor relative humidity. Lowering the relative humidity from 50% to 35% resulted in 69.2% reduction in fog recovery time. Additionally, operating the fixture at 35% relative humidity with anti-sweat heaters off yielded equivalent results to running the display case with anti-sweat heaters on, under indoor relative humidity conditions between 45% and 50%.

Supermarket designers and operators should reexamine various cost-effective means to maintain reasonably low relative humidity levels in stores. The trade-off between refrigeration savings and air conditioning penalties in achieving lower indoor humidity must be closely evaluated. Additionally, the use of smart defrost and anti-sweat heater control technologies could bring about more energy saving opportunities under low indoor humidity conditions.

It also seems important to investigate the design of more effective air curtain systems for reducing the infiltration load of open vertical cases. This load component was the only factor in introducing indoor moisture to these display cases. Also, researching the effects of evaporator configuration and arrangement on the frost formation density and pattern, as well as on defrost efficiency, could result in valuable energy efficiency opportunities.

References

[EPRI] Electric Power Research Institute (EPRI). December 1992. *Field Testing of High-Efficiency Supermarket Refrigeration*. EPRI TR-100351.

[ASHRAE] American Society of Heating, Refrigerating and Air-conditioning Engineers. 1993. *Fundamentals*. Handbook, I-P Edition.