Are They Cool(ing)?: Quantifying the Energy Savings from Installing / Repairing Strip Curtains

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Abstract

Strip curtains are used to reduce the refrigeration load associated with the infiltration of non-refrigerated air into the refrigerated spaces of walk-in coolers or freezers. This paper addresses the uncertainties in quantifying the savings that result from using strip curtains as energy efficiency measures for walk-in coolers and freezers. Generally, estimates of the savings that result from use of strip curtains are based on assumptions regarding the extent to which the strip curtains reduce the amount of infiltration, and the enthalpies of the refrigerated and infiltrating air, and the number and duration of door-openings per day. Infiltration rates with and without curtains are determined through tracer gas measurements. The enthalpies of the infiltrating and refrigerated air, door opening durations and frequencies, and activity levels inside the walk-in coolers and freezers are determined through short-term (two-week) monitoring. The tracer gas measurements and other monitoring are conducted on a total sample of about 230 facilities distributed among supermarkets, convenience stores, restaurants, and refrigerated warehouses that are located in different climate areas. These various data thus collected on changes in infiltration and door opening behavior are being used as inputs for analyses of energy use reductions, either through application of ASHRAE refrigeration algorithms or simulations with DOE 2.2R. This paper does not discuss actual realized gross savings, but rather discusses the evaluation methodology and reveals salient findings regarding the measurement process. Our findings suggest that the volumes of empty space in walk-in units may be reliably measured through the introduction of a measured amount of tracer gas, that, in the absence of strip curtains, the infiltration rates for smaller walk-in units vary significantly in the first 30 to 90 seconds of infiltration, and that equations based on Bernoulli's principle, along with a suitable empirical 'discharge coefficient' can provide adequate description of steady-state flow due to the stack affect.

Introduction

The air density difference between two adjacent spaces of different temperatures is the primary cause of air infiltration into walk-in coolers and freezers. The total refrigeration load due to infiltration through the main door into the unit depends on the temperature differential between the refrigerated and non-refrigerated airs, the door area and height, and the duration and frequency of door openings. Properly designed and installed strip curtains can potentially reduce the infiltration rate by over 90% (ASHRAE, 2006b). The calculation of the refrigeration load due to air infiltration, and the energy required to meet that load, is rather straightforward, but, relies on critical assumptions regarding the aforementioned operating parameters. In the absence of large datasets that describe the operating conditions of walk-in and reach-in units in different business environments and even in different geographical areas, the calculations are subject to large uncertainties that result from variations in the input data. For example, while one utility in a western U.S. state uses 465 kWh per square foot as the *ex ante* value for savings from using strip curtains, another utility in the same state reports 158 kWh per square foot as the ex ante value. In calculating *ex ante* savings for strip curtains, both utilities use a savings calculation procedure that is based on the approach laid out in the ASHRAE Handbook for calculating refrigeration loads. In the ASHRAE formula for calculating refrigeration load caused by infiltration, a factor is included that is indicative of the effectiveness of an infiltration barrier. The most striking difference between the savings calculations of the two utilities is attributable to the assumptions made about the baseline and post-retrofit effectiveness of strip curtains when calculating refrigeration loads and savings from strip curtains. One utility assumed that the base case is a freezer or cooler without strip curtains, and that new strip curtains reduce the infiltration by 80%. The second utility surmised that the base case is composed of two equally-weighted categories: freezers and coolers without strip curtains, and freezers and coolers that have dilapidated strip curtains that reduce infiltration by 80%. This utility assumes that properly installed, new curtains reduce infiltration by 92%. Strip curtains are a relatively low-cost energy efficiency measure. Vendors install them at about \$10.00 /ft^2. If the energy savings claimed by the utility programs are appropriate, then strip curtains are as cost-effective in energy savings as compact fluorescent light bulbs. This paper does not discuss actual verified savings, but rather motivates the EM&V methodology and discusses the salient findings regarding the sources of the uncertainty in the tracer gas measurements and in the overall energy savings.

Methodology

This study began with a literature review regarding utility program tracking data and “work papers” that detailed the energy savings estimation calculations associated with strip curtains. The sampling plan and field measurement approaches were devised according to the findings of the literature review.

Basic Theoretical Overview

Prior to field visits, the utility “work papers” that detailed the energy savings estimation calculations associated with strip curtains were reviewed. The energy savings calculations are lengthy but straightforward. The refrigeration load due to infiltration is calculated through the following equation (ASHRAE, 2006):

Equation 1: $\boxed{q_t = qD_tD_f(1-\delta)}$

Where,

q_t = the average heat gain over a 24 hour period

D_t = is the fraction of the time that the door is open

D_f = doorway flow factor, an empirically determined scale factor on the order of unity

δ = effectiveness of strip curtain at thwarting infiltration (1=100% effective, 0=no strip curtains present)

q = the refrigeration load due to infiltration for fully established flow (given below), Btu/h,

The refrigeration load due to infiltration for fully established flow is described fully in Equation 2 (Gosney & Olama, 1975):

Equation 2: $\boxed{q = 795.6A(h_i - h_r)\rho_r(1-\rho_i/\rho_r)^{0.5}(gH)^{0.5}F_m}$

Where,

q = refrigeration load in Btu/h

A = doorway area, ft^2

h_i = enthalpy of the infiltrating air, Btu/lb

h_r = enthalpy of the refrigerated air, Btu/lb

ρ_i = density of the infiltration air, lb/ft^3

ρ_r = density of the refrigerated air, lb/ft^3

g = gravitational constant = 32.174 ft/s^2

H = doorway height, ft

F_m is the density factor: $\boxed{F_m = \left(\frac{2}{1+(\rho_r/\rho_i)^{1/3}}\right)^{3/2}}$

The infiltration rate, in CFM, can be obtained from Equation 2 be removing the $(h_i\text{-}h_r)\rho_r$ term. The resulting equation becomes:

Equation 3: $\boxed{Q = 795.6A(1-\rho_i/\rho_r)^{0.5}(gH)^{0.5}F_m}$

There is another simplified formula for the prediction of infiltration due to the stack effect (ASHRAE 2005).

Equation 4: $\boxed{Q = 60C_D A\{((T_i - T_r)/T_i)(2g\Delta H_{NPL})\}^{0.5}}$

Where,

Q = infiltration rate, measured in cubic feet per minute

A = doorway area, ft^2

T_i = temperature of the infiltrating air, °R

T_r = temperature of the refrigerated air, °R

g = gravitational constant = 32.174 ft/s2

ΔH_{NPL} = height to the neutral pressure level (effectively half the door height)

C_D = discharge coefficient of the opening, for a single opening, $CD = 0.4 + 0.0025|\,T_i - T_r|$.

From an operational perspective, Equation 4 has the advantage that only the dimensions of the doorway and the temperatures of the refrigerated and surrounding spaces are necessary to determine the infiltration rate. This equation would facilitate the specification of the infiltration in thermal modeling software such as eQuest or DOE2. Furthermore, the discharge coefficient C_D above seems to be in better agreement with data than the discharge coefficient that is implicit in Equation 3. We modify

Equation 4 to better account for the case when the majority of the infiltration occurs through a single orifice. In this case, the neutral pressure level is half the height of the doorway to the walk-in refrigeration unit. The refrigerated air leaks out through the lower half of the door, and the warm, infiltrating air enters through the top half of the door. We deconstruct the lower half of the door into infinitesimal horizontal strips of width W and height dh. Each strip is treated as a separate window, and the air flow through each infinitesimal strip is given by Equation 4. In effect, this replaces the implicit $wh^{1.5}$ (one power from the area, and the other from ΔH_{NPL}) with the integral from 0 to $h/2$ of $wh'^{0.5}\,dh'$ which results in $wh^{1.5}/(3\times 2^{0.5})$. With this modification, Equation 4 is recast as:

Equation 5: $\boxed{Q = 20C_D A\{((Ti - T_r)/T_i)(gH)\}^{0.5}}$

The variable H in the above equation is the entire doorway height. Equation 5 is somewhat easier to use because the only required inputs are readily available: the physical dimensions of the units and the temperatures of the refrigerated and surrounding spaces. Of course, enthalpies and densities will be needed to obtain an actual refrigeration load. The discharge coefficient C_D typically takes on values 0.42-0.52 for the temperature regimes encountered. Although there is no formal discharge coefficient in Equation 3, the equation does contain an implicit assumption of $C_D = 0.663$.

Factors that Impact Energy Savings: Understanding What to Monitor

The energy associated with meeting the refrigeration load depends on the efficiency of the refrigeration system. The utility work papers use binned weather analysis to calculate the coefficient of performance (COP) based on a given set of refrigerated and outdoor air temperatures and humidities. The initial calculation review found the calculations to be correct (with the caveat that a literature review found that the equations describing the infiltration rates have demonstrated agreement with data at the ±50% level), but that the resulting savings estimations are quite sensitive to input variables that are based on informed assumptions rather than survey data. To understand the key drivers of the savings calculations, various input parameters were varied by 10%. Table 1 lists the relative changes in the calculated energy savings that result from 10% variations of key input parameters.

Table 1. Relative changes in the calculated energy savings that result from 10% variations of key input parameters.

10% Variation in Input Parameter	Corresponding Variation in Savings	10% Variation in Input Parameter	Corresponding Variation in Savings
Baseline Curtain Efficacy	7.7%	Relative Humidity of Refrigerated Air	0.1%
Post-Measure Curtain Efficacy	17.7%	Door Height	5.1%
Temperature Differential ($T_{inf} - T_{ref}$)	20.9%	Fraction of time that door is left open	1.7%
Relative Humidity of Infiltrating Air	4.2%	Number of Ingress/Egress Per Day	8.3%
Time Door Open per Ingress/Egress	9.0%	Refrigeration System COP	10.0%

The sensitivity study above helped to identify the major factors that affect the theoretical savings achievable by strip curtains, and also helped to develop an appropriate sampling approach as discussed below.

Sample Selection

In statistical terms, a domain of study is a major segment of the population that is identified in the overall sample design as one for which a certain level of detail and certain data reliability are required. The number and types of domains that are defined have an important bearing on the size and distribution of the sample. For the analyses of strip curtains, we define domains of study by three criteria:

- Type of business (Supermarket, Convenience store, Restaurant, Refrigerated Warehouse);
- Type of refrigeration unit to which the measures are applied (Walk-In Cooler, Walk-In Freezer); and
- Geographical location.

Geographical location of the sites where the measures are installed is considered in defining domains of study for two reasons. One reason, which is based on an administrative point of view, is that taking account of geographical location in defining domains allows consideration of utility service territory. However, there is also an analytical reason for considering geographical location in defining domains. The climate zone can affect the refrigeration systems' efficiencies, and may also influence the temperature of the infiltrating air in cases where the refrigeration unit opens to unconditioned space.

For strip curtains, we have developed the sample design using the concept of a paired study as the analytical framework. With a paired study, two measurements of infiltration are made for each site: with strip curtains in place and with strip curtains not in place. Infiltration depends on the effective area of a refrigerated door. Suppose that the effective area of the walk-in door = A - δA, where A is the area of the door and δ is a factor in the range $0 \leq \delta \leq 1$ indicating the degree to which strip curtain reduces infiltration. When strip curtains are not in place, $\delta = 0$. There are 140 units in the overall sample, split approximately evenly among the domains of study.

Field Measurement Methodology

Tracer Gas Measurements. The infiltration rates are measured by tracer gas measurements using CO2 as the tracer gas. Assuming that there are no sources or sinks of CO2 inside the walk-in units, the concentration of CO2 at a given time after the CO2 release is given by the following equation:

Equation 6

$$\boxed{C(t) = C_{out} + (C_0 - C_{out})\exp(-\tau t)}$$

Where,

$C(t)$ = the CO_2 concentration inside the walk-in cooler or freezer at time t,

C_{out} = the outdoor CO_2 concentration,

C_0 = the "initial" CO_2 concentration inside the walk-in just after the gas has been released,

τ = the infiltration rate into the walk-in box, in air changes per hour.

Equation 6 is readily modified to accommodate local sources and sinks of CO_2. However, preliminary measurements show stable CO_2 levels in well-sealed units with the doors closed. This indicates that there are no significant CO_2 sources or sinks inside the walk-in boxes.

The CO_2 levels inside and outside the unit are measured in 15-second intervals by Telaire 7001 Non-Dispersive Infrared (NDIR) sensors and are logged by HOBO loggers. The sensors are specified to work in temperatures ranging from 32 °F to 122 °F. To ensure proper function of the NDIR sensors in the freezers and coolers, the sensors are housed in a custom-built, insulated box equipped with heating coils and a fan that passes heated air over the sensor. The air temperature inside the box can be adjusted to be between 30 °F and 60 °F above ambient conditions. In addition to CO_2 levels, the temperature and humidity levels are logged by HOBO loggers placed inside and outside the cold boxes. To capture any potential temperature gradient between the front and rear of large walk-in units, two temperature loggers are used: (1) a thermocouple and HOBO combination just inside unit, aligned with the center of the doorway and (2) a Temperature/RH HOBO near the back end of the unit. The temperature sensor near the front of the unit is placed at ground level to capture the temperature of the air as leaves the unit. Up to six separate tests are conducted on a walk-in unit:

1. Measurement of infiltration with the door open and the strip curtains in place
2. Measurement of infiltration with the door open and the strips removed
3. Measurement of infiltration with the door closed and sealed – to capture any leakage through other orifices and cracks (e.g. gaskets of reach-in doors for walk-in/reach-in units)
4. Measurement of infiltration for an ingress/egress test (field technicians pass through the strip curtains – the disturbance of the strip curtains makes them less effective for a short amount of time)
5. A series of three tests with the strips removed:
   - 5.1. The door is opened for 15 seconds, and closed for three minutes
   - 5.2. The door is opened for 30 seconds, and then closed for three minutes
   - 5.3. The door is opened for 45 seconds, and then closed for three minutes.

The first three tests are conducted without exception for all sites. The last two tests are conducted if time allows. In particular, the last test is designed to address two purposes

1) For small freezer units, the changes in the CO_2 levels are so fast that they challenge the response-time of the Telaire 7001 sensor. The methodology above enables the sensor to accurately capture the CO_2 levels prior to and after the door openings.
2) For small freezers, the high air exchange rates that occur in the absence of strip curtains (often in excess of one air exchange per minute) causes significant warming of the 'refrigerated' air, which in turn diminishes the pressure differential that drives the infiltration process. Therefore, the infiltration rates diminish appreciably during the course of a test. Comparison of the data from the 15-second, 30-second, and 45-second tests captures this phenomenon.

Analysis of Tracer Gas Measurements. The decays of the CO_2 inside the unit are fit with exponential functions, similar to Equation 6, that have all parameters fixed by field data except for the air exchange rate, τ. The air exchange rate that results in the best fit of the data (determined by χ^2 minimization) is taken as the measured air exchange rate and converted into the actual air flow in CFM using the volume of empty space in the unit. The volume of the empty space is measured using two separate techniques. The first method, called the 'emptiness factor judgment method', involves an actual measurement of the interior dimensions of the unit, and the estimation of the 'emptiness' of the unit. On average, the units are estimated to be approximately 75% empty. A second method, called the 'gas release calculation' method involves comparison of the rise in CO_2 levels associated with the introduction of a known amount of CO_2 (the field technicians calculate, record, and release the amount of gas required to raise the CO_2 concentration to 2,500 ppm. Both methods provide similar estimates of the volume of empty space. Compared to the 'emptiness factor judgment' method, the 'gas release calculation' method is more prone to error for small volumes that may only require two or three seconds of tracer gas release at 10 CFM. However, larger volumes require much longer release times and the amount of gas released is known with much higher accuracy. Figure 1 shows data from three tests on a large walk-in/reach-in unit at a convenience store.

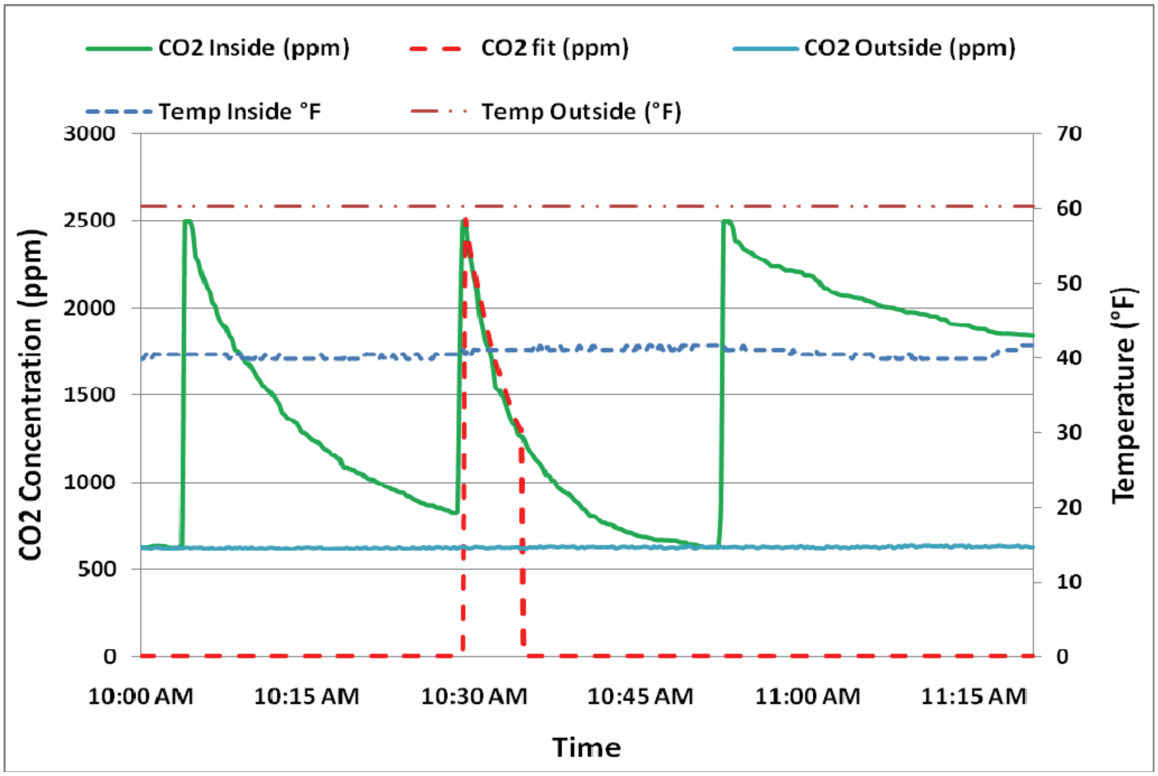

Figure 1. Data from testing a large walk-in / reach-in beverage cooler.

In Figure 1, the solid green profile corresponds to the CO_2 concentrations inside the unit. There are three releases of tracer gas that occur at approximately 10:03 AM, 10:30 AM, and 10:52 AM. The second test has the sharpest drop in CO_2 levels and corresponds to the "door open, no strip curtains" case. The dashed red line shows the exponential fit function that is used to determine the air exchange rate. This particular unit is a large walk-in beverage cooler with 12 glass reach-in doors on one side. The last test corresponds to the door-closed test, and indicates that there is significant leakage through the reach-in door-gaskets. Interestingly, there is a relatively sharp drop in the CO_2 levels at about 11:04 AM, which corresponds to a customer opening a reach-in door. Typically, only the walk-in/reach-in units demonstrate significant leakage when the doors are closed. In assessing the efficacy of the strip curtains, the leakage that occurs when the doors are closed is subtracted from both leakages that are measured with and without strip curtains. Thus, the efficacies of the strip curtains are obtained by the formula:

Equation 7: $$\boxed{\delta = (Q_{NoCurtains} - Q_{Curtains\Pr esnet})/(Q_{NoCurtains} - Q_{DoorClosed})}$$

Short Term Monitoring. In addition to tracer gas measurements, the units are monitored for at least a two-week period. The following data are collected:

- Door Open/Close states are monitored with state-loggers installed at both the handle and hinge of the door, to capture small-angle and relatively large-angle openings, respectively
- Temperature and relative humidity are monitored with HOBO loggers both inside the units, outside the units (placed appropriately to characterize the air that infiltrates the walk-in of interest), and outdoors.
- Activity inside the coolers are monitored with passive infrared motion sensors, and logged with HOBO loggers.

The data collected during short term monitoring will establish the times and durations of door openings, and the conditions of the refrigerated and infiltrating airs. The infiltrating air conditions depend on the space that the walk-in door opens to. Typically, walk-in units in restaurants open to conditioned space, walk-in units in convenience stores and grocery stores may open to conditioned space or to a 'loading bay' area. The loading bay temperatures depend on both indoor and outdoor temperatures and generally resemble the outdoor temperatures with attenuated diurnal swings. Although we obtain just two or three weeks of data for any given site, the body of data that can be used to compare indoor, outdoor, and 'loading bay' temperatures spans all four seasons of the year.

Preliminary Findings

Volume Measurement Methodology. The two approaches to volume measurement yield similar results, as shown by Figure 2. The 'gas release calculation' method predicts slightly larger empty volumes than the 'emptiness factor judgment' method. As shown in Figure 3, the "raw" agreements of data to the model equations for infiltration are slightly better if the 'gas release calculation' is used[1]. That is, the slope of the linear regression is closer to unity. However, the 'emptiness factor judgment' method has better predictive power, as indicated by the higher R^2 value of the linear fit. Provided that the predictive power of the model is sufficient, the actual slope of the linear regression is easily rescaled to unity with the application of a scale factor. The aforementioned 'discharge coefficient' C_D serves this purpose.

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[1] The units on the axes of certain figures are omitted to avoid any quantitative disclosure of M&V results. The M&V effort described herein is an ongoing process, and the authors will not present findings that can be used to assess gross savings estimations before the final report is supplied to the client.

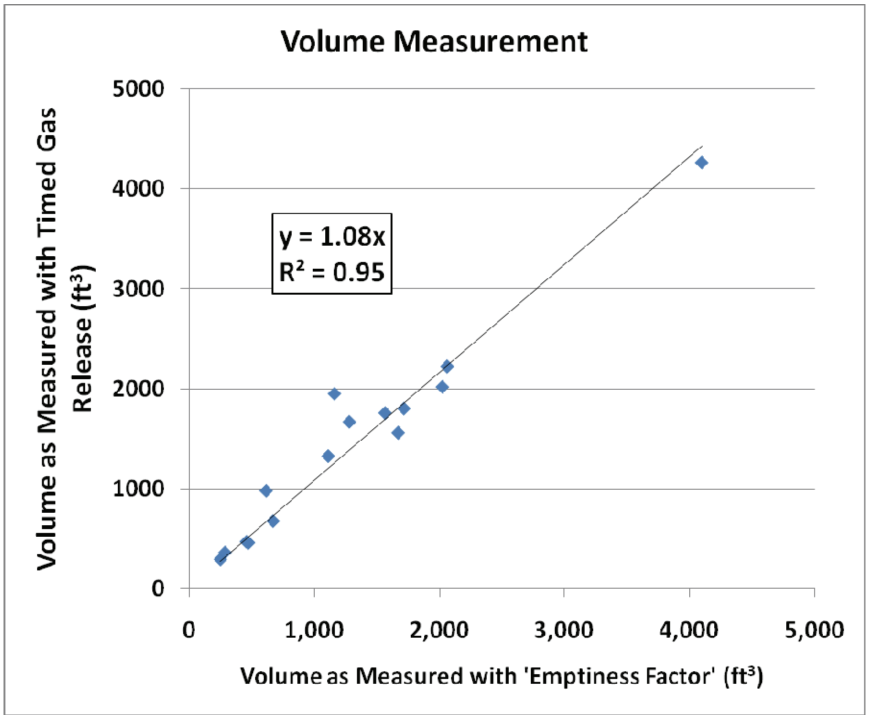

Figure 2. Unit Volumes as measured by the 'Emptiness Factor Judgement' method (horizontal axis) and 'Gas Release Calculation' method (vertical axis).

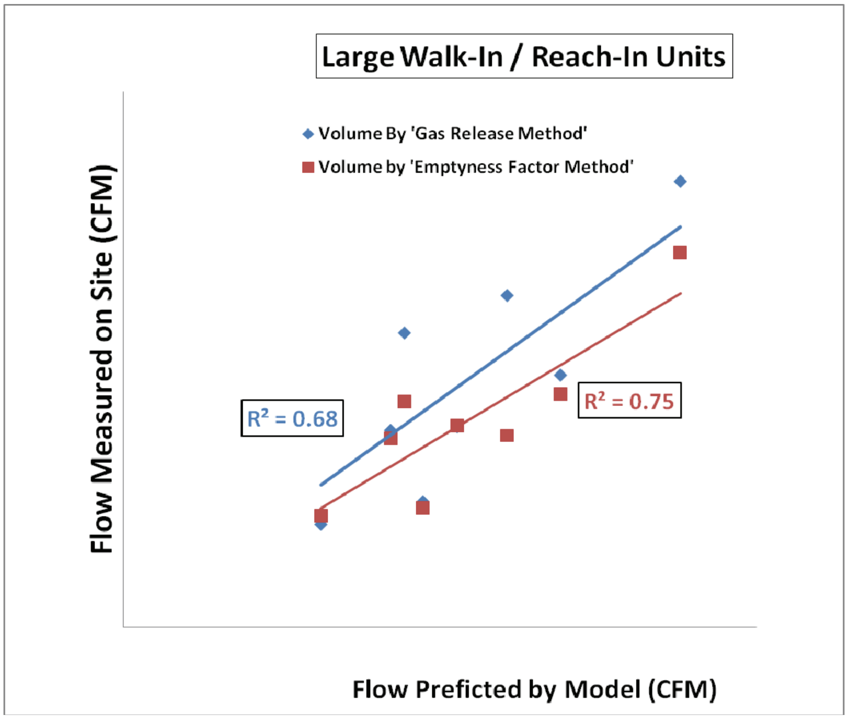

Figure 3. Measured (vertical axis) and predicted (horizontal axis) infiltration rates for large walk-in units. Two sets of predicted infiltration rates, corresponding to the two aforementioned volume estimation methods, are shown.

Comparison of ASHRAE Equations. Initial tracer gas measurements show that both Equation 3 and Equation 5 can result adequately predict the infiltration rates. Figure 4 compares the predictions of infiltration rates caused by the stack effect to field measurements for several small walk-in freezers. The integrated version of ASHRAE 27.11-30 and the more involved ASHRAE 13.4-12 both demonstrate sufficient predictive power. That the equations yield similar results is entirely expected due to the similar nature of both models – both are based on Bernoulli's principle, and differ mainly in the choice of overall scale factors. As shown in Figure 4, if the implicit value of 0.663 for C_D is replaced with the calculated C_D of ASHRAE 27-11.30, the agreement with data improves. One of the goals of this study is to come up with appropriate values for discharge coefficients, or more generally discharge factors (akin to the 'Form Factor' in Equation 2) for various classifications of walk-in units.

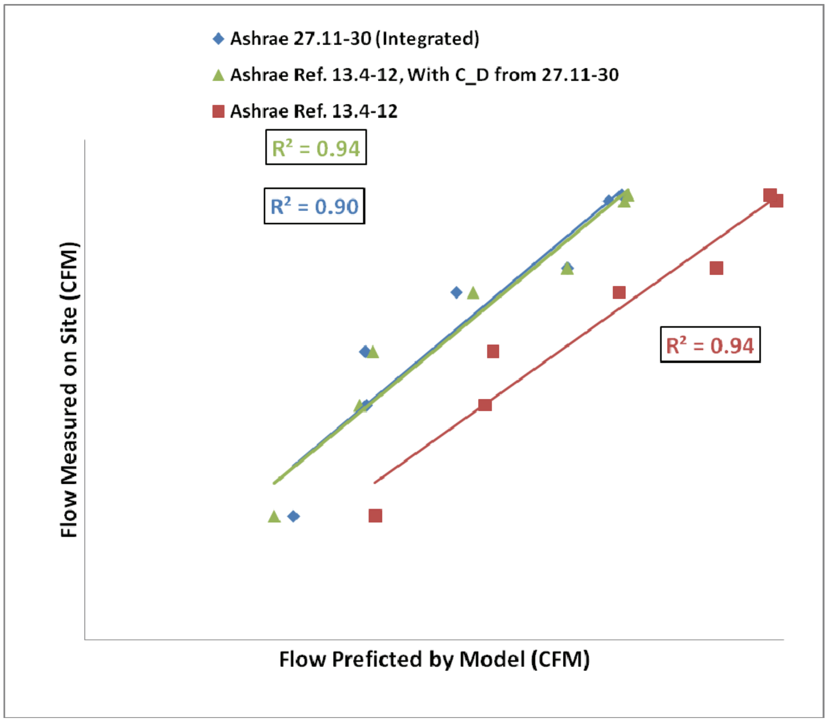

Figure 4. Airflow rates predicted by three models (horizontal axis) caused by the stack effect.

Dependence of Infiltration Rates on Door-Open Time. As the warm air infiltrates a walk-in unit, the temperature in the unit rises. The sensitivity study summarized in Table 1 shows that a 10% variation in the differential between refrigerated and infiltrating air temperatures will result in a 21% variation in the energy savings. A study of the temperature changes induced by infiltration can help to minimize the uncertainty in the final savings estimations. Walk-in freezers in particular are sensitive to this effect because they have the highest infiltration rates and associated refrigeration loads**.** Although freezer units typically have high refrigeration capacities relative to their sizes, they are unable to meet the initial refrigeration loads that result from leaving the door open without strip curtains in place. As the internal temperature rises, however, the infiltration rates decrease until at some point, equilibrium is established. Figure 5 presents the temperature rises and subsequent stabilization to 'equilibrium temperatures', where the refrigeration systems are capable of meeting the infiltration loads. The figure also shows theoretical predictions that are based on evaluations of the infiltration rate every four seconds using Equation 5, taking in account the temperature rises that occur from infiltration and the refrigeration system's ability to meet the infiltration loads.

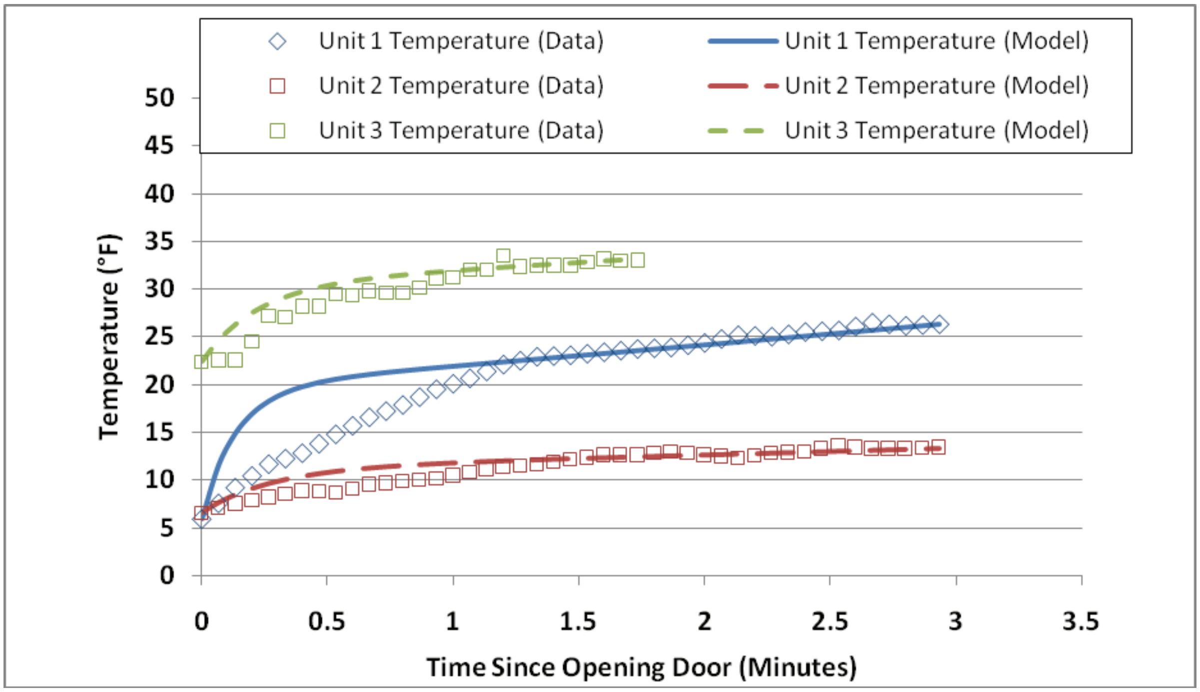

Figure 5. Measured (markers) and calculated temperature rises and equilibrium temperatures for three walk-in freezers with open doors and strip curtains removed.

Presently, the refrigeration capacities required to achieve the observed asymptotic equilibrium temperatures are somewhat larger than the capacities that are found on site. This is plausible based on the following two considerations. One possible cause is a buildup of recently exfiltrated air in the vicinity of the walk-in door that effectively creates a local cold buffer zone, thereby reducing the infiltration and associated refrigeration loads. The temperature sensor outside the unit would not capture the temperature drop in the air just outside the walk-in, as that sensor is placed far from the path of the outgoing air. Another possible cause can be referred to as 'reverse product load' – the incoming air cools as it passes over the product stored inside the unit. This alone may account for an additional 20% effective cooling capacity, depending on the cold box contents. This is a topic for further study as the EM&V effort continues. In any case, the results suggest that in the absence of strip curtains, the infiltration rates and associated loads are time-dependent for small freezers. Therefore, energy savings calculations should use the same iterative procedure described above to calculate the infiltration rates.

Conclusions

Initial findings from an M&V effort regarding strip curtains on walk-in freezers and refrigerators suggest that the tracer-gas measurement methodology can capture the energy savings associated with strip curtains. Test results can clearly distinguish air infiltration rates for walk-in units with and without strip curtains, and measure the curtains' efficacy in blocking infiltration. Two sets of equations, both based on Bernoulli's principle, demonstrate sufficient predictive power for infiltration into cold spaces through large, single openings. Furthermore, the equations can be used to capture the change in the infiltration rates that occur during the first two minutes for small freezers. For small walk-in freezers, initial infiltration rates are significantly higher than the equilibrium infiltration rates that occur if the doors are left open for prolonged periods (longer than two minutes). Further topics of study include a detailed analysis of the dynamics during the first two minutes of door openings for small freezers, and the determination of optimal 'discharge factors' to improve the predictive powers of the equations used to describe infiltration into cold stores.

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