HEFAT2012
9th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
16 – 18 July 2012
Malta

MEASUREMENT OF INFILTRATION RATE OF WARM AIR INTO WALK-IN COOLERS

Homayun K. Navaz*, Professor, Mechanical Engineering Department
Kettering University Flint, Michigan, 48504

Kristina Kamensky, Prismitech, LLC, 1700 University Avenue, Flint, Michigan 48504

Ramin Faramarzi, Refrigeration and Thermal Test Center
Southern California Edison Company, Irwindale, California 91702

Mazyar Amin, Post-Doctoral Fellow, Saint Louis University, Department of Biomedical Engineering
St. Louis, MO 63103

*Author for correspondence

ABSTRACT

The tracer gas technique is used to experimentally measure the infiltration of warm air into walk-in coolers during its nominal operating conditions. The tracer gas samples captured before, during, and after the infiltration process are collected through sampling probes inside and outside the cooler. The infiltration rate can be calculated from this data. The transient nature of the infiltration rate that is captured in this approach signifies the shortcoming of the existing methodologies currently practiced in industry. It is found that the infiltration rate is a function of the temperature gradient between the inside and outside air, relative humidity, and the void volume in the cooler. It is also demonstrated that it is possible to derive a closed form equation based on the experimental data that can replace the current equations.

NOMENCLATURE

A	[m^2]	Doorway area
C_i	[-]	Mass fraction
C_o	[-]	Orifice coefficient
D_t	[-]	Thermal conductivity
g	[m^2/s]	Gravitational acceleration
h	[kJ/kg]	Enthalpy
K_L	[-]	Corrective factor
M	[kg/kmol]	Molecular weight
$\dot{m}$	[kg/s]	Mass flow rate
n	[-]	Number of moles
P	[kPa]	Pressure
Q	[m^3/s]	Volumetric (Infiltration) flow rate
q	[kW]	Sensible and latent refrigeration load
RH	[%]	Relative Humidity
s	[-]	Ratio of warm air density to cold air density
T	[ºC]	Temperature
u	[cm/s]	Horizontal component of velocity
v	[cm/s]	Vertical component of velocity
W	[m]	Width
y	[-]	Mole fraction

Special characters

$\forall$	[m^3]	Air volume inside cooler
ρ	[kg/m^2]	Density
ω	[-]	Humidity ratio

Subscripts

Cleland	Derived by D. Cleland
CO_2	Carbon Dioxide
da	Dry air
inside	Air or volume inside the walk-in (refrigerated)
mix	Mixture of CO_2, *dry air and vapor*
outside	Air or volume outside the walk-in (ambient)
Tamm	Derived by W. Tamm
v	Vapor

INTRODUCTION

Walk-in coolers that are widely used for food storage and infiltration account for more than 50% of the cooling load [1, 2]. However, thus far there is no robust technology to precisely measure the infiltration rate of walk-in coolers during the door opening period. Upon systematic and direct measurement of the infiltration rate, those operating conditions that could reduce the infiltration rate can be identified. Furthermore, the infiltration rate of walk-in coolers due to small openings and unsealed (or poorly sealed) areas has never been accurately measured. We refer to this process as “natural infiltration.” Previous to this study, there was no experimental flow visualization completed of the infiltration phenomenon that occurs when the door is open.

There is a common equation that is frequently used to find the infiltration of warm air through doorways between a warm and cold room. This equation was derived by Tamm [3], and correlates the infiltration rate to geometric dimensions of the door and densities of warm and cold air. The effect of relative humidity is embedded in the density of air. This equation is given as:

$$Q_{Tamm} = 0.67WHD_t \sqrt{2gH \frac{(1-s)}{\left(1+s^{1/3}\right)^3}} \tag{1}$$

This equation has been modified by Chen et al. [4] for the impact of door open time, plastic strip curtains, and traffic through empirical equations. However, this equation is based on a fully developed flow between the warm air and cold air areas. The most recent work is presented by Reindl and Jekel [5], where they use carbon dioxide as a tracer gas in a blast freezing environment. The infiltration takes place naturally through small openings and is measured by a hand-held infrared detector.

Another widely used equation is Gosney and Olama [6] using a derivation of the cooling load as a function of the geometry of the door and density and enthalpy of the warm and cold air. This equation does not directly calculate the infiltration rate, but it links the infiltration rate, through an energy balance equation, to the cooling load. This derivation is also for fully developed flows. Walk-in coolers vary in size, but often experience a significant and transient exchange of air when accessed. The duration of the door opening event(s) and frequency also increases the transient nature of the problem. The validity of any of these equations has not been examined to see if the infiltration process is transient or not. The Gosney equation is:

$$q = 2754.25AD_t\left(h_{outside} - h_{inside}\right)\rho_{inside}\left(1-\frac{\rho_{outside}}{\rho_{inside}}\right)^{0.5} \times (gH)^{0.5}\left[\frac{2}{1+\left(\frac{\rho_{inside}}{\rho_{outside}}\right)^{1/3}}\right]^{1.5} \tag{2}$$

Another approach to quantify air infiltration based on hydrodynamic theory for a flow through an orifice is Cleland's [7] equation:

$$Q_{Cleland} = C_O AD_t \sqrt{2\frac{\Delta P}{\rho_{inside}}}$$

$$Where \tag{3a}$$

$$\Delta P = (\rho_{inside} - \rho_{outside})gH$$

To take abrupt expansion into account, a corrective factor is added:

$$Q_{Cleland} = C_O K_L AD_t \sqrt{2\frac{\Delta P}{\rho_{inside}}} \tag{3b}$$

$$K_L = \text{Correction for abrupt expansion}$$

Special attention should be given to the term of type $\left(1-\frac{\rho_{outside}}{\rho_{inside}}\right)$. If the values of inside and outside temperatures are fixed at a prescribed value, both of these equations will yield a constant value of infiltration that is somewhat far from the reality. For this assumption to be true, both rooms must be considered as reservoirs, which is not the case. However, if the cooler air density is taken to be a function of time as infiltration dictates, a more realistic estimate of infiltration by these two equations may be obtained. This requires information about the average air temperature in the cooler as a function of time after the air inside the cooler stabilizes. In our experiment this stabilization of inside air could be easily detected by the tracer gas, enabling us to find this functionality and use a transient value for air density inside the cooler to present "modified" Tamm, Gosney or Cleland equations.

The lack of a methodology to measure the infiltration rate into walk-in coolers during the door opening period has prompted the initiation of this project. This project will provide the manufacturers with a tool and a protocol that can be used to find the infiltration rate into walk-in coolers very accurately through direct measurements of the tracer gas concentration. This method has been used by Amin, et al. [8] for measuring the infiltration rate of open refrigerated display cases and is adopted in this work as a robust, accurate and simple-to-use technique

EXPERIMENTAL SETUP

Series of tests were performed with the walk-in cooler at the TTC facilities to study the infiltration rate and also visualize the flow pattern at the door during the event of infiltration. CO_2, an inexpensive and safe tracer gas was used to monitor the infiltration rate. The process consists of bringing the tracer gas concentration to a stable level inside the cooler when the door is closed and monitoring the concentration during the opening period. After the closing of the door, the concentration in the room becomes uniform due to the operation of the fan and the convective motion of air. The difference between the initial and final concentration at steady state conditions can be correlated to the amount of CO_2 loss during infiltration. This concentration can be related to the amount of cold air that leaves the cooler or the warm air that infiltrates into the cooler. The derivation of these equations is given in Appendix A.

Several probes were installed throughout the cooler for collecting samples to obtain a good representation of the average CO_2 concentration inside the cooler. These collected samples were taken to the gas analyzer for data logging. Suction pumps drew the mixture of tracer gas and air from the desired points and transferred it to the gas analyzer. The pumps should be installed between the sampling probes and the gas analyzer. Each gas analyzer channel requires its own dedicated pump. The outside area where the warm air was infiltrating into the cooler was a controlled environment room. To retain accuracy of the data, the CO_2 concentration had to be monitored inside this room. The maximum amount was only about 6% of the total amount of the initial tracer gas, and is accounted for throughout the calculations. 25% of the cooler was filled with food products yielding a cold air volume of 58.7 m^3. The outside room is conditioned at several temperature and relative humidity combinations as described in the results section. Another parameter that was investigated was the fan speed that varied from zero to 100% capacity. The temperature of the cooler was recorded in time. However, the infiltration was only initiated when the cooler temperature was stabilized at 1.7°C. Furthermore, we used the varying air density inside the cooler to capture some of the transient nature of the infiltration process in the conventional methods.

RESULTS

1. Conditioned Space 24°C and RH=55%

Tamm's model with constant cooler temperature and time varying temperature (during the infiltration process) for this case is shown in Figures (1a) and (1b).

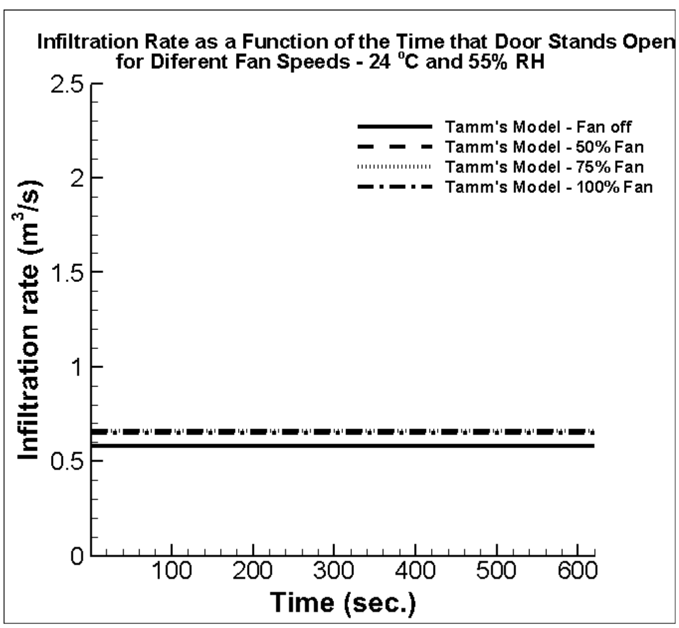

Figure 1a: Tamm's model prediction with constant cooler temperature

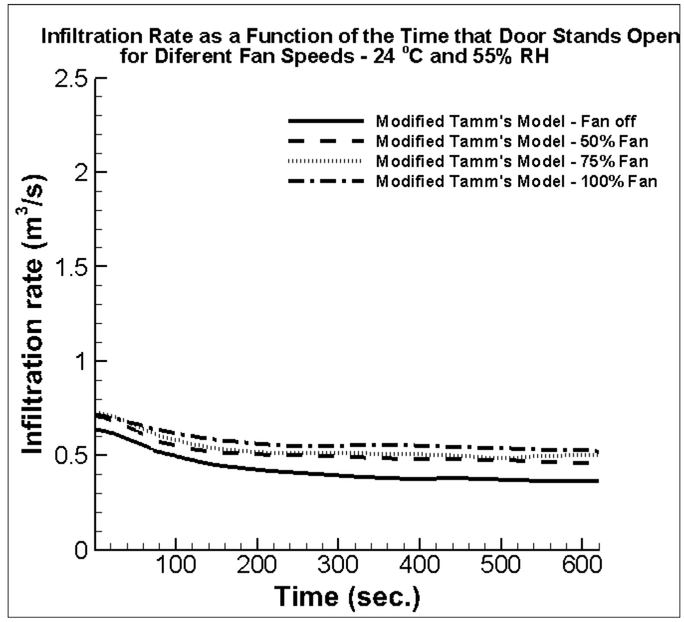

Figure 1b: Tamm's model prediction with time varying cooler temperature

It is understood that time varying temperature during the time that the door stays open is closer to reality and therefore we only present time varying cooler temperature. This model predicts lower infiltration if the fan stops during the duration of door being kept open.

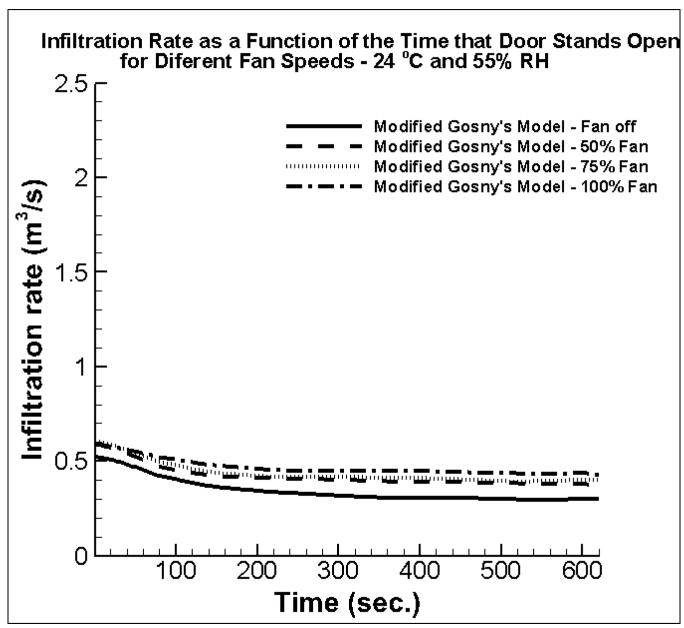

Figure 2: Gosney's model prediction with time varying cooler temperature

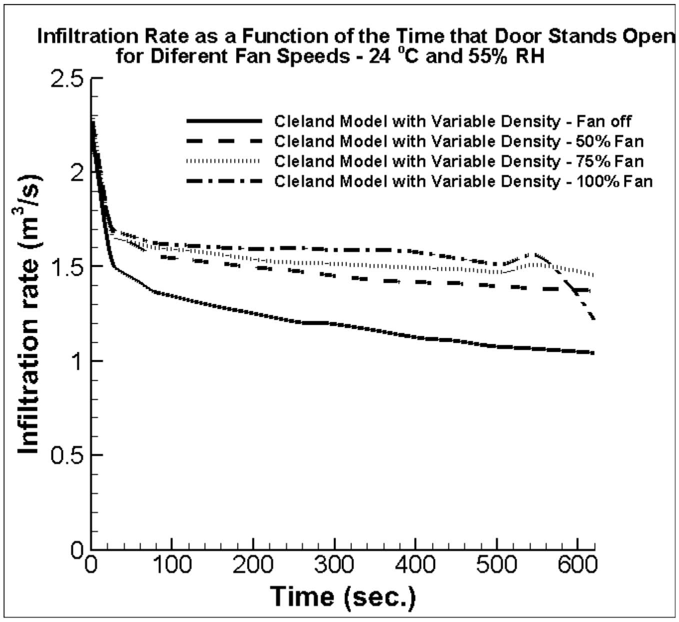

Figure 3: Cleland's model prediction with time varying cooler temperature

Similar results as predicted by Gosney's model are shown in Figure 2. It seems that the Gosney model predicts somewhat lower infiltration rates. The Cleland's model in Eq. (3a) over-predicts the infiltration by a factor of 4 compared to the other two models. This model is based on the analogy between the infiltration phenomenon and the orifice flow. However, it can be further corrected for abrupt expansion (into the outside room) (Eq. 3b) which lowers the over-prediction by 25%. The results of the Cleland's model are shown in Figure 3. It can be seen from Figures 1-3, that all these models predict about 10% lower infiltration if the fan stops while the door is open.

The result of the tracer gas method is shown in Figure 4. Based on the tracer gas model, only 5% of the infiltration difference can be attributed to fan speed. Furthermore, the transient nature of the infiltration is captured in this method. The infiltration as a function of time has to asymptotically go to zero and that is when there are no temperature or humidity gradients between the inside cooler and outside air. The area under the curve, $\int_{time} \frac{d\forall}{dt} dt = \forall$ represents the total volume (mass) of air displaced. This value cannot be more than the initial volume of air inside the cooler. The earlier models do not consider a finite volume for the cooler, and therefore, they cannot be accurate for the entire time period in which the infiltration process is taking place.

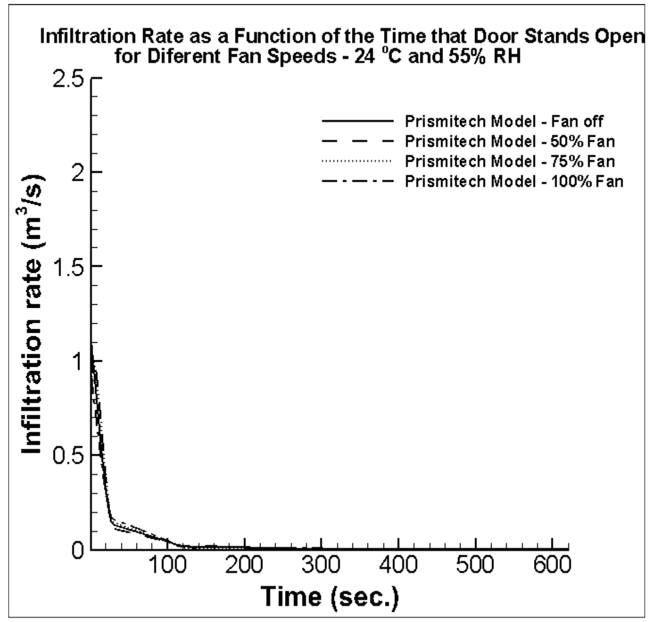

Figure 4: Tracer gas method predictions.

Furthermore, based on the tracer gas results shown in Figure 4, the area under the curve can be calculated to be about 59.5 m^3 which is very close to the earlier calculations of the empty (cold air) volume inside the cooler. This is actually a verification of the method that indicates the decaying nature of the infiltration for the cooler as the inside and outside air come into equilibrium.

2. Conditioned Space 29°C and RH=82%

Similar results are shown for higher outside temperature and RH of 29°C and 82%, respectively.

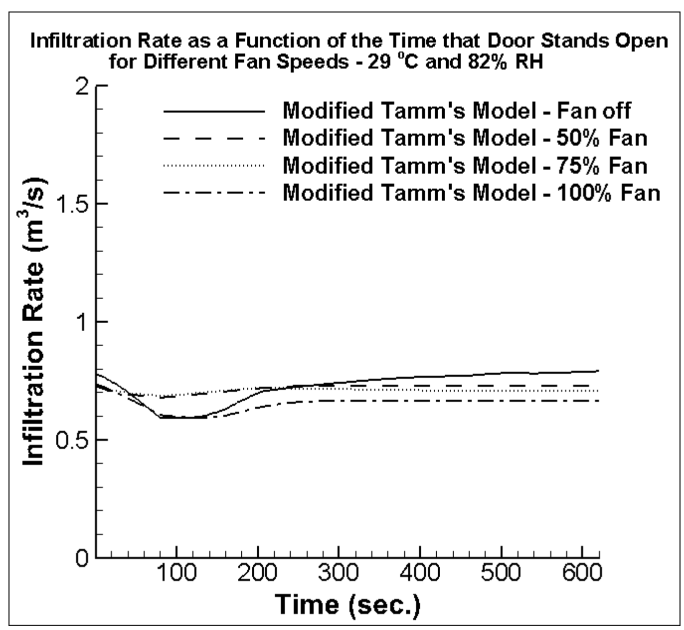

Figure 5: Tamm's model prediction with time varying cooler temperature

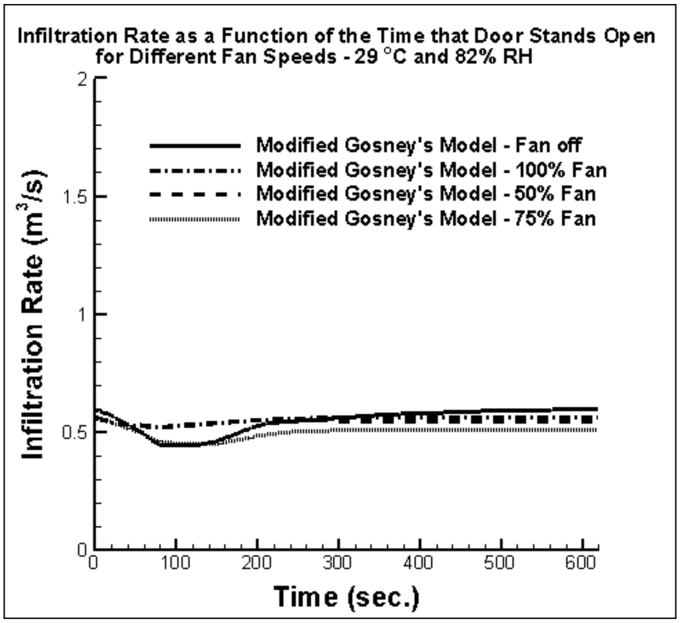

Figure 6: Gosney's model prediction with time varying cooler temperature

Figures 5-8 display the results for all models. It is seen that the infiltration rate has somewhat increased as the temperature gradient has increased.

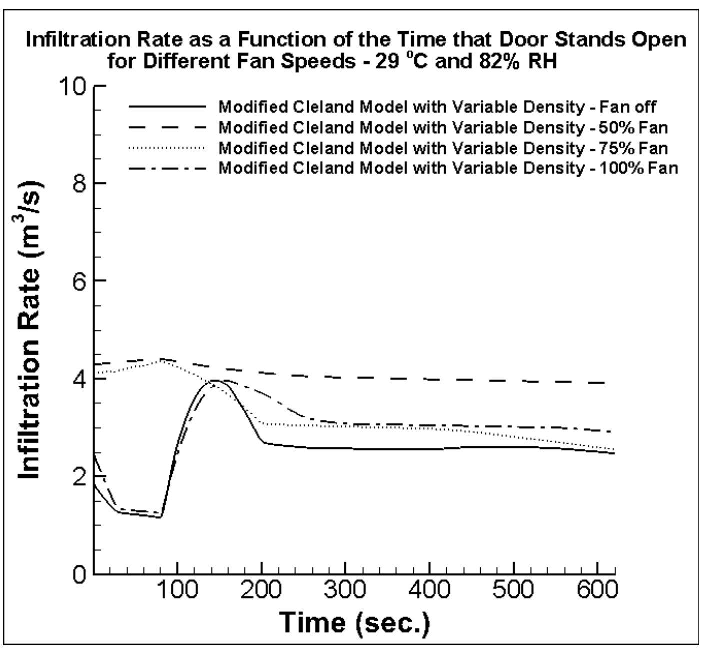

Figure 7: Cleland's model prediction with time varying cooler temperature

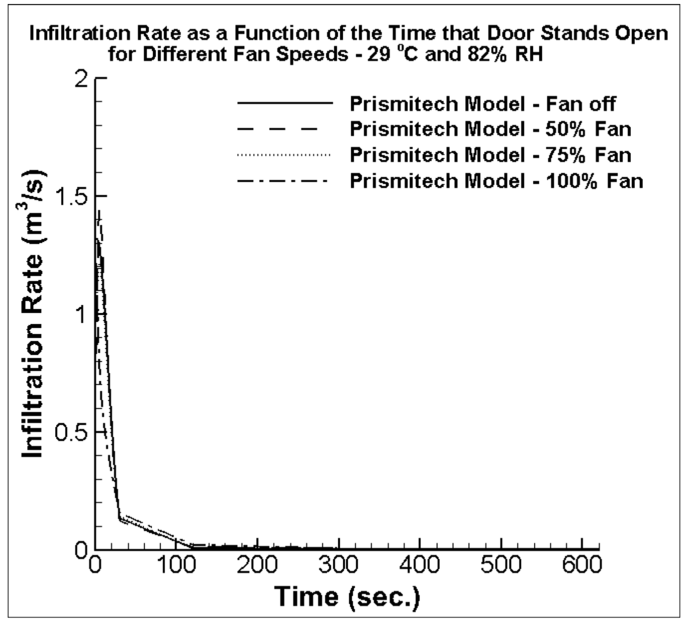

Figure 8: Tracer gas method predictions

3. Conditioned Space 46°C and RH=14%

Similar results are shown for higher outside temperature and lower relative humidity. Figures 9-12 show that the infiltration rate increases as the temperature gradient increases. Furthermore, the tracer gas method indicates that a significant portion of cold air moves outside the cold room during the first 30 seconds of the process.

All models predict a more significant reduction in infiltration when a lower temperature difference between the cooler and outside air exists. The tracer gas method also predicts about 20% less infiltration for the fan-off position during the first 15 seconds of the process for this case.

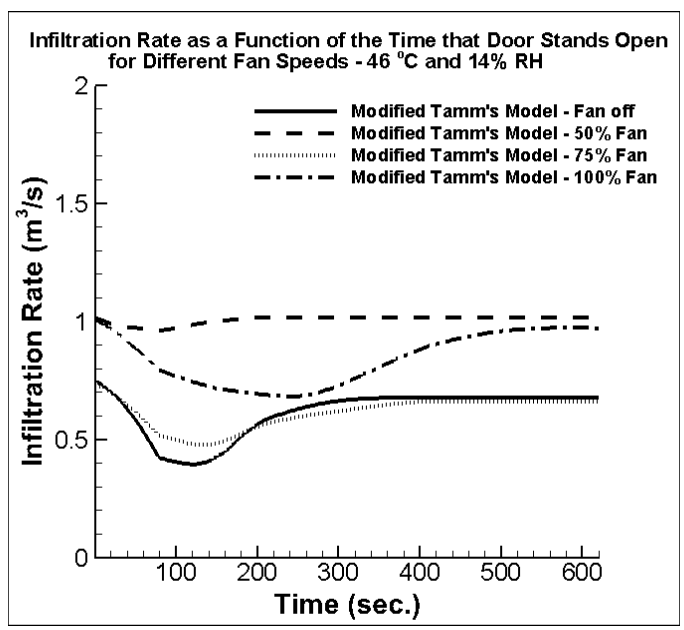

Figure 9: Tamm's model prediction with time varying cooler temperature

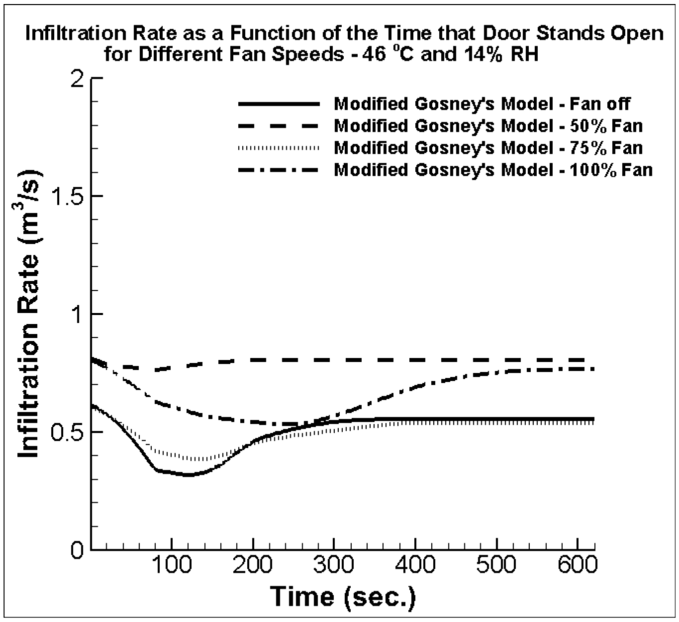

Figure 10: Gosney's model prediction with time varying cooler temperature

It should also be noted that for all the cases where the infiltration rate is measured by using the tracer gas technique, the area under the curve (total volume of the cold air) is calculated to be about 59.5 m^3. Furthermore, the tracer gas method indicates that 75% of the infiltration occurs during the first 30 seconds of the infiltration process for this case. The equivalent times for the same area (59.5 m^3) under the curve for all the earlier models correspond to 20-30 seconds of infiltration. Therefore, the Tamm and Gosney model predictions may be correct for the first 20-30 seconds of infiltration, in terms of the total amount of displaced air, but are invalid for longer times.

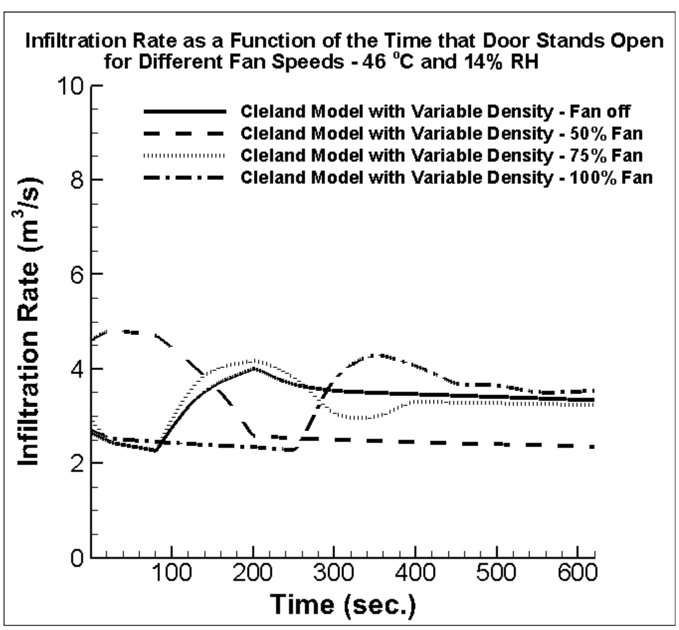

Figure 11: Cleland's model prediction with time varying cooler temperature

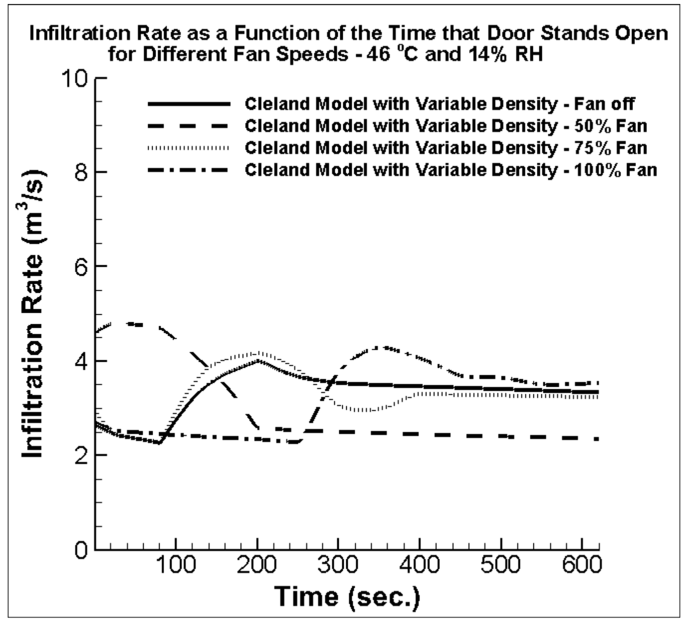

Figure 12: Tracer gas method predictions.

The modified Cleland's model (by K_L Factor) significantly over-predicts the initial infiltration and therefore is only valid for shorter period of times (about 15-20 seconds).

VELOCITY PROFILE AT THE DOORWAY

In this experiment the particle image velocimetry (PIV) flow visualization technique is used to map the velocity profile and magnitude during infiltration. The air is seeded with smoke (very small particles) and the trajectory of the particles in smoke will be captured through an interrogation window of 13cm x 13cm with a high speed camera. Two velocity components, horizontal (u) and vertical (v), are measured. The experiment is repeated to capture images along the height of the sliding door opening in the mid-plane. All the images are assembled and the results are shown in Figure 13. This image is consistent with the previous schematics shown in the ASHRAE [1] handbook. The maximum velocity occurs at the lower section of the doorway and the outside warm air infiltrates into the cooler from the upper portion of the door. The maximum velocity is about 65 cm/s in the horizontal direction. It is interesting to see that the maximum (downward) vertical component occurs at the upper level of the doorway by the warm air that is entrained into the cooler.

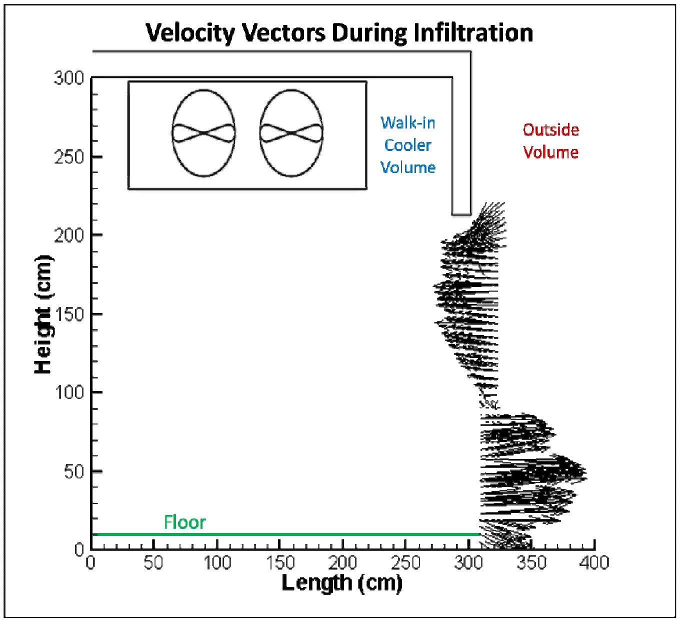

Figure 13: Velocity vectors (profile) during the infiltration mapped by PIV technique

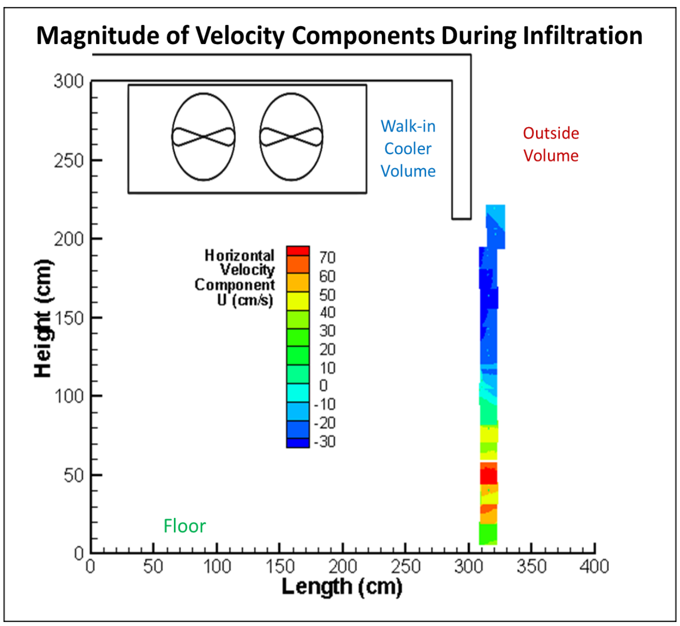

Figure 14: Horizontal velocity contours during the infiltration by PIV technique

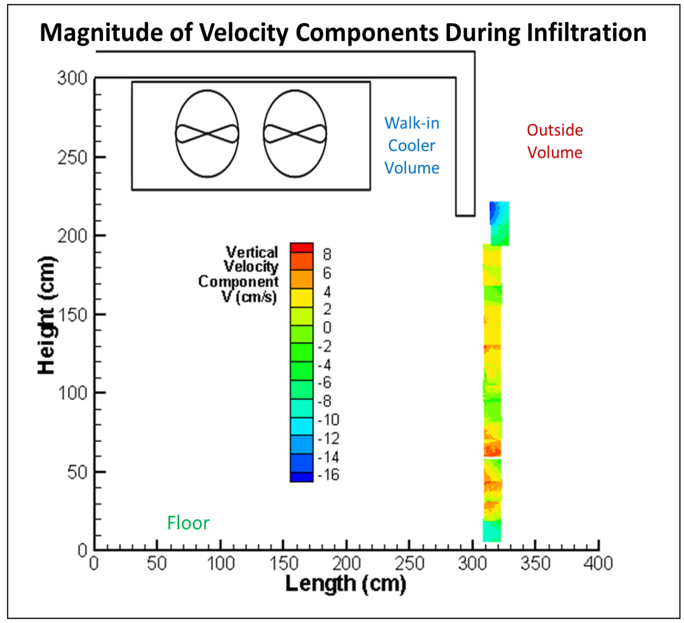

Figure 15: Vertical velocity contours during the infiltration by PIV technique

CONCLUSIONS

The tracer gas technique was successfully implemented to measure the infiltration rate of a typical walk-in cooler subject to different temperature and relative humidity combinations, resulting in different gradients across the cooler doorway. It was found that higher temperature gradient increases the infiltration rate. It was also concluded that the tracer gas method captures the transient nature of infiltration unlike any other previously used models. The velocity profile at the doorway that has never been captured was determined by flow visualization technique of particle image velocimetry (PIV).

ACKNOWLEDGEMENT

This work has been supported and initiated by the Technology Test Center (TTC) at Southern California Edison Company.

REFERENCES

[1] A Comprehensive Study of Infiltration Rate into Walk-in Coolers by Tracer Gas Technique and Particle Image Velocimetry, Southern California Edison Company Report, February 2011

[2] ASHRAE (2009), Refrigeration Load, 2006 ASHRAE Handbook, Chapter 13

[3] Tamm, W. (1965), Air Flow with air curtains to protect cold rooms. Proceedings 11th International Congress of Refrigeration, Vol. 2, pp. 1025-1038.

[4] Chen, P., Cleland, D., Lovatt, S., and M. Bassett (2002), Am empirical model for predicting air infiltration into

refrigerated stores through doors, International Journal of refrigeration, Vol. 25, pp. 799-812.

[5] Reindl, D., and T. Jekel (2009), Infiltration Rate Determination for Low Temperature Freezing Systems, ASHRAE Transaction SL-08-027

[6] Gosney, W., and H. Olama (1975), Heat and enthalpy gains through cold room doorways. Proceedings of the Institute of Refrigeration, Vol 72, pp. 31-41

[7] Cleland, D., Lovatt, S., Chen, P., and M. Bassett (2004), A Modified Model to Predict Air Infiltration into Refrigerated Facilities Through Doorways, ASHRAE Document 4672

[8] Amin, M., D. Dabiri, and Navaz, H.K., "Tracer Gas Technique: a New Approach for Steady State Infiltration Rate Measurement of Open Refrigerated Display Cases," *Journal of Food Engineering*, Vol 92., pp. 172-18.

Appendix A

Calculations of Mixture Density for Air

The mixture of gases is composed of CO_2, dry air (*da*), and water vapor (*v*). The mixture density is given as:

$$\rho_{mix} = \sum_i (\rho_i C_i)(kg/m^3)$$

where

ρ_i = Density of each constituent (CO_2, *da*, *v*)

C_i = Mass fraction of each constituent (CO_2, *da*, *v*)

(A-1)

The density of each constituent is obtained from the ideal gas law with the corresponding gas constants as:

$$\rho_{CO_2} = \frac{P(kPa)}{0.189T(^oK)}, \qquad \rho_v = \frac{P(kPa)}{0.462T(^oK)},$$

$$\rho_{da} = \frac{P(kPa)}{0.287T(^oK)}$$

(A-2)

The mole fraction of CO_2 in time can be obtained from Figures 5, 7, 8, and 9 (or similar figures). If *y* represents the mole fraction, $y_{CO_2}(t)$ as a function of time (t) is known.

The humidity ratio can be obtained from the temperature and RH. Let us designate the symbol ω to humidity ratio. So:

$$C_v = \frac{\omega}{1+\omega} \qquad \text{(A-3)}$$

$$C_{da} = 1 - C_v$$

The mole fraction of water vapor and dry air can be obtained as:

$$n_v = \frac{C_v}{18}$$

$$n_{da} = \frac{C_{da}}{28.97}$$

$$n_{total} = n_v + n_{da} \qquad \text{(A-4)}$$

$$y_v^{'} = \frac{n_v}{n_{total}}$$

$$y_{da}^{'} = \frac{n_{da}}{n_{total}}$$

However, these mole fractions are based on 1 mole of the dry air and vapor mixture. We have only $1 - y_{CO_2}(t)$ moles available, therefore the mole fraction of each constituent becomes:

$$y_{CO_2}(t)$$

$$y_v(t) = y_v^{'}\left[1 - y_{CO_2}(t)\right] \qquad \text{(A-5)}$$

$$y_{da}(t) = y_{da}^{'}\left[1 - y_{CO_2}(t)\right]$$

The mass fractions of each constituent can be obtained according to the following formulas:

$$m_{total} = y_{CO_2}(t) \times 44 + y_v(t) \times 18 + y_{da}(t) \times 28.97$$

$$C_{CO_2}(t) = \frac{y_{CO_2}(t) \times 44}{m_{total}}$$

$$C_v(t) = \frac{y_v(t) \times 18}{m_{total}} \qquad \text{(A-6)}$$

$$C_{da}(t) = \frac{y_{da}(t) \times 28.97}{m_{total}}$$

Note that:

M = Molecular weight in $kg/kmol - K$

$M_{CO_2} = 44 kg/kmol$

$M_v = 18 kg/kmol$

$M_{da} = 28.97 kg/kmol$

The specific heat of the mixture to be used in Gosney's equation can be calculated as:

$$c_{p_{mix}} = \sum_i c_{pi} y_i \qquad \text{(A-7)}$$

The enthalpy difference for Equation 2 is calculated as:

$$h_i - h_r = c_{p_{mix}}(T_i - T_r) \qquad \text{(A-8)}$$

Where i and r refer to the inside and outside conditions, respectively.

To find the infiltration rate, the variation of CO_2 concentration in time should be obtained. The variation of air concentration in time can be obtained from

$$C_a = 1 - C_{co_2} \Rightarrow \frac{dC_a}{dt} = -\frac{dC_{CO_2}}{dt} \Rightarrow \forall \frac{dC_a}{dt} = -\forall \frac{dC_{CO_2}}{dt} = Q$$

$$\text{or} \quad \rho_{mix} \forall \frac{dC_a}{dt} = -\forall \rho_{mix} \frac{dC_{CO_2}}{dt} = \rho_{mix} Q = \frac{dm}{dt} = \dot{m} \qquad \text{(A - 9)}$$

Where :

C = Mass fraction ("a" = humid air)

$\forall$ = Volume of the room $\left(m^3\right)$

ρ_{mix} = Gas mixture density $\left(\frac{kg}{m^3}\right) = \rho_{da} C_{da} + \rho_{CO_2} C_{CO_2} + \rho_v C_v$

("da" = Dry Air, "v" = Water vapor - humidity)

Q = Volumetric Flow rate $\left(m^3 / s\right)$ or infiltration rate

$\dot{m}$ = Mass Flow Rate $\left(kg / s\right)$