3-1-2018

A Novel Approach to Visualize and Quantify the Transient Air Infiltration/Exfiltration in Walk-in Coolers

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ABSTRACT

Infiltration of warm and moist air from the adjacent surroundings into the refrigerated walk-in accounts for over 50% of the cooling load of walk-ins. Infiltration is influenced by the size of cracks within the envelope, the integrity of door gaskets, and the duration and frequency of door openings. Infiltration occurs concurrently and dynamically with the exfiltration of cold air. Understanding the thermo-fluid characteristics of infiltration can help engineers and researchers to develop robust methodologies and correlations for calculating the heat gain through infiltration in walk-ins.

This study deploys a novel approach based on a combination of particle image velocimetery (PIV) and tracer gas methodology to visualize and quantify air infiltration under several operational scenarios. The tracer gas selected for this project was carbon dioxide (CO_2). The tracer gas experiment foundation was designed to measure infiltration as a function of mass of cold air spillage through the door openings. Measurements were initiated when the air temperatures inside the walk-in (cold) and the adjacent room (warm) reached equilibrium. The project precisely measured the concentration of CO_2 within the enclosed volume of the walk-in. It then analysed the rate of decay of CO_2 within the walk-in space when warm air was introduced through the door openings. The volumetric exchange between the cold air spilled from the walk-in and warm air infiltration demonstrates the transient nature of this process. The study further investigates the sensitivity of infiltration rates to important operation variables including evaporator fan speed, temperature differential across the door opening, and the percentage of the walk-ins volume occupied by products. The results indicated that tracer gas methodology provides a reliable foundation for quantifying the infiltration through the door opening and the envelop of a refrigerated walk-in. Temperature differential across the door opening had the largest impact on the rate of

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infiltration through the door openings. Furthermore, the PIV provided an insightful map of the velocity profile along the door plane.

NOMENCLAUTRE AND ABBREVIATIONS

A	Doorway area
ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
C_i	Mass fraction
CFD	Computational fluid dynamics
g	Gravitational acceleration
M	Molecular weight
$\dot{m}$	Mass flow rate
n	Number of moles
P	Pressure
PIV	Particle Image Velocimetry
Q	Volumetric (Infiltration) flow rate
RH	Relative Humidity
T	Temperature
t	Time
TG	Tracer gas
u	Horizontal component of velocity
v	Vertical component of velocity
W	Width
y	Mole fraction

Special characters

V	Air volume inside cooler
ρ	Density
ω	Humidity ratio

Subscripts

CO_2	Carbon Dioxide
da	Dry air
inside	Air or volume inside the walk-in (refrigerated)
mix	Mixture of CO2, dry air and vapor
outside	Air or volume outside the walk-in (ambient)
v	Vapor

Superscripts

.	per unit time

1. Introduction

Walk-ins are room sized, insulated, and refrigerated compartments for food product storage. Walk-ins have areas equal or below *280* m^2 (*3000* ft^2) and are classified either as coolers operating above $0\,^oC$ (medium-temperature) to store fresh fruit, vegetables, and dairy products, or freezers that operate below $0\,^oC$ (low-temperature) to meet health and safety standards of frozen food products. Walk-ins are typically found in restaurants as well as small and medium to large grocery stores or supermarkets.

According to California Energy Commission [1] refrigeration contributes to about *20%* of total energy usage in restaurants, and to about *38%* of total energy usage in supermarkets and grocery stores. This estimation agrees with Southern California Edison's Technology Test Center's (TTC) [2-3] energy audit data conducted for two major chain supermarket customers. According to this data refrigeration can contribute somewhere between *35%* and *55%* of total energy usage depending on the supermarket's size and layout. In addition, up to *20%* of the refrigeration energy usage is due to the walk-ins. It is evident that this energy usage also depends on the amount of warm air that will infiltrate into the walk-ins mainly because of frequent door openings and slowly through imperfections in the envelope and seals, such as cracks. However, the amount of infiltrated warm air into the walk-ins (or exfiltrated cold air from the walk-ins) has never been directly measured as a function of variables such as temperature difference between the inside and outside air, time, initial volume of cold air inside the cooler, relative humidity (RH) of the outside air (adjacent room), fan speed inside the cooler, and finally the extent of door opening. Furthermore, the location of this exchange and the direction and magnitude of warm and cold air velocity through the door area has never been visualized.

The tracer gas method has been used in HVAC applications for determining the duration that the air inside a confined space can be refreshed or to identifying stagnant air inside spaces in a building [4]. Carbon dioxide as a tracer gas has been used in blast freezing environment [5]. The use of carbon dioxide as a marker to measure the infiltration of warm air into open vertical refrigerated display cases has been shown to be a viable and accurate method [6-8] under the steady state conditions of operation. In these recent works the infiltration of warm air into the display case was estimated by using a CFD computer program, and experimental techniques of PIV, and tracer gas (TG) and they all produced consistent and agreeable results.

This work was inspired by the need for an experimental method to accurately measure the transient and time dependent infiltration rate of warm air into coolers. There is no consensus in industry for a reliable methodology to measure the infiltration rate of warm air into walk-ins during the door opening. It is evident that this infiltration rate can be minimized if time period for this process is shortened by not allowing the complete discharge of the cold air. This requires the correct measurement of this transient process. It is obvious that for larger walk-ins the time period for complete exfiltration of cold air become longer and the duration of door opening period can be controlled and shortened. Carbon dioxide was chosen to be the TG and the methodology of measurements will be explained in the next sections. It should also be mentioned that the terms exfiltration and infiltration are used interchangeably in this manuscript because the exfiltrated mass of cold air is replaced by infiltrated mass of warm air. The schematic shown in ASHRAE Handbook [9] shows the cold air is discharged from the lower section, and the warm air moves inside the cooler through the upper section of the doorway. We extended our research to realistically visualize the velocity vectors representing the cold and warm air movements at the doorway. The PIV technique was used for flow visualization at the doorway. This technique has been successfully used in the past for flow visualization and measuring the infiltrated warm air into open vertical display cases [10].

2. Experimental Set Ups

The cooler was next to an adjacent (large) room whose temperature and RH was controlled. The following values for these quantities in the adjacent space were set and tested†.

a. $24\,^{o}C$ ($75\,^{o}F$) and RH=55%
b. $27\,^{o}C$ ($80\,^{o}F$) and RH=60%
c. $29\,^{o}C$ ($84\,^{o}F$) and RH=84%
d. $46\,^{o}C$ ($115\,^{o}F$) and RH=14%

In above scenarios, the cooler temperature was stabilized at $2\,^{o}C$ prior to the door opening which

† These values were required by the customer at the time

immediately initiates the infiltration of warmer air in the adjacent room. Although, these tests were conducted with a sliding door, additional experiments were performed with a swinging door (on the opposite wall of sliding door in the same cooler), but the results are not included in this manuscript for brevity. The sliding door was set to automatically open and close to preserve the integrity of the velocity profiles (cold and warm air) at the door opening.

The cooler's empty volume was 23.8 m^3 (842 ft^3). The food products were placed in the room filling 25*%* of the cooler total volume. This amount was changed in a few experiments afterward to examine the dependency of the infiltration on the available cold air volume in the cooler. The cooler had two fans that could be controlled and run at different percentages of its full speed. For this research, only one of the fans at different speeds was run.

Numerous thermocouples for temperature measurements, TG injection points, and sampling probes were installed around the room to have sufficient data representing the TG concentration even ensuring a thorough mixing of the TG and air inside the cooler. Diaphragm pumps draw the mixture of tracer gas and air from the desired points and transferred it to the gas analyzer. The pumps were installed between the sampling probes and the gas analyzer and each gas analyzer channel required one separate pump. Each channel also had a flow meter with an adjustable pin valve in order to monitor and control the flow rate of the sampled flow.

A Horiba gas analyzer (VA-3000) that utilizes Non-Dispersive Infrared (NDIR) technology was used for measuring the concentration of the CO_2 tracer gas. This instrument includes three input channels as there are three sample inlets to the analyzer. The rate at which the samples were analyzed, and concentrations were reported was 1 data/sec. By using Horiba's DL-3000 software, the data was logged and stored in a computer. The Repeatability, Linearity and Zero/Span shift errors of the gas analyzer are, 0.5%, 1%, and 0.5% of the full-scale value, respectively; while the sensitivity of the instrument was less than 1%. The resolution of the instrument is 1 ppm. The overall uncertainty is about ±480 ppm equivalent to ±1.9% of the full-scale value.

For calibrating the gas analyzer, first, the system was "zeroed" by a gas with tracer gas concentration equal to zero. Next, a span gas with a known concentration of the tracer gas was flown into the gas analyzer. By performing these two steps the analyzer will recognize its linear calibration through these two concentrations. In these experiments nitrogen was the zero gas and the span gas contained 24,350 ppm CO_2 (equivalent to 2.435% concentration). The flow rate of the calibration gasses was 0.5 Liter/min.

The PIV method is an averaging cross-correlation technique, implying that sequential pairs are processed to produce a velocity field. For each sequential pair, a small interrogation window subsamples a portion of each of the images at the same locations and a cross-correlation is performed, resulting in the shift of particles within the interrogation windows. This interrogation is then, through calibration, converted into a velocity vector. The interrogation window is systematically moved through the sequential images to produce a vector field. Once the vector field is obtained for each pair through time, they are averaged to produce the mean velocity flows and streamlines. For the present experiment, a 768x480 pixel camera acquired images at 30 frames per second. A 120-

mJ ND:Yag laser with a combination of optical lenses and mirrors is used to create a laser sheet and illuminate the area of interest. The final velocity maps with 50% overlap are then assembled to map the centerline of the door height. The PIV setup was similar to that of Reference [10] and will not be repeated here.

Procedure of infiltration rate measurements

The infiltration rate is a function of the mixture density, void volume, and TG concentration gradient (or change) between two consecutive times as shown in detail in Appendix A. According to Eq. (A-1), the TG concentration gradient should be measured. To accomplish this, the carbon dioxide concentration was raised to a prescribed value while the cooler's door was closed (values referred to with subscript "*i*" in Eq. A-8). Enough time elapsed so that the TG was uniformly distributed inside the cooler. At this point, the cooler door was opened for a time interval (for instance 30 seconds) and infiltration occurred during this time. Then the cooler's door was closed and the air inside the cooler was mixed long enough before the sampling of the TG the next time interval (values referred to with subscript "*i+1*" in Eq. A-8). The carbon dioxide concentration difference between time interval of $(t_{i+1} - t_i)$ and the time interval for the door opening represent the concentration gradient for the tracer gas and by knowing the void volume and mixture density, the infiltration rate can be calculated. By varying the duration of time that the cooler's door was left open, this concentration gradient and therefore infiltration rate as a function of time can be obtained. This procedure was repeated for each case starting from the identical cooler's initial conditions (TG concentration and temperature). It was mentioned earlier that infiltration occurs through the cracks and seals of coolers (referred to as natural infiltration). The magnitude natural infiltration is important and should be measured independently and be accounted for in the concentration gradient calculations.

Procedure for flow visualization

In the particle image velocimetry (PIV) technique, an ND:Yag laser was used in combination with sheet generating optics to illuminate the cross-section of the flow of interest. The refrigerated air was then seeded and allowed to mix before the event of a door opening. The reflective particles consist of a mixture of glycerin and water with a size range of 0.2-0.3 micrometer (μm) to accurately follow the flow. Upon illumination, the particles within the very thin laser sheet reflect laser light. A camera situated at 90 degrees from the incident laser sheet captured the images focused on the laser sheet. These sequential images were recorded in a $13cm \times 13cm$ $(5in \times 5in)$ interrogation window, and post-processed, as explained in Ref. [10] to obtain the velocity and streamline fields.

3. Results

In the first set of experiments, the natural infiltration was measured for all (a)-(d) conditions in section 2 for the adjacent room. Four fan speeds (0%, 50%, 75%, and 100%) were considered in each of the cases resulting in 16 tests to measure the natural infiltration rate. Figure 1 shows four cases that represent a subset of total number of 16 tests. These four cases show the minimum, maximum, and two additional cases in between corresponding to the adjacent room conditions. Figure 1 indicates that the maximum natural infiltration occurs at $27\,^{o}C$, RH=84% with 100% fan speed. It will be seen later that the infiltration will be practically terminated after 100 seconds when the door is opened which in this case 1% of the infiltration can be attributed to cracks and seals. Obviously, the actual natural infiltration will be less than 1% for this case when the door is opened. Based on these results, natural infiltration did not seem to impact the accuracy of our data.

To measure the infiltration rate, after the TG concentration and temperature reached to the prescribed values at each time, the door was opened for 3, 30, 120, and 300 seconds, respectively in separate experiments and the concentration was measured after the door was shut after these time intervals. The infiltration rate was calculated by using Eq. (A-1).

The infiltration rate for case (a) in section 2 representing the adjacent room conditions at $24\,^{o}C$ ($75\,^{o}F$) and RH=55% and is shown in Figure 2. It can be seen the discharge of the cold air from the cooler happens fast and the cooler loses almost the entire cold air in about 2 minutes. The fan speed has some impact, but not very significant, so it can be neglected for this case.

The next case (b) results are shown in Figure 3. It appears that the discharge of the cold air happens faster as the temperature of warmer air in the adjacent room increases. It seems that the fan speed makes very small change in the infiltration rate.

The results for case (c) are similar to case (b), so it was decided to present Figure 4 that shows the infiltration rate for case (d) that has the maximum temperature in the adjacent room. Figure 4 indicates that larger the temperature difference between the air inside the cooler and outside air, the infiltration occurs the fastest. This implies that the main driver for the infiltration rate being the temperature differential between the inside and outside of the cooler. It also appears that the fan speed becomes of lesser importance when the temperature differential increases.

As it was mentioned earlier, the amount of food products inside the cooler will affect the infiltration rate because it changes the volume of air in Eq. (A-1). Figure 5 shows the infiltration rate for the empty walk-in and the cases that were previously considered with the 25% of the volume filled with food products.

The infiltration as a function of time asymptotically goes to zero and that is when there are no temperature and/or humidity gradients between the inside cooler and outside air. The area under the curve for each case should yield the air volume in the cooler. The integral $\int_{time} \frac{dV}{dt}dt = V$ represents the total volume (mass) of air displaced. This value for the case where 25% of the volume is occupied by food products can be calculated from any of Figures 2-4 and it will be about 17.8 m^3 (640 ft^3) that is very close to 75% of the total volume of the cooler mentioned in Section 2.

Velocity Profile at the Doorway

According to ASHRAE 2009 handbook [9] schematic of infiltration through the door of walk-ins, the cold air should be discharged from the lower part of the door and the warmer air in the adjacent room should move into the cooler from the upper part of the door. However, this flow pattern has never been experimentally visualized. Therefore, the decision was made to visually observe this interaction by PIV technique.

In this experiment images are captured through an interrogation window. This window is moved vertically in separate experiments for the same case to capture images along the height of the sliding door opening and in its mid-plane. All the images are assembled, and the results are shown in Figure 6. This image is consistent with the previous schematics shown in the ASHRAE (2009) 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 61 cm/s (2 ft/s) in the horizontal direction. The results indicate that the maximum vertical velocity component occurs at the upper level of the doorway by the warm air that is entrained into the cooler.

4. Conclusions

The tracer gas technique was successfully implemented to measure the infiltration rate through the envelope cracks and door openings of a typical walk-in. These measurements were made under different adjacent temperature and relative humidity conditions, and fan speeds. It was found that the method is thorough and is reliable for transient process of infiltration of warm air into walk-ins. The temperature difference between the cold air inside the cooler and the warm air in the adjacent room seems to be the main driver for the infiltration. It also appears that the effect of relative humidity on the infiltration is of second order, and the fan speed has the minimum impact on infiltration. The unprecedented deployment of the PIV methodology for velocity profile characterization of infiltration/exfiltration at the doorway provided improved quantification and visualization of the infiltration.

This tracer gas method offers a promising technique to industry for measuring the infiltration rate by controlling door closure before a complete discharge of cold air occurs. This information could enable engineers to improve their analysis capabilities in estimating the cooling load, design parameters and equipment sizing requirements for walk-ins.

ACKNOWLEDGMENTS

This project was initiated by Southern California Edison's Technology Test Centres and sponsored by the emerging technologies program.

REFERENCES

1. California Energy Commission, "*Commercial Energy Demand Forecast Developed for: California Energy Demand, 2000-2010"*. Publication No. CEC-200-00-002. 2000.
2. Southern California Edison, "*2002 Express Efficiency Program: Refrigeration Technical Report, Draft 1*", 2001.
3. Southern California Edison, "*Walk-in Coolers and Freezers: Study of Energy Efficiency Measures*," 2007.

4. ASHRAE Handbook of Fundamentals, *American Society of Heating, Refrigeration and Air-Conditioning Engineers,* 2005.

5. Reindl, D., and Jekel T., "*Infiltration Rate Determination for Low Temperature Freezing Systems"*, ASHRAE Transaction SL-08-027, 2009.

6. Navaz, H. K., R. Faramarzi, and Amin, M., "*CFD Design of Air Curtain for Open Refrigerated Display Cases"*, Chapter 5, in the Computational Methods in Food Processing, CRC Press, 2007.

7. Amin, M., Dabiri, D., and H. Navaz, "*AERODYNAMIC ISOLATION OF OPEN REFRIGERATED VERTICAL DISPLAY CASES USING AIR CURTAINS"*, Chapter in Handbook of Research on Advances and Applications in Refrigeration Systems and Technologies, (2 Volumes), July 2015.

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. 2009.

9. ASHRAE, Refrigeration Load, 2006 ASHRAE Handbook, Chapter 13, 2009.

10. Navaz, H.K., Faramarzi, R., Dabiri, D., Gharib, M., and Modarress, D., "*The Application of Advanced Methods in Analyzing the Performance of the Air Curtain in a Refrigerated Display Case*," Journal of Fluid Engineering, ASME Transactions, Vol. 124, pp. 756-764, 2002.

Appendix A

In our experiments, we have considered "*air*" (denoted by subscript *a*) to be composed of three constituents: dry air (*da*), water vapor or humidity (*v*), and the tracer gas, Carbon Dioxide (CO_2). If C is defined as the mass fraction of each constituent, we can find the mass fraction of air to be:

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

$$V\frac{dC_a}{dt} = -V\frac{dC_{CO_2}}{dt} = Q$$

$$\text{or} \quad \rho_{mix}V\frac{dC_a}{dt} = -V\rho_{mix}\frac{dC_{CO_2}}{dt} = \rho_{mix}Q = \frac{dm}{dt} = \dot{m}$$

Where :

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

V = Void 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 *exfiltration* rate

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

(A-1)

Our goal is to determine the time derivative of CO_2 mass fraction that requires the mixture density and the volume of the freezer that is ***not*** occupied by food products (total air volume). Note that $\frac{d_{CO_2}}{dt}$ is negative during the mass exchange process with the outside room therefore we refer to it as ***exfiltration***. It is evident that the mass of air that leaves the room is replaced by an equal amount of mass of warmer air *infiltrating* into the room. This is why we have used the *exfiltration* and *infiltration* interchangeably. The gas analyzer measures the mole fraction of the tracer gas. The mixture density can be calculated according to:

$$\rho_{mix} = \sum_i \left(\rho_i C_i\right)$$

where

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

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

(A-2)

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

$$\rho_{CO_2} = \frac{P(kPa)}{0.189\,T(^oK)}, \rho_v = \frac{P(kPa)}{0.462\,T(^oK)}, \rho_{da} = \frac{P(kPa)}{0.287\,T(^oK)}$$

(A-3)

The humidity ratio is known for a specific testing conditions (by knowing the dry bulb and wet bulb temperatures). Let us designate the symbol ω to humidity ratio. So:

$$\omega = \frac{m_v}{m_{da}}, \qquad m_v = \omega m_{da} \qquad \text{(A-4)}$$

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

$$n_v = \frac{m_v}{M_v}, \quad n_{da} = \frac{m_{da}}{M_{da}},$$

$$n_{total} = n_v + n_{da} = \frac{m_v}{M_v} + \frac{m_{da}}{M_{da}}$$

$$y_v^{'} = \frac{n_v}{n_{total}} = \frac{\frac{m_v}{M_v}}{\frac{m_v}{M_v} + \frac{m_{da}}{M_{da}}} = \frac{m_v}{m_v + \frac{M_v}{M_{da}}m_{da}},$$

$$y_{da}^{'} = \frac{n_{da}}{n_{total}} = \frac{m_{da}}{\frac{M_{da}}{M_v}m_v + m_{da}}$$

Replacing from Eq. (A-4)

$$y_v' = \frac{\omega m_{da}}{\omega m_{da} + \frac{M_v}{M_{da}} m_{da}} = \frac{\omega}{\omega + \frac{M_v}{M_{da}}},$$

$$y_{da}' = \frac{1}{\frac{M_{da}}{M_v}\omega + 1} \quad \text{(A-5)}$$

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 in the presence of CO_2, therefore the transient mole fraction of each constituent becomes:

$$y_{CO_2}(t) \quad \text{Measured by Gas Analyzer}$$

$$y_v(t) = y_v'\left[1 - y_{CO_2}(t)\right] \quad \text{(A-6)}$$

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

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

$$M_{mixture} = y_{CO_2}(t) \times M_{CO_2} + y_v(t) \times M_v + y_{da}(t) \times M_{da}$$

$$C_{CO_2}(t) = \frac{y_{CO_2}(t) \times M_{CO_2}}{M_{mixture}} \Rightarrow \frac{dC_{CO_2}(t)}{dt} = \frac{M_{CO_2}}{M_{mixture}} \frac{dy_{CO_2}(t)}{dt}$$

$$C_v(t) = \frac{y_v(t) \times M_v}{M_{mixture}} \Rightarrow \frac{dC_v(t)}{dt} = \frac{M_v}{M_{mixture}} \frac{dy_v(t)}{dt}$$

$$C_{da}(t) = \frac{y_{da}(t) \times M_{da}}{M_{mixture}} \Rightarrow \frac{dC_{da}(t)}{dt} = \frac{M_{da}}{M_{mixture}} \frac{dy_{da}(t)}{dt} \quad \text{(A-7)}$$

Note that:

M = Molecular weight in $kg / kmol$

The mixture density required in Eq. (A-1) can now be calculated from Eq. (A-2) where the mass fractions are taken from Eq. (A-7). The time gradient of carbon dioxide is also obtained from Eq. (A-7) to be used in Eq. (A-1) to find the infiltration rate. It is intended to eliminate the need for difficult measurements of velocity and concentration (of the tracer gas) at the doorways which most likely is far from a two-dimensional flow configuration. For this purpose, we measure the term $\frac{dy_{CO_2}}{dt}$ in Eq. (A-1) in a discrete manner. That is to say that we measure a finite difference form of this term,

$$\frac{C_{CO_2}(t_{i+1}) - C_{CO_2}(t_i)}{t_{i+1} - t_i} \quad \text{(A-8)}$$

Where *(i+1)* and (*i*) represent two consecutive time intervals.

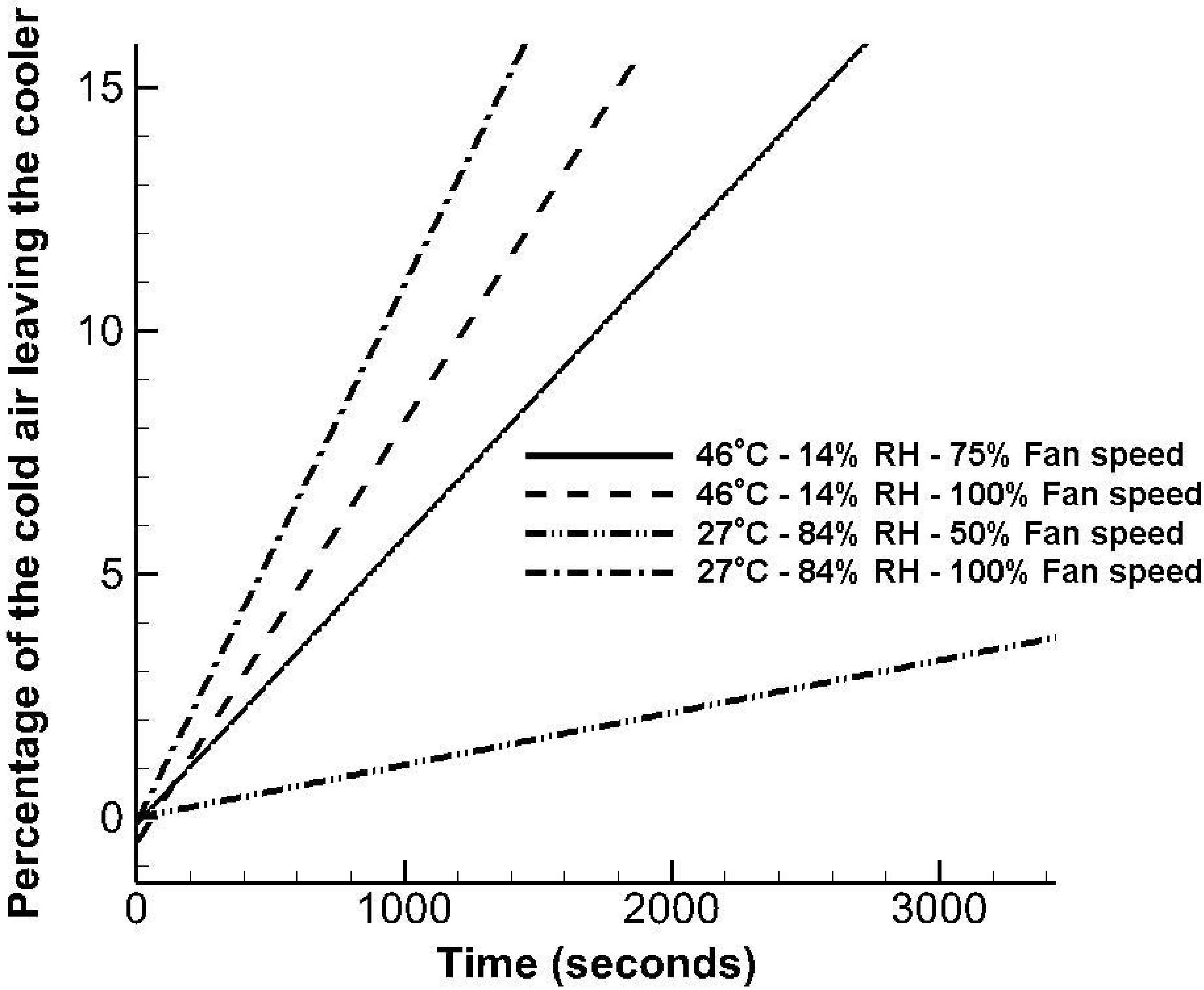
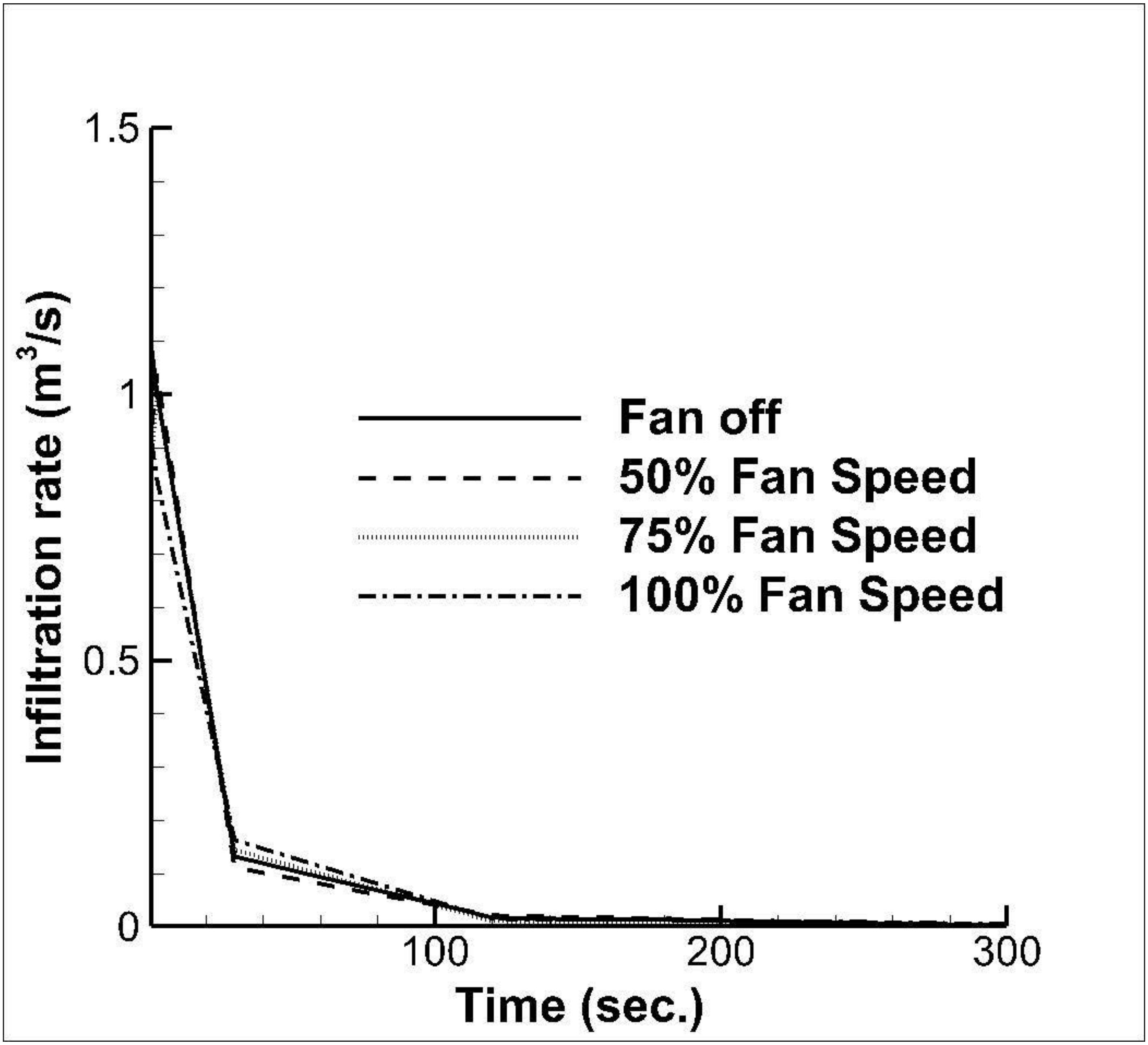

Percentage of the cold air leaving the cooler
15
10
5
0
0
1000
2000
3000
Time (seconds)
46°C - 14% RH - 75% Fan speed
46°C - 14% RH - 100% Fan speed
27°C - 84% RH - 50% Fan speed
27°C - 84% RH - 100% Fan speed

Figure 1



1.5
1
0.5
0
Infiltration rate (m³/s)
Fan off
50% Fan Speed
75% Fan Speed
100% Fan Speed
100
200
300
Time (sec.)

Figure 2

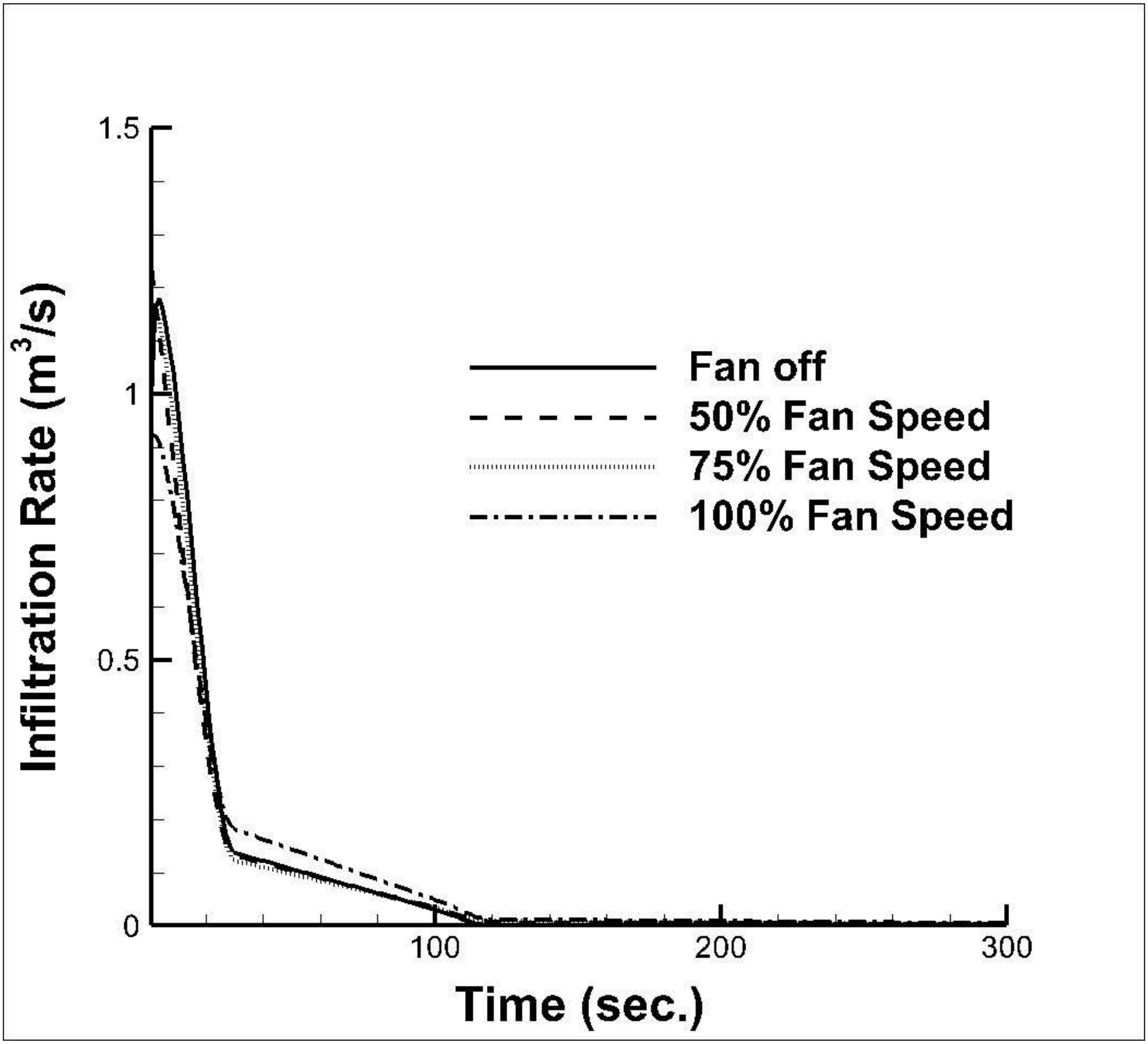
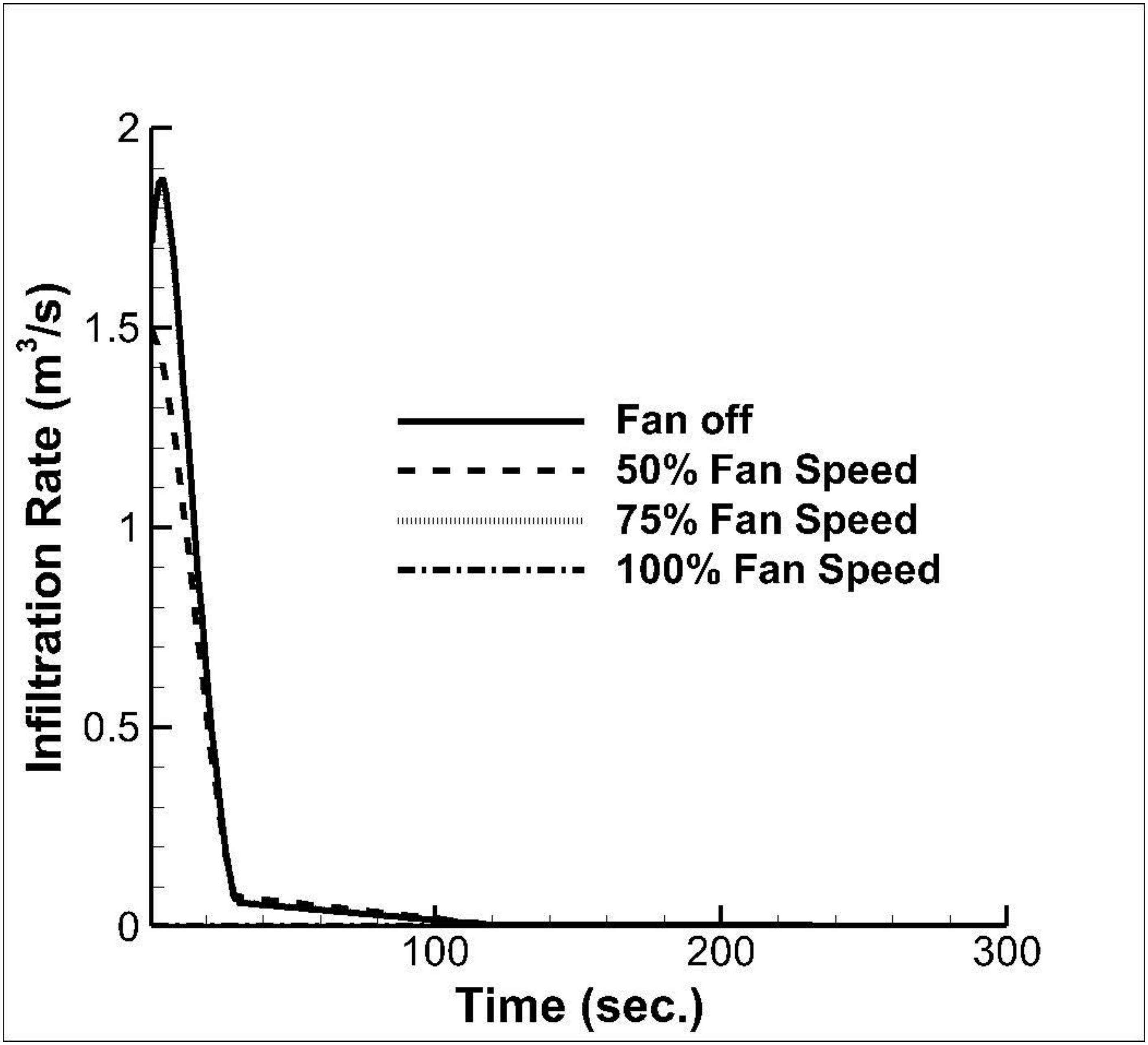
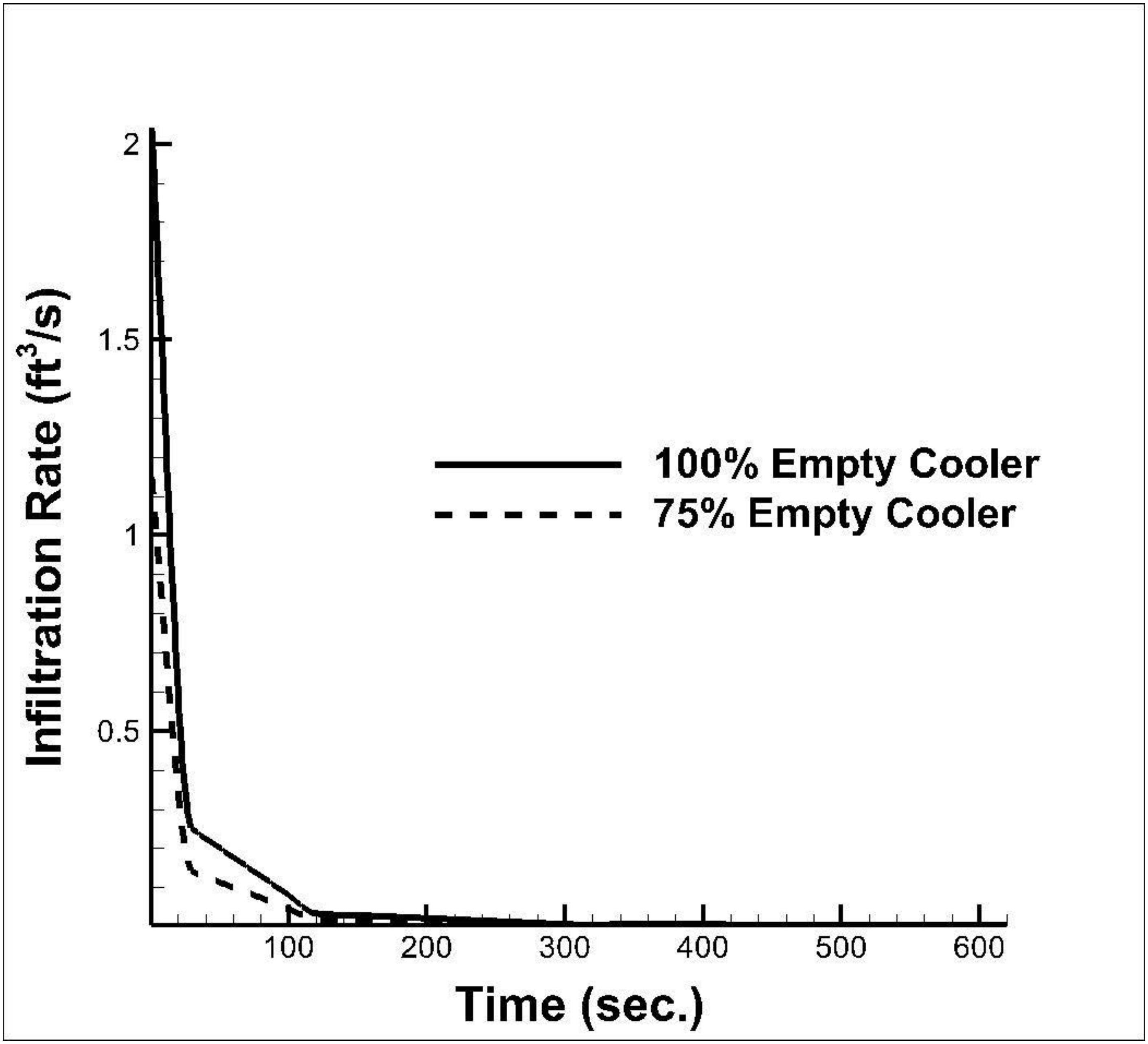

1.5
1
0.5
0
100
200
300
Infiltration Rate (m3/s)
Time (sec.)
Fan off
50% Fan Speed
75% Fan Speed
100% Fan Speed

Figure 3



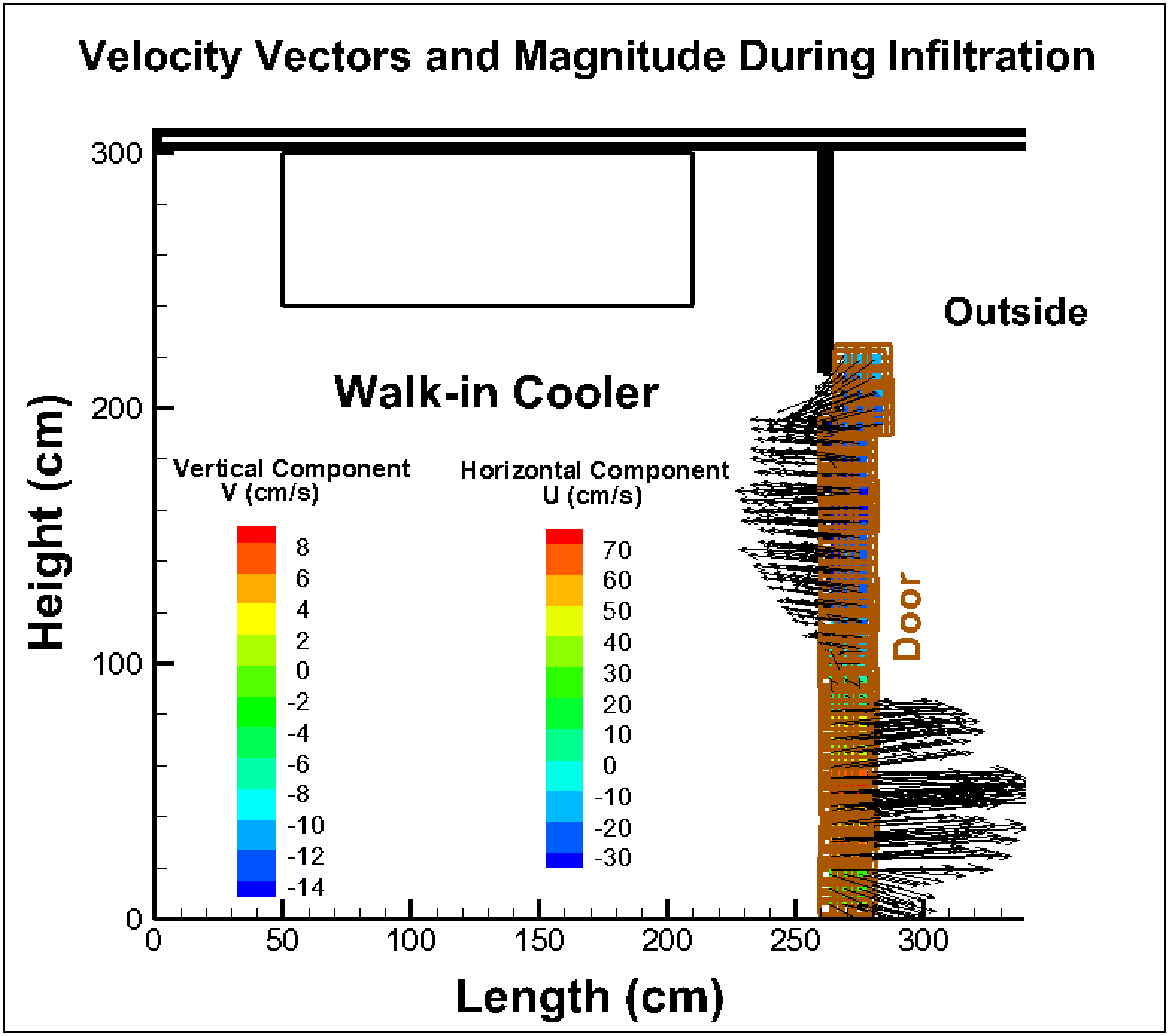
Infiltration Rate (m^3/s)
2
1.5
1
0.5
0
100
200
300
Time (sec.)
Fan off
50% Fan Speed
75% Fan Speed
100% Fan Speed

Figure 4



Infiltration Rate (ft^3/s)
2
1.5
1
0.5
100
200
300
400
500
600
Time (sec.)
100% Empty Cooler
75% Empty Cooler

Figure 5



Velocity Vectors and Magnitude During Infiltration
Walk-in Cooler
Outside
Door
Vertical Component
V (cm/s)
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
Horizontal Component
U (cm/s)
70
60
50
40
30
20
10
0
-10
-20
-30
Height (cm)
Length (cm)
0
100
200
300
50
150
250

Figure 6

Figure Captions

Figure 1 Natural infiltration of warm air into the walk-in cooler. The maximum loss of the cold air occurs at $27\,^oC$, RH=84% with 100% fan speed. The minimum value is at the same conditions except the fan speed of 50%

Figure 2 Infiltration rate at different fan speeds for case (a) in section 2 with the adjacent room conditions at $24\,^oC$ ($75\,^oF$) and RH=55%

Figure 3 Infiltration rate at different fan speeds for case (b) in section 2 with the adjacent room conditions at $27\,^oC$ ($80\,^oF$) and RH=60%.

Figure 4. Infiltration rate at different fan speeds for case (d) in section 2 with the adjacent room conditions at $46\,^oC$ ($115\,^oF$) and RH=14%

Figure 5 Infiltration rate for 100% and 75% empty cooler. For the second case, 25% of the cooler is filled with food products. This results are for case (a) in section 2 with the adjacent room conditions at $24\,^oC$ ($75\,^oF$) and RH=55%.

Figure 6 Velocity vectors (profile) showing the infiltration/ exfiltration process mapped by PIV technique. The magnitude of horizontal and vertical velocities are also shown.