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Effect of door opening frequency and duration of an enclosed refrigerated display case on product temperatures and energy consumption

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ABSTRACT

Retail display of highly perishable foods behind glass doors ensures uniform product temperatures below the FDA Food Code threshold of 5 °C, resulting in better-preserved foods while reducing energy costs. However, only a handful of studies have evaluated the effect of repeated door openings on product temperatures and energy consumption with contrasting reports. In this paper, we evaluated the effects of two frequencies (doors opened every 5 or 15 min) and four durations (doors held ajar for 5, 15, 30 or 60 s) on product simulator temperatures in a display case installed in our research supermarket. At ambient conditions (19.6–20.9 °C, 63% RH), with a case thermostat setting of 0.6 °C and a daily 30-min defrost cycle, the only statistically significant fluctuation in product simulator temperatures was found for the most aggressive opening schedule where the door was opened every 5 min for 60 s at each opening. Pairwise comparisons demonstrated that this treatment resulted in product simulator temperatures (up to 6.6 °C during defrost cycle) that were significantly higher ($p < 0.001$) or somewhat significantly higher ($p < 0.03$) compared to product exposed to all other combinations. Product exposed to all other treatment combination resulted in temperatures that either never exceeded 5 °C or briefly exceeded it only during the single 30-min defrost cycle. As a result, we selected an average opening sequence (every 10 min for 12 s) to perform an energy consumption assessment of the case. Energy consumption was determined to be 66% lower than that compared to an open-retail display case (same model, mark, size, operating schedule and thermostat setting). Even with the most extreme schedule where three of the six doors remained open continuously, there was still a measured 45% reduction in energy consumption as compared to that of the open-retail display case.

1. Introduction

Supermarket chains have increasingly embraced the use of refrigerated cases with doors in recent years for the display of food products. The introduction of doors provides several advantages over the standard open display case design, including improved energy savings, more uniform temperatures, and better product quality with a corresponding longer shelf-life. The improved energy savings that can be realized with the display case with doors was reviewed by Chaomuang, Flick, and Laguerre (2017) who compared studies from different countries at the laboratory and retail level, reporting potential energy savings from 23% to 73%. Furthermore, the return-on-investment to retrofit open cases with doors has been estimated at the retail level to be 2.8–5 years (NREL, 2013; Robertson, 2015; Slott, 2015, p. 31). Previous work in our research supermarket assessed the effect of temperature on the quality of fresh-cut leafy greens in both open and closed display cases, finding that the lower and improved temperature uniformity resulting from the case with doors correlated with better product quality and safety (de Frias et al., 2018; de Frias, Luo, Kou, Zhou, & Wang, 2015).

Despite the advantages of displaying food products behind glass doors, the use of open display cases remains ubiquitous at the retail level. Reasons include the associated customer convenience of picking the product right off the shelf without the need to open doors, the

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enrichment of the visual and tactile customer experience, and above all, the potentially detrimental impact of display case doors on product sales. On the latter point, increasing evidence from several large retailers that installed new closed cases or retrofitted open cases with doors, shows no impact on sales (Fricke & Becker, 2010; Garry, 2010; Robertson, 2015; Slott, 2015, p. 31) or the experience has been positive for customers as they understand the benefits of a better quality product (NREL, 2013; Lindberg, Salomonson, Sundstrom, & Wendin, 2018; Slott, 2014, 2015, p. 31).

On a product quality and safety basis, the rationale to install closed cases or retrofit open cases with doors is more critical if the retail products such as vegetables, fish, meat or milk are highly perishable. In 2009, the U.S. Food and Drug Administration (FDA) Food Code included a recommended holding temperature threshold at 5 °C for packaged ready-to-eat leafy greens to help prevent pathogen proliferation (FDA, 2017, pp. 1–698). Previous work on open display cases found that products near the front of the case are at risk of temperatures above 5 °C due to the infiltration of ambient air into the case. (Evans, Scarcelli, & Swain, 2007; Faramarzi, 2002; Kou, Luo, Ingram, Yan, & Jurick, 2015). Moreover, in studies with leafy greens displayed in open cases, it was reported that the percentage of product temperatures above 5 °C was 24% (de Frias et al., 2015) and 30% (Zeng et al., 2014) after three days. On the other hand, for cases with doors using a set-point temperature of 0.6 °C, de Frias et al. (2015) also found that 99–100% of product temperatures were below the FDA limit of 5 °C after a 3-day storage period in the enclosed display case. These studies found no differences in product temperatures or energy consumption with doors closed all the time versus partial door openings every 10 min for 12 s (de Frias et al., 2015, 2018).

In contrast, a review by Chaomuang et al. (2017) referenced a study by Vallée (2015), reporting that energy consumption in a display case with doors under an opening sequence based on the ISO 23,953 standard (ISO, 2015), was 15% higher. Also, Li, Zhu, Wang, and Zeng (2007) suggested that opening frequency and duration in a case with doors may cause increased energy consumption. In the study by Vallée (2015), the author used the ISO 23,953 standard, Refrigerated display cabinets — Part 2: Classification, requirements, *and test conditions,* which states that each door be opened every 6 min with a duration of 15 s. In our research, the opening sequence was based on ISO 23953 and ASHRAE Standard 72–2014, *Method of testing open and closed commercial refrigerators and freezers,* by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (ANSI/ASHRAE, 2014). This standard state that each door be sequentially and fully opened every 10 min for 6 s during 8 h. The results of a retail-level study by Fricke, Becker, and Ashrae (2011) are more in line with ASHRAE than with ISO; revealing an opening sequence more likely to occur in a real-life scenario. The authors found that 90% of door-opening durations in display cabinets were less than 60 s, with an opening duration mean of 12 s and a frequency of 6.3 openings per hour (ca. every 10 min). The duration with the most frequent openings was 5 s.

Recent work by Chaomuang, Flick, Denis, and Laguerre (2019), evaluated aggressive opening treatments starting at 10 openings per hour (every 6 min) through 60 openings per hour (every min), for 15 s, and found that air infiltration caused by the door openings resulted in product temperature increases by the front of the case and temperature decreases at the back. Even with the extreme opening frequencies, the authors concluded that the display case with doors provided lower and more uniform product temperatures than the open display case, in agreement with previous work from our group (de Frias et al., 2015).

The purpose of the present study was to provide experimental evidence to better understand the effect of door openings on product temperatures and energy consumption in a closed case. For temperature differences, we evaluated opening frequencies and durations that would comprise the typical scenarios outlined by the American ASHRAE standard and the European ISO standard, as well as more extreme and likely infrequent door openings and durations. Energy consumption in the case with doors was tested under contrasting situations, with doors opened or closed all the time versus a tested opening sequence.

2. Materials and methods

2.1. Setup of the refrigerated display case with doors

A dedicated room [3.8 m (L) x 3.6 m (W) x 2.4 m (H)] was prepared at the USDA-ARS, Beltsville Agricultural Research Center to house one vertical retail display case, 3.66 m long, weighing 635 kg. The case was hard-wired to a dedicated 120V/60Hz 20A GFCI (ground fault circuit interrupter) and plumbed with 1 ¼” (3.2 cm) Schedule 40 PVC for drainage. A 208V single-phase condensing unit was installed outside the room and raised above ground level on a concrete slab. The case was retrofitted with six, French-style, double-pane glass doors, with a concave wiper design to reduce door-to-door interference, and designed to be opened, stay open, and be closed with little effort. Each glass door [0.6 m (W) x 1.9 m (H)] is “low-e” (low emissivity) coated to minimize infrared light infiltration without affecting transmission of visible light. The void between glass panes was filled with Argon to help keep the glass moisture-free. A digital thermostat set at 0.6 °C regulated the duty operations of the case. The case was outfitted with air curtain and LED fixtures (120VAC, 50/60Hz) in the canopy (0.82A, 98W) and shelves (1.74A, 209W). The case has three-1.22 m sections, each section consisting of six columns of Trion Wonderbar™ spring-loaded push-shelves (Trion Industries, Inc. Wilkes-Barre, PA, USA) for a total of 18 columns. Each column has four push shelves and bottom rack space (fifth shelf) that can accommodate six bags of product per shelf. From a separate compressor, refrigerated air was circulated via three fans that conducted the air upwards through the evaporator coils (one set per 1.29 m section), discharged from the rear and the top grille at 0.1 m/s. The perforated area in the back panel, for the air discharged from the rear, is different per shelf (Table 1). Defrosting was programmed for 30 min with an interval of 24 h.

Table 1
Percentage of perforations in the back panel of the refrigerated display case. The total area of the back panel is 3.3 m^2, and the area of each perforation is 6.0×10^{-5} m^2

Spatial location		Number of perforations	Perforated area (m^2)	Percentage of perforated area (%)
Top	Shelf 1	150	0.009	0.27
↓	Shelf 2	300	0.018	0.54
	Shelf 3	300	0.018	0.54
	Shelf 4	300	0.018	0.54
Bottom	Bottom rack	0	0	0
	Total	1050	0.063	1.90

Fig. 1. Pictures of the display case with doors loaded with product simulators (left), and the automatic door opener (right). A cord is attached to the sliding arm of the door opener and three of the six display case doors.

Fig. 2. Schematic of the refrigerated retail display case with glass doors. Numbers 1 through 5 (Bottom rack) indicate the shelves, top to bottom. F → B (front-to-back) refers to depths (front-D1, middle-D3, and back-D5). Product simulators with dataloggers attached were loaded in the adjacent columns highlighted in the figure. The rest of the case was also filled with product simulators.

2.2. Automatic door opener set

An automatic door opener set was temporarily acquired and set up to program the display case door opening frequencies and durations (NurturEnergy, Maryland Heights, MO, USA). The set was powered by an independent circuit separate from the case power demand. The set included a base with a sliding arm connected to a controller programmed for each experiment to the desired door opening frequency (Fig. 1). A cord was attached to the sliding arm on one end and three of the six doors on the other end. Opened doors corresponded to each of three sections of the display case (Section 2.1). Door opening duration was defined as the length of time the door was left opened, and used four levels (5 s, 15 s, 30 s, or 60 s). Door opening frequency was defined as how often doors were opened and used two levels (every 5 min or every 15 min). Each opening duration and frequency combination were tested during one day from 9 a.m. to midnight (15 h).

2.3. Product load and temperature monitoring in the display case

The display case was loaded with product simulators representative of packaged leafy greens volume and weight. Product simulators consisted of 3.78 L Ziploc bags filled with 65 g of shredded sponge saturated with 266 ml of chlorine solution (7.5 ml bleach/1L water) (Kou et al., 2014). Forty-five (45) temperature dataloggers (model LogTag Trix-8, MicroDaQ.com, Ltd., Contoocook, NH, USA) were taped onto the exterior of selected product simulators. The dimensions of the dataloggers are 86 mm long x 54.5 mm wide x 8.6 mm thick and they were "sandwiched" between adjacent product simulators. The datalogger resolution is 0.1 °C and accuracy is ±0.5 °C in the temperature range used in this study. It was determined in previous research that no temperature differences exist at equilibrium between data loggers placed inside bags versus on the outside of bags (de Frias et al., 2015). The 45 product simulators selected for monitoring were in three adjacent columns on shelves 1 to 5, with three bags per shelf (front, middle, and back). Bags were loaded at the same time on day 0 and temperature monitoring frequency was set for a 2-min interval for 15 h needed to test all treatment combinations (Fig. 2). At the end of the experiments, 22,995 temperature data points from the loggers were downloaded per bag and per treatment combination (door opening frequency and door opening duration), corresponding to the respective 15 h treatment periods.

2.4. Testing conditions

One data logger measured ambient temperature (model LogTag Trix-8, MicroDaQ.com, Ltd., Contoocook, NH, USA) and another data logger measured relative humidity (model LogTag Haxo-8, MicroDaQ.com, Ltd., Contoocook, NH, USA). Ambient temperatures in the room throughout the 15-h experimental period ranged from 19.6 °C to 20.9 °C (Table 2), with an average relative humidity of 63%. The digital thermostat setting for the display case with doors was 0.6 °C and a daily 30 min defrost cycle (planned off-cycle) was set throughout the experiments. Frost build-up in the evaporator coils melted as the evaporator fans continued circulating air across the evaporator when the condensing unit stopped during the defrost cycle. Spatial and temporal temperature profiles of the product simulators were plotted using MATLAB 9.4 (The Mathworks, Inc., Natick, MA).

2.5. Electrical energy consumption of the display case with doors

Electrical energy consumption data of the display case with doors was measured in kWh as the sum of the individual consumption of the condensing units, LED lights, and evaporator fans in the case. Metering equipment was set up consisting of transducers with pulse output, current transformers (20 A), and 3-phase energy meter/transmitters, and installed exactly as previously reported in (de Frias et al., 2015). Data from the metering equipment was transmitted to a dual-radio access point connected to a wireless hot spot, which allowed for remote access of data via a client software. (Venergy, Magnum Energy Solutions, Hudson, OH). The door-opening treatments evaluated to determine energy consumption were as follows: 1) three doors out of six opened all the time, 2) all doors closed all the time, and 3) three doors opened every 10 min for 12 s. For these sequential door-opening treatments, we followed the ASHRAE standard 72–2014, "Method of testing open and closed commercial refrigerators and freezers", which states that each door be sequentially and fully opened six times per hour for 6 s for a period of 8 h (ANSI/ASHRAE, 2014). Experiments were conducted during three consecutive days, testing one treatment per day. Each experiment lasted 2 h, starting 3 h after the start of the defrost cycle. During each experiment, electrical energy consumption data were recorded from an open display case filled with product simulators and installed in the same dedicated room as the display case with doors. This open display case is of the same mark and model as the display case with doors, and was set up under the same conditions (section 2.1), except for two 12-h defrost cycles per day for 30 min.

2.6. Statistical analysis

The experiments were performed under a completely randomized design with temperature (°C) as the dependent variable. The two independent variables were door opening frequency (every 5 min or every 15 min) and door opening duration (5 s, 15 s, 30 s, 60 s), replicated three times (adjacent columns in the case correspond to three replicates). Treatment means were compared using the Least Significant Difference Method (LSD) and the Mixed Procedure in SAS (ver. 9.3, SAS Institute, Cary, NC) to test the null hypothesis at $\alpha = 0.05$. The null hypothesis for the effect of door opening duration and frequency on temperature variations in the display case was tested at $\alpha = 0.05$. Assumptions of normal distribution and homogeneity of variance were tested with an analysis of studentized residuals. Departures from the assumptions were addressed with bootstrap re-sampling (PROC MULTTEST) non-parametric analyses. Pairwise comparisons between treatments were based on the differences of least-square means and tested for significance using Tukey adjusted p-values to maintain experiment-wise error ≤ 0.05.

3. Results and discussion

3.1. Spatial and temporal temperature map of the display case with doors under contrasting opening sequences

The contrasting extremes tested for opening sequences mapped as spatial and temporal product simulator temperatures for the display case with doors were A) doors opened every 15 min for 5 s and B) doors opened every 5 min for 60 s (Fig. 3). The y-axis is "shelf", spatially represented in the graphs as in the display case, from shelf 1 (top) to the bottom rack. The z-axis is "depth", also displayed in the figures from front (depth 1) to back (depth 6). Time is depicted on the x-axis from right (1 h) to left (15 h). Temperatures are color-coded in the 3-D spectrum from deep blue (0 °C) to bright yellow (6 °C).

For a period of 15 h, temperature differences for the product simulators by shelf and depth for both treatments were statistically

Table 2
Mean ambient temperatures in the room that housed the display case with doors, recorded during each of the treatment trials.

Mean ambient room temperatures by opening treatment of the display case (°C)				
Frequency	Door opening duration (s) 5	15	30	60
Every 5 min	20.8 ± 0.4	20.9 ± 0.7	20.1 ± 0.9	20.9 ± 0.6
Every 15 min	20 ± 0.6	19.8 ± 0.4	20.2 ± 0.4	19.6 ± 0.4

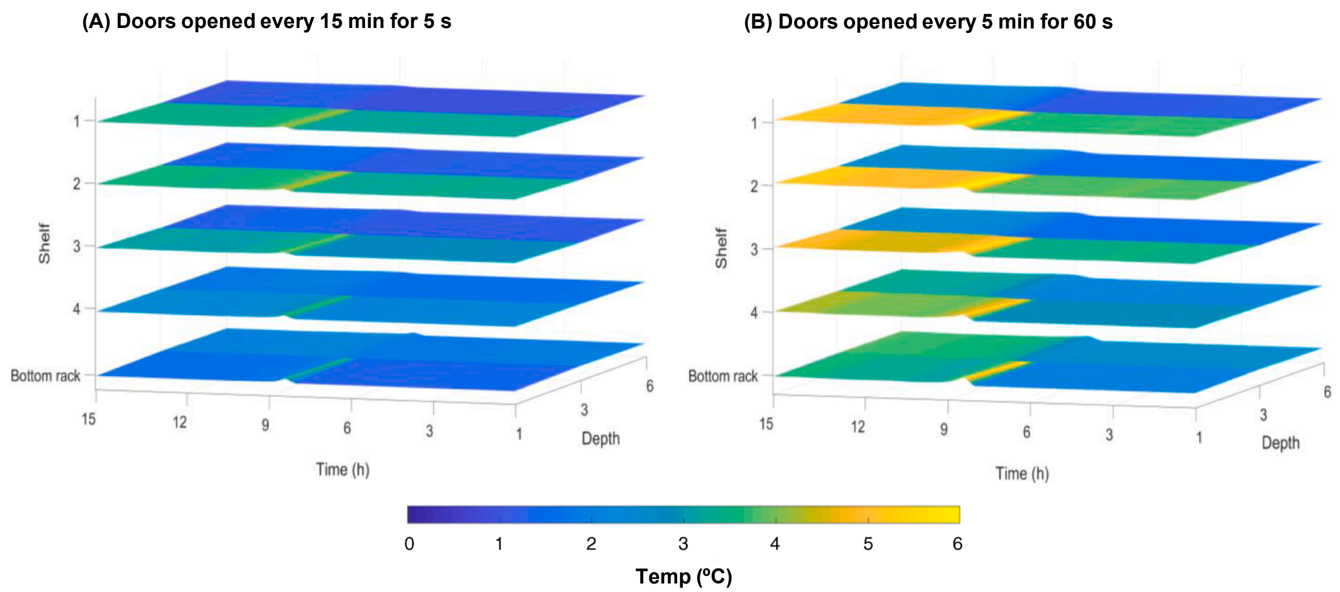

Fig. 3. Temperature profiles of the product simulators in the display case with doors for two contrasting treatments for period of 15 h: (A) Door opened every 15 min for 5 s and (B) Door opened every 5 min for 60 s. Shelves 1 to 4 start from the top of the case to the bottom rack ("shelf 5"). Depths 1 to 6 denote placement from the front to the rear of the case. (Depth 1-front, depth 3-middle, and depth 6-rear). Temperature peaks are consistent with one 30-min scheduled defrost cycle per day set for the display case. Room temperature conditions were constant at 19.6 to 20.9 °C with relative humidity at 63%.

Table 3
Mean product simulator temperatures recorded over a 15-h period in the display case with doors, by opening treatment. Depth 1, 3, and 6 represent the spatial locations of products in the front (1), middle (3), and back (6). Shelves are organized top-down, I (top), V (bottom rack). Col 1, 2, and 3 are the adjacent columns in the display case.

Mean product temperatures (°C) in the display case with doors by opening treatment														
			Door Opening Duration (s)											
			5			15			30			60		
Freq.	Shelf	Depth	Col 1	Col 2	Col 3	Col 1	Col 2	Col 3	Col 1	Col 2	Col 3	Col 1	Col 2	Col 3
Every 5 min	I	1	3.5	3.4	3.9	3.7	3.5	3.9	3.6	3.4	4.0	4.3	4.1	4.6
		3	1.2	1.4	1.6	1.5	1.6	1.9	1.2	1.4	1.6	1.6	1.8	2.0
		6	0.5	0.7	0.9	0.7	0.9	1.1	0.5	0.8	0.9	0.9	1.2	1.4
	II	1	3.6	3.2	3.4	3.9	3.4	3.7	3.7	3.3	3.5	4.4	4.1	4.3
		3	1.4	1.4	1.2	1.8	1.7	1.6	1.5	1.5	1.3	1.9	1.9	1.8
		6	0.7	0.6	0.8	0.9	0.8	1.0	0.8	0.7	0.8	1.2	1.1	1.3
	III	1	3.2	2.9	3.0	3.4	3.2	3.2	3.3	3.1	3.1	4.0	4.0	3.9
		3	1.4	1.3	1.5	1.7	1.7	1.9	1.4	1.4	1.6	1.9	1.8	2.1
		6	1.0	0.9	1.2	1.2	1.2	1.5	1.1	1.0	1.3	1.6	1.5	1.9
	IV	1	2.6	2.5	2.5	2.8	2.7	2.7	2.7	2.7	2.7	3.5	3.5	3.6
		3	1.9	1.9	1.9	2.3	2.3	2.3	2.0	2.1	2.1	2.6	2.7	2.7
		6	1.2	1.3	1.6	1.5	1.6	1.9	1.3	1.4	1.8	2.0	2.1	2.4
	V	1	1.8	1.8	1.8	2.0	2.0	2.0	1.9	1.9	2.0	2.7	2.8	2.9
		3	2.2	2.2	2.2	2.6	2.6	2.6	2.4	2.4	2.4	3.0	3.1	3.1
		6	1.8	1.8	1.6	1.9	2.2	2.0	1.9	2.0	1.8	2.6	2.6	2.5
Every 15 min	I	1	3.3	3.2	3.7	3.2	3.1	3.6	3.3	3.2	3.8	3.3	3.2	3.8
		3	1.1	1.3	1.4	1.1	1.3	1.4	1.2	1.3	1.5	1.1	1.3	1.5
		6	0.4	0.6	0.8	0.4	0.6	0.8	0.5	0.7	0.9	0.5	0.7	0.9
	II	1	3.4	3.0	3.2	3.3	2.9	3.0	3.4	3.0	3.2	3.4	3.0	3.2
		3	1.4	1.3	1.1	1.3	1.3	1.1	1.4	1.4	1.2	1.4	1.4	1.2
		6	0.7	0.5	0.7	0.7	0.5	0.6	0.7	0.6	0.7	0.7	0.6	0.7
	III	1	3.0	2.7	2.7	2.8	2.6	2.6	3.0	2.8	2.8	3.0	2.8	2.8
		3	1.3	1.2	1.4	1.3	1.2	1.4	1.3	1.3	1.5	1.3	1.3	1.4
		6	0.8	0.8	1.1	0.9	0.8	1.1	0.9	0.9	1.1	0.9	0.9	1.2
	IV	1	2.4	2.2	2.3	2.3	2.2	2.2	2.5	2.3	2.4	2.5	2.4	2.4
		3	1.7	1.7	1.7	1.7	1.7	1.7	1.8	1.9	1.9	1.8	1.9	1.8
		6	1.0	1.1	1.4	1.0	1.1	1.4	1.1	1.2	1.5	1.1	1.2	1.5
	V	1	1.6	1.5	1.6	1.5	1.5	1.6	1.6	1.6	1.7	1.7	1.6	1.8
		3	2.0	2.0	2.0	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.1	2.1
		6	1.5	1.6	1.3	1.5	1.6	1.4	1.6	1.7	1.5	1.6	1.7	1.5

significant ($P < 0.001$), as products in the back of the case (depth 6) were as low as 0.4 °C (mean) for treatment A, and as high as 4.6 °C in the front (mean) for treatment B, both during regular refrigeration cycles outside of defrost periods. Also, for shelves, temperature differences of 2.1 °C were recorded at depth 1 for treatment A (Table 3). Temperature differences are visually evident by the color changes from depth 1 to depth 6 (front to back) and from shelf 1 (top) to the bottom rack (Fig. 3).

Higher product simulator temperatures at depth 1 for both treatments are a result of the proximity to the glass doors and ambient air during the opening and closing sequences. Notwithstanding, all mean temperatures were below the 5 °C threshold established by the FDA Food Code to prevent microbial growth in packaged leafy greens; the products simulated in volume and weight in these experiments. Lower simulated product temperatures at depths 3 and 6 for both treatments were a result of their spatial location farther away from the door, in addition to the cold air being released out of the rear of the display case on shelves 1 through 4. The product simulator temperature peaks at 9 h after the start of the experiments represent the scheduled 30-min defrost cycle. The 15 h long temperature monitoring for each treatment, over the course of the tests conducted, ensured that we captured an overall and accurate representation of the effect of the door opening sequences on product temperatures.

It could be argued that the 2-min interval used in this study for logging product simulator temperatures might not have accurately captured the instantaneous temperature changes during the <2 min door opening durations. However, the fact that product temperature changes lag behind air temperature changes and that the temperatures were monitored for 15 h for each treatment suggest that overall accurate representations of the effect of the door opening sequences on product temperature were captured over the course of the tests as they were conducted.

3.1.1. Doors opened every 15 min for 5 s (treatment A)

A door opening sequence every 15 min with a duration of 5 s (four openings per hour) is likely the closest to a real-life scenario at the retail level, and it is the most conservative treatment in the present work. In a field study of display cases with doors conducted by (Fricke et al., 2011) during 51 days, customer traffic data showed that the opening duration that occurred the most frequently was 5 s, with a daily mean door opening frequency of 6.3 per h, or just below every 10 min. These findings are validated by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard, *Method of testing open and closed commercial refrigerators and freezers (Standard 72–2014),* which states that each door be sequentially and fully opened six times per h for 6 s for a period of 8 h (ANSI/ASHRAE, 2014).

In Fig. 3A, the highest product simulator temperature was encountered at depth 1 on shelf 1, which was 3.7 °C (mean), and the lowest temperature was at depth 6 on shelf 1, which was 0.4 °C (mean) (Table 3). In comparison, temperature differences reported in previous studies for open display cases are 3–4 times higher (de Frias et al., 2015; Kou et al., 2015). The single defrost cycle depicted by the product simulator temperature peak at 9 h, reached 4.9 °C on shelf 1, depth 1, is shown as a yellow-green peak (Fig. 3A). Interestingly, there was an apparent decrease in product simulator mean temperatures at depth 1, from the top rack (shelf 1; 3.7 °C) to the bottom rack (1.6 °C), evident by the changes in color from green to blue in the figure (Table 3, Fig. 3A). This trend was also observed in a recent study by Chaomuang et al. (2019) about the effect of varying operating conditions on temperature distributions in a closed display case. The authors found that at a door opening frequency of every 6 min (10 openings per hour) for 15 s, product simulator temperatures in the front of the case decreased from 2.0 °C in the top shelf to 0.8 °C on the bottom shelf.

In our study, even though product simulator temperatures on shelves 1-4 decreased from depth 1 to depth 6, as expected due to cold air flow from the rear of the case, there was an increase in temperature from depth 1 to depth 3 on the bottom rack (color changes from deep blue to clear blue in Fig. 3A). This reversal is explained because there is no air flow from the rear of the display case at the bottom rack level (Table 1). Also, product simulators on the bottom rack did not sit in parallel to the rest of the products on the shelves, so the spatial effect on product temperatures was different from the shelves.

3.1.2. Doors opened every 5 min for 60 s (treatment B)

Relative to treatment A, the opening sequence of every 5 min for 60 s (12 openings per hour), is less likely to occur in actual retail settings. The frequency of openings is double the guidelines of the ASHRAE Standard 72–2014 and the opening duration is ten times longer. Mean product simulator temperatures were expectedly higher for treatment B than treatment A, as a result of the more aggressive opening treatment; however, no mean temperatures were higher than the 5 °C threshold established by the FDA Food Code to prevent microbial growth in leafy products (Table 3). Also, greater temperature differences were observed with treatment B, with the largest ΔT at 3.7 °C, which was 0.4 °C greater than for treatment A.

Treatment B exhibited the same spatial and temporal effects on product simulator temperatures as in treatment A, albeit higher (Fig. 3B). For instance, the highest product mean temperature for treatment B was recorded at depth 1, shelf 1, which was 4.6 °C, and the lowest mean temperature was at depth 6, shelf 1, which was 0.9 °C (Table 3). Lower product simulator temperatures at depth 1, shelf 1 compared to the bottom rack were again observed (Fig. 3B), as well as the reversed tendency of product simulator temperatures on the bottom rack from depth 1 to depth 6 compared to the rest of the shelves, as there is no air flow from the rear of the case in the bottom (see section 3.1.1). Also, the highest defrost cycle temperature peak was 6.6 °C on shelf 1, depth 1, shown as a bright yellow peak (Fig. 3B).

As opposed to treatment A, with no product simulator temperatures above 5 °C even during defrosting, it is relevant to note that in treatment B it took 66–104 min after the start of the defrost cycle for temperatures to fall below 5 °C (Table 4). This data confirms the observation by (Chaomuang et al., 2017) that it can take an hour after the defrost operation to re-establish the desired temperatures for the display case. Despite the potentially detrimental effects of rising temperatures during defrosting on product shelf life, the advantages of door barriers in display cases in minimizing defrosting cycles are relevant. de Frias et al. (2015) found that, for a display case with doors, defrosting can be reduced from two, 30-min cycles needed in an open display case, to one, 30-min cycle every 24 h in a case with doors; minimizing the percentage of higher temperatures above 5 °C.

3.2. Significance of door opening frequencies and duration

In the previous section, we analyzed the two extreme opening sequences from eight treatments evaluated in this work. For all spatial locations (shelf, depth, column-*as replicate*) 22,995 temperature data points were obtained per treatment and its means are depicted in Fig. 4.

In each level of door opening frequency (every 5 min or every 15 min), the differences were not significant; except for the "every 5 min and 60 s opening duration" (treatment B in section 3.1.2). Pairwise comparisons among opening frequency x opening duration combinations reflect the letter group differences in product simulator temperatures (Fig. 4). For instance, the opening sequence "every 5 min for 60 s" (treatment B) versus all opening durations at "every 15 min" and "every 5 min for 5 s", is significant at $p < 0.001$. Significance is lower ($p < 0.03$) when treatment B is compared with opening durations 15 s and 30 s within the "every 5 min" frequency.

The large data set brought forth the statistical differences observed, which can be tied in practice to higher product simulator temperatures at depth 1 for all shelves, on shelf 5, depths 3-to-6 (Table 3), and temperature increases after the start of the single 30-min defrost cycle (Fig. 3, Table 4). For the "every 5 min for 60 s" treatment, mean

Table 4
Spatial locations with the highest product simulator temperature peaks for each door opening sequence during the single defrost cycle. Time elapsed for product simulator temperatures to fall back below 5 °C (FDA Food Code threshold) is determined from the start of the defrost cycle. The highest product temperatures during defrosting were encountered on shelf 1 (S1), depth 1 (D1), or shelf 2 (S2), depth 1 (D1).

Opening sequence	Spatial location	Defrost cycle temperature peaks (°C)	Time to return to 5 °C (min)
Every 5 min			
For 5 s	S1 D1	5.5	26
		5.5	20
	S2 D1	5.3	14
		5.2	10
For 15 s	S1 D1	5.7	28
		5.6	30
	S2 D1	5.5	24
		5.4	24
For 30 s	S1 D1	5.4	26
		5.4	16
	S2 D1	5.2	12
		5.2	10
For 60 s	S1 D1	6.6	70
		6.4	104
	S2 D1	6.4	66
		6.3	80
Every 15 min			
For 5 s	No product temperatures above 5 °C		
For 15 s	No product temperatures above 5 °C		
For 30 s	No product temperatures above 5 °C		
For 60 s	No product temperatures above 5 °C		

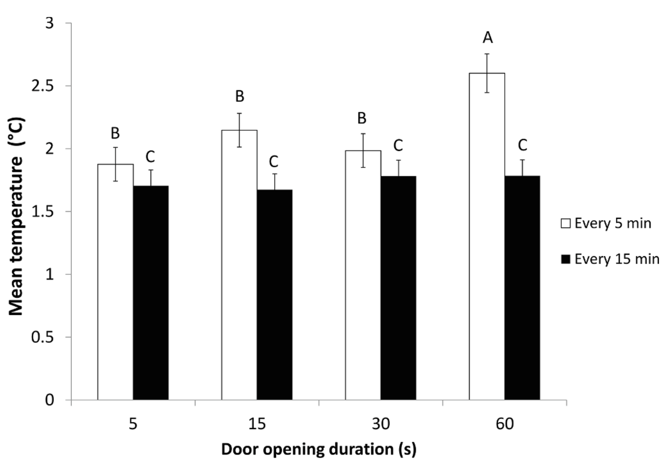

Fig. 4. Temperature means versus door opening duration, for the two levels of door opening frequency tested (every 5 min, every 15 min). Different letters within each opening frequency, are statistically different at $p = 0.05$.

product simulator temperatures were up to 1 °C higher in those spatial locations, and temperatures fell back below 5 °C after the start of the defrost cycle 66–104 min later with peaks at 6.6 °C in shelf 1 depth 1 (Table 4). Temperatures around defrost for all other opening sequences never exceeded 5 °C (for the 15-min opening frequency) or peaked at 5.7 °C (for the 5-min opening frequency); taking 30 min or less to fall back to 5 °C (the duration of the defrost cycle) (Table 4).

3.3. Energy savings of the display case with doors under different opening treatments

Table 5 presents an electrical energy consumption assessment of the display case with doors for three different treatments: 1) three doors out of six opened all the time, 2) all doors closed all the time, and 3) three doors opened every 10 min for 12 s. Each treatment was tested separately for a period of 2 h along with an open display case fully loaded with product simulators.

The contrasting treatments of three doors opened or closed all the time (treatments no. 1 and no. 2) are compared with the opening sequence of three doors opened every 10 min for 12 s (treatment no. 3). The latter treatment is based on the door opening testing procedure suggested by the ASHRAE Standard 72–2014 (every 10 min per hour for 6 s). Even though the opening duration time tested is double that suggested by the standard, it is in line with mean door opening frequencies found in actual retail settings by Fricke and Becker (2011) (12 s). The opening duration time in the ASHRAE Standard reflects the most frequent opening duration in that study (5 s).

The results for the display case with doors show that total electrical energy consumption of the condensing unit, evaporator fans, and lights with the typical opening sequence (treatment no. 3) was just 0.1 kWh higher than the energy consumption with doors closed all the time. Energy savings compared to the open display case were 66% and 68% for the typical opening sequence and doors closed all the time, respectively (Table 5). This data confirms previous assessments in our lab on energy savings from the use of a display case with doors versus an open case, which found 69% savings for treatments nos. 2 and 3 (de Frias et al., 2015). Similarly, Lindberg, Axell, and Fahlén (2010) determined at the lab level that with an opening sequence of every 6 min for 6 s (10 openings per hour) energy savings were 66% compared to the open case. Also, Faramarzi (2002) found that retrofitting open cases with doors reduced total cooling load by 68%. Chaomuang et al. (2017) tabulated these studies and others at the laboratory and retail level comparing the potential energy savings of the display case with doors, reporting energy savings from 23% to 73%.

In our work, the significant energy savings from the case with doors was chiefly a result of the lower consumption of the condensing unit resulting from the lower refrigeration load. While energy use by fans was the same in both cases, energy consumption by lights was double in the case with doors due to the extra set of lights. Even when comparing treatment no. 1 (three doors out of six opened all the time) versus the open case, although the energy savings were not as great as with the other treatments tested, at 45% they were still significant (Table 5).

4. Conclusion

We tested eight opening sequences in a retail display case with doors under a thermostat setting of 0.6 °C, a daily defrost cycle of 30 min, and found that mean product simulator temperatures for all treatments were below the 5 °C Food Code threshold to prevent microbial growth. Spatial and temporal temperature maps of the display case contrasted the most aggressive treatment (every 5 min for 60 s) with the most conservative (every 15 min for 5 s). With 22,995 product simulator temperature data points obtained at 2-min intervals for each treatment, differences for each level of door opening frequency (every 5 min or every 15 min) were not significant, except for the most aggressive schedule (every 5 min for 60 s). Pairwise comparisons of this treatment with the other seven, confirmed that temperature differences were significantly different from the rest of the treatments, even though temperatures never exceeded 5 °C or peaked around it during the 30-min defrost cycle. Energy consumption of the display case with doors closed all the time and with a typical opening sequence was practically the same; with energy savings at 68% and 66%, respectively, compared to an open case. All these findings will help the retail industry to continue embracing the display of highly perishable foods behind glass

Table 5
Electrical energy consumption of the display case with doors under different treatments and an open display case, both installed in a dedicated room at USDA-ARS. Data from both cases were recorded during three consecutive days, testing one treatment per day along with the open display case. Each experiment lasted 2 h, starting 3 h after the start of the defrost cycle. Energy savings of using the display case with doors versus the open display case is also shown.

Treatment	Condensing unit (kWh)	Fans (kWh)	Lights (kWh)	Total consumption (kWh)[b]	Energy savings from open case
Open display case[a]	4.2	0.3	0.2	4.7	NA
3 doors out of 6 opened all the time	1.9	0.3	0.4	2.6	45%
All doors closed all the time	0.8	0.3	0.4	1.5	68%
3 doors opened every 10 min for 12 s	0.9	0.3	0.4	1.6	66%

[a] Mean consumption throughout the different treatments of the display case with doors.
[b] Total energy consumption during the duration of the experiments (2 h).

doors to support compliance with US Food Code with significant energy savings.

Author contribution statement

J. Atilio de Frias: Conceptualization, methodology, validation, formal analysis, investigation, writing (original draft, review and editing), visualization. Yaguang Luo: Conceptualization, validation, writing (review and editing), resources, supervision, project administration, funding acquisition. Bin Zhou: Methodology, investigation. Boce Zhang: Investigation, writing (review and editing). David T. Ingram: Investigation, writing (review and editing). Keith Vorst: Writing (review and editing). Jeffrey K. Brecht: Writing (review and editing). John Stommel: Writing (review and editing).

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