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Utilizing Thermal Mass in Refrigerated Display Cases to Reduce Peak Demand

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ABSTRACT

The potential to store energy within refrigerated food products presents convenience store and supermarket operators with an opportunity to participate in utility sponsored demand response programs, whereby electricity usage can be shifted or reduced during peak periods. To determine the feasibility of reducing peak demand by shifting the refrigeration load to off-peak times, experimental and analytical analyses were performed. Simulated product, consisting of one-pint containers filled with a 50% ethylene glycol and 50% water solution, were stored in a medium-temperature vertical open refrigerated display case. Product temperature rise as a function of time was determined by turning off the refrigeration to the display case, while product temperature pull-down time was subsequently determined by turning on the refrigeration to the display case. It was found that the thermal mass of the product in a medium-temperature display case was such that during a 2.5 hour period with no refrigeration, the average product temperature increased by 5.5°C. In addition, it took approximately 3.5 hours for the product to recover to its initial temperature after the refrigeration was turned on. Transient heat conduction analyses for one-dimensional objects is in good agreement with the experimental results obtained in this study. From the analysis, it appears that the thermal mass of the stored product in refrigerated display cases is sufficient to allow product temperatures to safely drift for a significant time under reduced refrigeration system operation. Thus, strategies for shifting refrigeration system electrical demand can be developed. The use of an advanced refrigeration system controller that can respond to utility signals can enable demand shifting with minimal impact.

1. INTRODUCTION

Refrigeration systems in supermarkets and convenience stores operate continuously to maintain proper product storage conditions, and these refrigeration systems can account for 40% or more of the electrical energy consumption of a supermarket or convenience store. Furthermore, peak demand for refrigeration system electricity typically occurs during the afternoons and summer months, corresponding to when the general demand and price for electricity are the highest. In order to reduce peak demand and its associated costs, it may be possible to shift refrigeration system electrical energy use by utilizing the thermal mass of the stored product. The traditional electric grid is *load-following* and is based on centralized generation assets that are controlled to compensate for load changes in order to maintain a stable grid. Demand-shifting will be become increasingly more important as intermittent and unpredictable renewable sources of energy such as photovoltaic (PV) and wind power become more prevalent. Storage solutions provide a unique opportunity to capture electricity produced by renewable sources to

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potentially offset peak demand. However, current electrical storage technologies require large capital investments, making alternatives that require less investment attractive. An attractive lower investment option is the deployment of building assets as virtual storage. Significant literature exists on the use of building thermal mass as a storage technology by employing novel control techniques like pre-cooling and pre-heating to shift demand (for example see, Henze *et al.*, 2007; Braun, 2003; Turner *et al.*, 2015; Nutaro *et al.*, 2015; and Zhang *et al.*, 2012). Some literature exists on the use of conditioned warehouses and self-storage units. These building types, representing 7% of commercial energy use, have wider limits on internal temperature swings compared to occupied buildings and would therefore be more easily utilized in demand response programs (Scott *et al.*, 2014; Goli *et al.*, 2011; and Bisio and Rubatto, 1991). While there is a large amount of research in using technologies like ice storage as a thermal storage technique either as an additional system in the building or part of refrigeration systems, there is limited research in using existing display case product for enabling thermal storage. While storage density is minimized due to product constraints and quantity, the retrofit potential at a very low-cost is significant. In this paper we address the use of existing display case products for enabling storage.

During early morning hours, when electricity demand and price are lower and refrigeration system efficiency is greater, the temperature set point of the refrigeration system can be reduced in order to pre-cool the stored products to below their normal storage temperature, in anticipation of a demand response event later in the day. Subsequently, refrigeration system operation can be reduced during the mid to late afternoon when electricity demand and price are high, and product temperature may be allowed to drift upwards. This operating strategy is particularly feasible with products that are not adversely affected by variations in temperature, such as water and canned or bottled beverages. The key to utilizing the thermal storage is to understand the storage potential and associated time constants of the display cases.

To determine the feasibility of reducing peak demand by shifting the refrigeration load to off-peak times, experimental and analytical analyses were performed. Simulated product were stored in a medium-temperature vertical open refrigerated display case, and product temperature rise as a function of time was determined by turning off the refrigeration to the display case, while product temperature pull-down time was subsequently determined by turning on the refrigeration to the display case. The experimental results were validated using transient heat conduction analyses for one-dimensional objects (such as infinite slabs, infinite cylinders, or spheres). Based on the analysis, strategies for shifting refrigeration system electrical demand can be developed. The use of an advanced refrigeration system controller that can respond to utility signals can enable demand shifting with minimal impact.

2. OPPORTUNITY

In the United States, it is estimated that the electrical energy consumption of refrigeration for the food retail sector, including supermarkets and convenience stores, is 74×10^6 GJ. (EIA, 2003). Refrigeration system capacities in food retail establishments vary from 30-60 kW in small convenience stores to over 400 kW for large supermarkets, with annual energy consumption varying from 100,000 to 1.5 million kWh or more per store. Due to their high energy intensity, it would appear that convenience stores could participate in load shifting using their refrigeration systems. In addition, since a significant portion of sales from convenience stores results from packaged beverages, many of which are refrigerated, convenience stores would be a candidate for load shifting via refrigeration, given that beverages would not be adversely affected by variations in temperature. Thus, we will focus our investigation on the potential for demand response in convenience stores.

Convenience stores are small food retailers that sell a limited number of grocery items and snacks, as well as gasoline, and are typically open 18 to 24 hours per day. There are over 150,000 convenience stores is the United States, with an average store size of 250 m^2, with the trend for newer stores to be bigger, up to 330 m^2 on average (NACS, 2016). According to data from the Commercial Buildings Energy Consumption Survey (CBECS), the food retail sector, which includes both convenience stores and supermarkets, has an average electric energy intensity of 532 kWh per square meter per year (EIA, 2003). However, some reports suggest that the average electric energy intensity of convenience stores may be as high as 1010 kWh per square meter per year (Michaels Energy, 2013). Based on this data, and assuming that refrigeration accounts for up to 40% of the electrical energy consumption of a convenience store, the annual electrical energy consumption of the refrigeration equipment in a convenience store is estimated to be 135,000 kWh. It would not be unreasonable then to assume that a convenience store could reduce its refrigeration system power consumption by approximately one kilowatt during a short demand response event through modified operation of the refrigeration system. Assuming that there could be several hundred or even thousands of convenience stores within the service area of a power generating station, this would represent a significant load reduction during periods of peak generation.

3. EXPERIMENTAL ANALYSIS

3.1 Approach

A laboratory-scale supermarket refrigeration system, shown in Figure 1 and consisting of components typically found in most U.S. supermarket refrigeration systems, was used to determine the impact of system operating strategies on product temperature. The refrigeration system, which uses R-404A refrigerant, has a low-temperature (LT) cooling capacity of approximately 18 kW at a saturated evaporating temperature of −29°C and a medium-temperature (MT) cooling capacity of approximately 35 to 53 kW at a saturated evaporating temperature of −4°C. Three open vertical display cases, each 3.7 m in length, constitute the low-temperature load. The medium-temperature load consists of two open vertical display cases, each 3.7 m in length, as well as a “false” load provided by a plate heat exchanger and glycol loop. The system contains two LT and two MT reciprocating compressors as well as an air-cooled condenser. The compressor rack and air-cooled condenser are installed in a temperature and humidity controlled “outdoor” environmental chamber while the refrigerated display cases are installed in a separate temperature and humidity controlled “indoor” environmental chamber. For both chambers, the temperature can be controlled between −18 to 54°C and the humidity can be controlled between 30 to 90%. Thus, the air-cooled condenser can be exposed to typical outdoor ambient conditions while the refrigerated display cases operate in an environment typical of that found in the sales area of a supermarket. Furthermore, this hydrofluorocarbon (HFC)-based refrigeration system is fully instrumented to determine its performance.

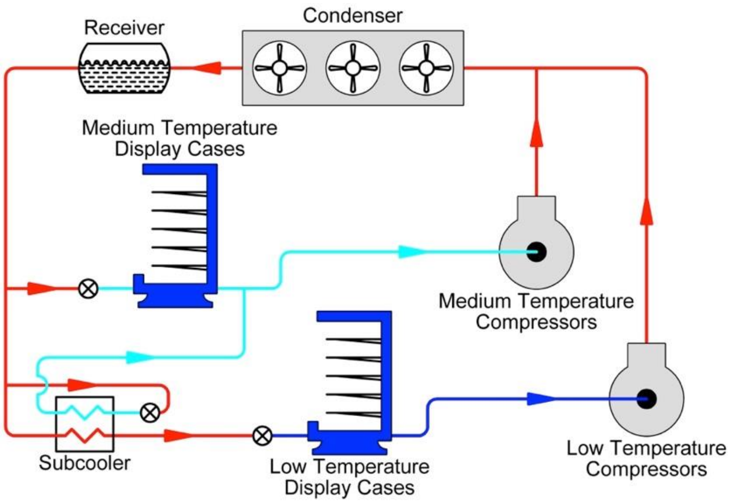

Figure 1: Laboratory-scale supermarket refrigeration system

3.2 Results

Food products were simulated with 473 mL containers filled with a 50% ethylene glycol and 50% water solution. Each of the product simulators contained a thermocouple located at the center of its thermal mass, and a total of 48 of these instrumented product simulators were distributed throughout one of the medium-temperature open refrigerated display cases, as specified in ASHRAE Standard 72 (2005).

As shown in Figure 2 at 18:30, the average temperature of the 48 product simulators within the display case was −3.56°C, and the display case discharge air temperature was approximately −3.89°C. The supply of refrigerant to the display case was turned off at 18:30, and the air temperature and product temperature began to rise. As shown in Figure 2, by 21:00 (2.5 hours after turning off the refrigeration), the average product temperature had risen by approximately 5.5°C to 2.33°C and the discharge air temperature had risen to 6.11°C. At 21:00, the refrigerant supply to the display case was turned on, and by 0:40, the product temperature had returned to −3.56°C, and the discharge air temperature was −4.56°C.

Thus, the thermal mass of the products in the display case was such that during a 2.5 hour period with no refrigeration, the product temperature increased by 5.5°C, or roughly 2°C per hour. In addition, it took approximately 3.5 hours for the product to recover to its initial temperature after the refrigeration was turned on.

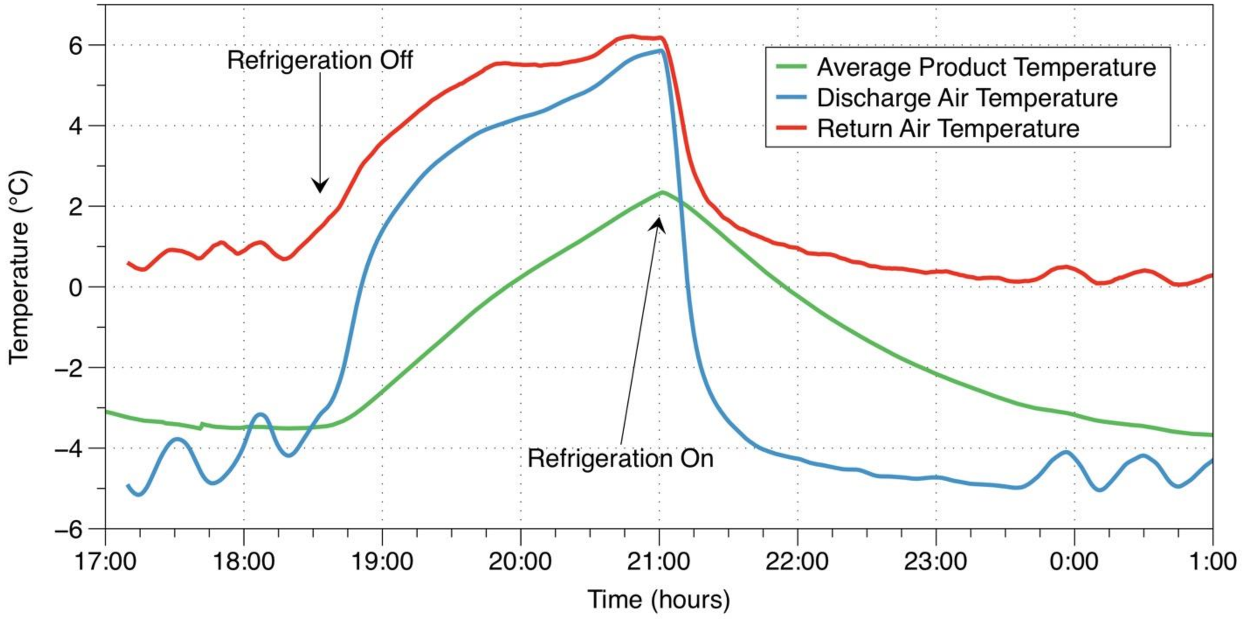

Figure 2: Product and air temperatures in a medium temperature refrigerated display case

Note that this represents a worst-case scenario, since the display case used in this study was an open, multi-deck display case, in which a large percentage of the heat load on the case is due to infiltration of warm moist air into the case. If a doored display case was used, infiltration would be greatly reduced and the "cold" would remain within the case for a longer period. Thus, the product temperature would rise less over time. Regardless of display case type, an additional strategy which could be utilized during demand response events would be to turn off display case lighting and reduce anti-sweat heater power and evaporator fan speed to reduce the heat load on the display case.

Figure 3 shows the power consumed by the medium temperature compressors during the same time period. Before the refrigerant supply was turned off to the medium-temperature display case, the compressor power was approximately 6,880 W. Between 18:30 and 21:00, during which time the refrigerant supply was shut off to the medium temperature display case, the compressor power was on average approximately 6700 W. Subsequently, for the time period 21:00 to 1:00, the average compressor power was 6,950 W. It can be seen that the medium-temperature compressor power consumption decreased by approximately 180 W, or about 3%, during the time when the refrigeration to the medium-temperature display case was turned off.

The refrigerating capacity of the laboratory-scale supermarket refrigeration system used in this study is comparable to that of a typical convenience store, and the one medium-temperature display case investigated in this study represents approximately 11% of the total medium-temperature load on the refrigeration system. If more medium-temperature load could be turned off during an actual demand response event (say 50% of the total medium-temperature load), then nearly 1 kW of electrical energy reduction per store could be achieved during the demand response event. Given that there could be several hundred or even thousands of convenience stores within the service area of a power generating station, this would represent a significant load reduction during peak generation. In addition, if the duration of the demand response event were on the order of 0.5 hours, product temperatures would be expected to rise by approximately 1°C.

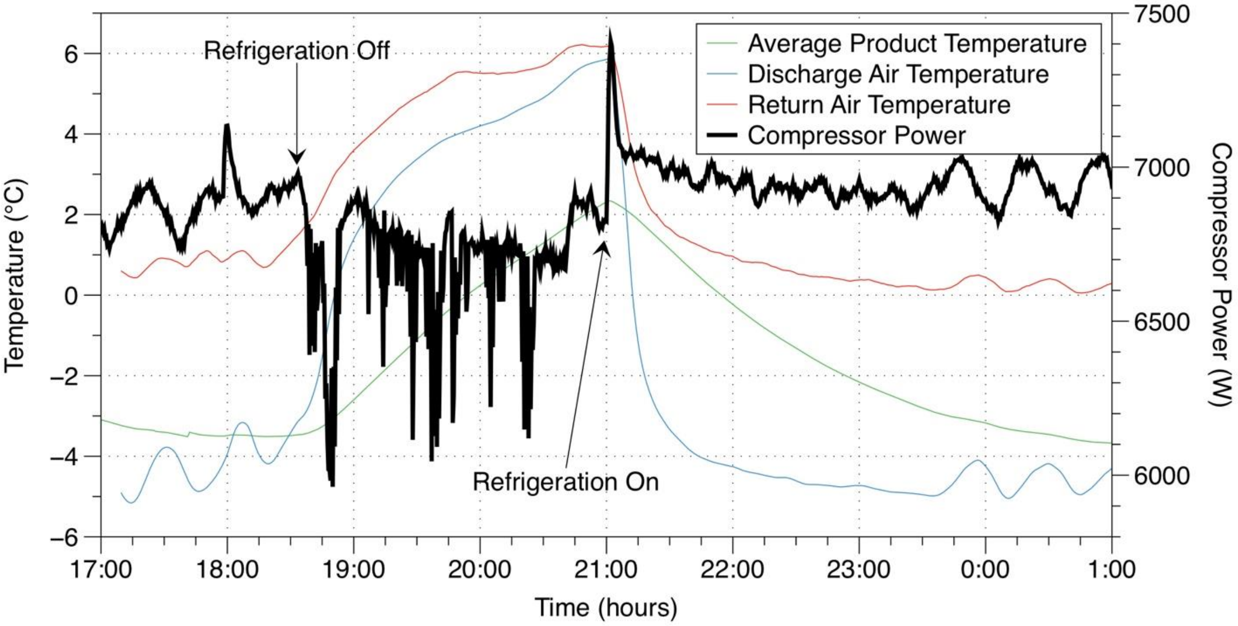

Figure 3: Medium-temperature compressor power before, during and after turning off refrigeration to a medium-temperature display case.

4. ANALYTICAL ANALYSIS

To validate the experimentally determined thermal response of simulated food products described above, transient heat conduction analyses for one-dimensional objects (such as infinite slabs, infinite cylinders, or spheres), was used to estimate the cooling or heating times of food items. The general form of the transient conduction model is:

$$Y = \frac{T_{air} - T_{final}}{T_{air} - T_{final}} = je^{-\frac{2.303\theta}{f}} \tag{1}$$

where j represents the lag between the onset of heating/cooling and the exponential increase/decrease in temperature, and f represents the time required for a 90% increase/reduction in the non-dimensional temperature difference, Y. Solving for the process time, θ, yields:

$$\theta = \frac{-f}{2.303} ln\left(\frac{Y}{j}\right) \tag{2}$$

Assuming that the shape of the simulated products in the display case approximates an infinite cylinder of radius, r, the factors f and j may be estimated as follows (Lacroix and Castaigne, 1987):

$$\frac{f\alpha}{r^2} = \frac{ln(10)}{v^2} \tag{3}$$

$$j_c = \frac{2J_1(v)}{v[J_0^2(v) - J_1^2(v)]} \tag{4}$$

where

$$\begin{aligned} v = 1.257493 + 0.48794ln(Bi) + 0.025322[ln(Bi)]^2 + 0.026568[ln(Bi)]^3 \\ - 0.002888[ln(Bi)]^4 + 0.001078[ln(Bi)]^5 \end{aligned} \tag{5}$$

and $J_0(v)$ and $J_1(v)$ are zero- and first-order Bessel functions, respectively. The ratio of external heat transfer resistance to the internal heat transfer resistance of an object is given by the Biot number, Bi, as follows:

$$Bi = \frac{hr}{k} \tag{6}$$

where h is the convective heat transfer coefficient, r is the object radius, and k is the thermal conductivity of the object.

The food product simulators used in the experimental analysis described in Section 3 were cylindrical in shape, with a diameter of 6.4 cm and a height of 12.7 cm. Furthermore, the simulated product has thermal properties similar to that of water, as follows:

Initial Product Temperature:	$T_{initial} = -1.1$°C
Final Product Temperature:	$T_{final} = 4.4$°C
Thermal Conductivity:	$k = 0.549$ W·m^{-1}·K^{-1}
Specific Heat:	$c = 4{,}224$ J·kg^{-1}·K^{-1}
Density:	$\rho = 1{,}000$ kg·m^{-3}
Air Temperature:	$T_{air} = 7.2$°C
Heat Transfer Coefficient:	$h = 20$ W·m^{-2}·K^{-1}

It is assumed that the cylindrical food product is to be heated by 7.2°C air from an initial temperature of −1.1°C to a final temperature of 4.4°C. For this example of heating a cylindrical food product by 5.5°C, the above analytical method predicts a heating time of 2.2 hours, which is in good agreement with the experimental results presented previously.

5. FUTURE EFFORTS

As noted previously, supermarkets, grocery, and convenience stores are energy intensive operations. Heating ventilation and air conditioning (HVAC), refrigeration, and lighting loads account for approximately 85% of the total energy use with in these facilities. Typically the loads are controlled separately with minimal or no coordination resulting in energy losses and peak demand charges. Significant savings potential exist through retrofit control systems that can enable coordination various type of loads. Additionally, significant portion of the convenience store energy use is dispatchable making them responsive to electric grid needs, particularly to support higher penetration of renewable and energy storage technologies.

Retrofit automation and control systems for convenience stores can enable 1) improved energy efficiency and reduced peak demand, 2) enable responsive loads for renewable and storage (real and virtual) integration at distribution-level, and 3) provide reliability and regulation services to the electric grid. Significant portion of these loads have similar control interfaces (e.g., thermostats) facilitating scalable deployment. The ubiquitous presence of these stores provides a unique opportunity to spatially and temporally control them to provide transactive energy services to electric grid. However novel, retrofit-compatible automation and control systems are required for unlocking the energy savings and transactive potential of convenience stores while operating within the safety and business constraints.

The authors propose to develop, demonstrate, and deploy retrofit automation technology within small footprint supermarkets and convenience stores. The proposed collaborative project will address the gaps specified above by accomplishing four specific objectives: 1) whole-store, supervisory load control for improving energy efficiency and reducing peak demand, 2) grid responsive load control for providing transactive energy services, 3) fault detection and diagnosis techniques for HVAC and refrigeration systems, and 4) utilize real and virtual energy storage for optimal store operation. The outcome of the proposed project is to demonstrate low-cost, low-touch sensing and control retrofits to convenience store loads that, in a coordinated fashion, provide load-shaping response needed to integrate high-levels of renewable penetration.

6. CONCLUSIONS

To determine the feasibility of reducing peak demand in convenience stores and supermarkets, by shifting the refrigeration load to off-peak times, experimental and analytical analyses were performed. Simulated product, consisting of one-pint containers filled with a 50% ethylene glycol and 50% water solution, were stored in a medium-temperature vertical open refrigerated display case. Product temperature rise as a function of time was determined by turning off the refrigeration to the display case, while product temperature pull-down time was subsequently determined by turning on the refrigeration to the display case. It was found that the thermal mass of the product in a medium-temperature refrigerated display case was such that during a 2.5 hour period with no refrigeration, the average product temperature increased by 5.5°C. In addition, it took approximately 3.5 hours for the product to recover to its initial temperature after the refrigeration was turned on. Furthermore, transient heat conduction analyses for one-dimensional objects (such as infinite slabs, infinite cylinders, or spheres) validated the experimental results, predicting that heating a cylindrical product by 5.5°C, from -1.1°C to 4.4°C would take approximately 2.2 hours.

It was estimated that nearly 1 kW of electrical energy reduction per convenience store could be achieved during a demand response event. Assuming that there could be several hundred or even thousands of convenience stores within the service area of a power generating station, this would represent a significant load reduction during periods of peak generation. In addition, if the duration of the demand response event were on the order of 0.5 hours, product temperatures would be expected to rise by approximately 1°C.

From the analysis, it appears that the thermal mass of the stored product in refrigerated display cases is sufficient to allow product temperatures to safely drift for a significant time under reduced refrigeration system operation. Thus, strategies for shifting refrigeration system electrical demand can be developed. The use of an advanced refrigeration system controller that can respond to utility signals can enable demand shifting with minimal impact.

NOMENCLATURE

Bi	Biot number	(-)
c	specific heat	($J\cdot kg^{-1}\cdot K^{-1}$)
f	heating/cooling time constant	(s)
h	convective heat transfer coefficient	($W\cdot m^{-2}\cdot K^{-1}$)
j	heating/cooling lag factor	(-)
j_c	heating/cooling lag factor at thermal center	(-)
$J_0(v)$	zero-order Bessel function	(-)
$J_1(v)$	first-order Bessel function	(-)
k	thermal conductivity	($W\cdot m^{-1}\cdot K^{-1}$)
r	radius	(m)
T_{air}	air temperature	(°C)
T_{final}	final product temperature	(°C)
$T_{initial}$	initial product temperature	(°C)
Y	non-dimensional temperature difference	(-)
α	thermal diffusivity	($m^2\cdot s^{-1}$)
θ	heating/cooling time	(s)
ρ	density	($kg\cdot m^{-3}$)

CBECS	Commercial Buildings Energy Consumption Survey
EIA	Energy Information Administration
HFC	hydrofluorocarbon
LT	low-temperature
MT	medium-temperature
PV	photovoltaic

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