Demand Defrost Strategies in Supermarket Refrigeration Systems

Interim Report

Submitted to:

Refrigeration Project Team
Retail Energy Alliance

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1. Goals and Objectives

The objective of this project was to determine the potential energy savings associated with implementing demand defrost strategies to defrost supermarket refrigerated display case evaporators, as compared to the widely accepted current practice of controlling display case defrost cycles with a preset timer. The defrost heater energy use of several representative display case types was evaluated. In addition, demand defrost strategies for refrigerated display cases as well as those used in residential refrigerator/freezers were evaluated.

Furthermore, it is anticipated that future work will include identifying a preferred defrost strategy, with input from Retail Energy Alliance members. Based on this strategy, a demand defrost system will be designed which is suitable for supermarket refrigerated display cases. Limited field testing of the preferred defrost strategy will be performed in a supermarket environment.

2. Motivation and Benefits of Demand Defrost

Retail food stores and supermarkets operate their refrigeration systems continuously to maintain proper food storage conditions within their refrigerated display cases and storage areas. Inevitably, moist air will be entrained within the refrigerated display cases and storage areas. Since the temperatures of the evaporators within the display cases and storage areas are below 32°F (0°C), which is lower than the dew point of the entrained air, water vapor within the air will condense and freeze on the evaporator surfaces, forming frost (Lawrence and Evans 2008). Over time, the frost accumulation on the evaporator is sufficient to both impede heat transfer and to dramatically decrease the airflow through the evaporator, leading to a decrease in the refrigerating capacity. Thus, in order to maintain system performance and proper storage temperatures within the display cases and storage areas, evaporators require periodic heating to melt and remove the frost (Tassou, Datta and Marriott 2001).

Defrosting of refrigerated display case evaporators may be achieved by several methods. For medium temperature display cases, defrosting is often accomplished by simply interrupting the flow of refrigerant to the evaporator. The frost then melts naturally as the evaporator fans blow air over the evaporator surfaces. Electrical resistance heaters are commonly used to defrost low-temperature display cases, and in a few circumstances, they may even be used to defrost medium-temperature display cases. Electric heating elements are placed in front of the evaporator or embedded within the evaporator. During an electric defrost cycle, the refrigerant flow to the evaporator is interrupted, the electric heating elements are energized, and the evaporator fans blow hot air over the evaporator surfaces to melt the frost. In another defrost technique known as hot gas defrost, high temperature refrigerant vapor from the compressor discharge is routed through the evaporator via a series of valves and piping. The high temperature vapor provides the required heating to melt the frost which has accumulated on the evaporator coils.

Defrosting of supermarket display case evaporators is commonly controlled by a preset time cycle. Defrosts are typically scheduled to occur every six or eight hours, with a duration of 20 to 30 minutes. This method has the advantage of simplicity, reliability and low cost. However, a time-based defrosting strategy is determined from worst case conditions to ensure complete defrosting under extreme conditions. Thus, unnecessary defrost cycles will likely occur, thereby reducing the energy efficiency of the refrigeration system (Tassou, Datta and Marriott 2001).

A significant amount of energy is required to defrost the evaporators in refrigerated display cases. Mei et al. (2002) report that electric defrost heaters can account for up to 25% of the total electrical energy consumption of refrigerated display cases. A review of manufacturers' data indicates that electric defrost energy consumption can range from 10% to 30% of the total display case energy consumption, with an average of approximately 20% (Hill Phoenix 2011) (Hussmann 2011). Furthermore, defrosting adds heat to the refrigerated display cases, which must be removed by the refrigeration system after termination of the defrost cycle, thereby increasing compressor operation and energy use.

Defrosting also negatively impacts the shelf-life of food items in the refrigerated display cases. The temperature of the food items within the display case increases during defrosting since heat is added during this process. Food temperatures in certain locations within the display case may increase to levels above those which are considered safe. According to the FDA Food Code, foods which require refrigeration to limit pathogenic microorganism growth or toxin formation must be maintained at 41°F (5°C) or lower (FDA 2009). In addition, the fluctuation of temperature experienced by the food items as display cases cycle between cooling and defrosting can also cause product weight loss and deterioration in appearance (Lawrence and Evans 2008).

An automatic defrost system that initiates defrost and varies the interval between defrosts according to actual need is referred to as a demand defrost system (Allard and Heinzen 1988). There is clearly an opportunity to reduce supermarket refrigeration system energy consumption by utilization of demand-controlled case evaporator defrost. In addition, optimization of defrosting will minimize the deleterious impact that temperature cycling has on food safety and quality.

Outline of Interim Report

This interim report describes the progress made on this project to-date, including a review of demand defrost technologies as well as an evaluation of current defrost energy use in supermarkets and the potential energy savings associated with the implementation of demand defrost.

The following outline summarizes the remaining content of this report.

- Section 3, Types of Defrost

    A summary of methods used to defrost refrigerated display case evaporators is given.

- Section 4, Factors Affecting Defrost Frequency and Energy Use

  A discussion is given regarding the factors which affect the quantity of ice deposited on refrigerated display case evaporator coils, which, in turn, affects the frequency and energy use of the defrost system.

- Section 5, Energy Use of Current Defrosting Strategies

  An evaluation is given of the energy use associated with the defrosting of refrigerated display case evaporators. The defrost energy consumption analysis is performed for several types of low temperature refrigerated display cases.

- Section 6, Defrost Control Strategies

  A summary is given of various demand defrost strategies which have been used in commercial and domestic refrigeration applications.

- Section 7, Discussion

  A discussion is given regarding the application of various demand defrost strategies to refrigerated display cases.

- Section 8, Next Steps

  Based on the results presented in this interim progress report, future work for this project is proposed.

3. Types of Defrost

The most common defrost methods used in supermarket applications include off-cycle defrost, electric defrost and hot gas defrost. Other methods of defrost have been investigated, including cool vapor defrost and warm liquid defrost, but these techniques are not commonly utilized in supermarket applications.

Off-Cycle Defrost

The most basic defrost method is the off-cycle defrost, in which the refrigerant flow to the evaporator is interrupted. The evaporator fans then blow air across the frosted evaporator, thereby melting the accumulated frost. Since this method relies on the circulation of relatively warm air over the evaporator to melt the frost, this technique is limited to only medium temperature applications.

The off-cycle defrost method has the advantage of being energy efficient because no additional heating is required to melt the frost. However, complete defrosting of an evaporator does require a considerable amount of time using the off-cycle defrosting technique.

Electric Defrost

Electric defrost methods make use of electrical heating elements which are mounted adjacent to the evaporator coil or integrated into the evaporator coil. During a defrost cycle, the refrigerant flow to the evaporator is interrupted and the heating elements are energized. The evaporator fans then blow hot air over the evaporator surface. Radiation, conduction and/or convection heat transfer between the heating elements, air and the evaporator causes the frost to melt.

Since heat is being added externally to the evaporator, only a portion of the heat generated is used to melt the frost. The remaining portion of the heat is transferred to the refrigerated space and the food products. As illustrated in Section 5, approximately 1% or more of the heat generated by the electric defrost heaters goes into melting the frost while the remaining excess heat is transferred to the air and food products within the display case. This excess heat must then be removed when the refrigeration system resumes operation after the defrost cycle.

Compared to off-cycle defrosting, the electric defrost method is relatively quick. In addition, electric defrost has low first cost but high operating cost.

Hot Gas Defrost

In the hot gas defrost method, the liquid refrigerant flow to the evaporator is first interrupted via a solenoid valve and the evaporator fans are turned off. Then, the hot gas defrost solenoid opens, which allows high pressure, high temperature refrigerant gas from the compressor discharge to flow into the evaporator. As the hot refrigerant gas flows through the evaporator, it condenses, thus releasing its latent heat. This warms the evaporator and melts the frost (Hoffenbecker, Klein and Reindl 2005).

Compared to electric defrosting, hot gas defrosting can remove the accumulated frost approximately 1.5 times faster (Rainwater 2009). In addition, since the evaporator is being heated from the inside, the amount of excess heat transferred to the display case and food products is less than that associated with electric defrost. It has been estimated that only 15% to 25% of the heat generated by hot gas defrost goes into melting the frost while the remaining excess heat is transferred to the air and food products within the display case (Niederer 1976).

Other Defrost Methods

One disadvantage of the hot gas defrost method is that the high temperature refrigerant vapor comes into contact with the low temperature evaporator and its associated piping. This can result in thermal shock which, over time, can lead to cracks and leaks in the refrigerant piping near the evaporator. In an effort to reduce the effects of thermal shock, cool vapor defrost and warm liquid defrost methods have been proposed (Gage and Kazachki 2002) (Baxter and Mei 2002) (Mei, et al. 2002). In the cool vapor defrost system, saturated vapor from the liquid receiver is directed through the evaporator while in the warm liquid defrost system, saturated liquid from the liquid receiver is directed through the evaporator. The temperature of the saturated vapor or the saturated liquid is not nearly as high as that of the compressor discharge gas, so the effect of thermal shock with a cool vapor defrost system or a warm liquid defrost system is reduced. While these defrost techniques can prolong equipment life as compared to hot gas defrost, they are not commonly used in supermarket applications.

It is suggested that supermarket display case evaporators should be defrosted in stages. That is, rather than defrosting all the evaporators in a display case line-up at the same time, groups of evaporators in the line-up should be defrosted in a staggered fashion. By staging or staggering the defrost of the display case evaporators, less demand is placed on the refrigeration system following a defrost and display case temperature fluctuations are reduced. In a similar vein, it has been suggested that a "modular" defrost could be implemented, in which a single display case incorporates two evaporators, rather than one, and each evaporator is defrosted independently from the other (RTTC n.d.). The modular defrost was found to reduce product temperature swings while slightly increasing the compressor energy use of the refrigeration system

4. Factors Affecting Defrost Frequency and Energy Use

The relative humidity within a supermarket greatly affects the amount of frost formation on display case evaporators (Tassou, Datta and Marriott 2001). Thus, relative humidity is directly related to the required defrosting frequency and associated energy use. Several studies have reported on the energy use associated with defrost heaters as a function of supermarket relative humidity (Tassou and Datta 1999) (Henderson and Khattar 1999) (Kosar and Dumitrescu 2005). Other factors which influence the rate of frost formation on evaporator coils include ambient air temperature, evaporator fin spacing, and air flow rate (Bullard and Chandrasekharan 2004). The Refrigeration and Thermal Test Center operated by Southern California Edison has extensively investigated the impacts of energy efficient technologies for refrigerated display cases, including defrost strategies, low emissivity shields, anti-sweat heater control, and display case design (RTTC n.d.) (RTTC n.d.) (RTTC 1997) (RTTC 1997) (Faramarzi, Coburn and Sarhadian 2000) (Sarhadian, et al. 2004) (Mitchell 2005) (Rauss, Mitchell and Faramarzi 2008). These reports provide

Tassou and Datta (1999) performed both field and laboratory investigations to quantify the effect of supermarket humidity on the frost accumulation on the evaporators of medium temperature vertical multi-deck display cases. For a supermarket located in Airdrie, UK, where the summertime store relative humidity ranged from 45% to 55% and the wintertime store relative humidity ranged from 22% to 25%, it was found that twice as much defrost condensate was collected from a multi-deck dairy display case in the summer as compared to the winter. Thus, the diary case studied at this supermarket theoretically required 50% fewer defrost cycles in the winter as compared to the summer.

In laboratory testing, Tassou and Datta (1999) found that for a medium temperature open display case, frost accumulation increased exponentially with increasing relative humidity. After a display case being studied had operated for a six hour period, 2.2 gallons (8.4 liters) of condensate were collected following a defrost cycle when the relative humidity was 65% while 1.7 gallons (6.3 liters) of condensate were collected at 45% relative humidity. Thus, a 23% reduction in condensate collection was observed when the relative humidity was reduced from 65% to 45%. On the other hand, condensate data presented by Faramarzi et al. (2000) exhibits a linear trend with relative humidity. They noted a 61.7% reduction in condensate collection from an open, medium temperature meat case when the relative humidity was reduced from 55% to 35%, while a 73.2% reduction in condensate collection occurred from an open, medium temperature dairy case when the relative humidity was reduced from 55% to 35%.

From the database review performed by Kosar and Dumitrescu (2005), it was found that if proactive measures were taken, then defrost electrical energy savings anywhere from 0% to 7.4% could be achieved by using temperature terminated electric defrost rather than time-terminated defrost in low-temperature display cases, if the store relative humidity was maintained at 35% rather than 55%.

Thus, it can be seen that the ambient conditions within the supermarket can greatly influence the frequency and duration of defrost cycles. Since these conditions are environmental and seasonal in nature, they cannot be strictly controlled by the supermarket operator. Thus, demand defrost strategies are required for the energy efficient operation of supermarket refrigeration systems.

Figure 1 shows the relationship between frost accumulation, air velocity and air pressure drop across an evaporator coil (Stoecker 1998). The data shown in Figure 1 is for an evaporator coil with a fin spacing of 4 fins per inch (1.6 fins per cm) and entering air conditions of 32°F (0°C) and 72% relative humidity. It can be seen that the pressure drop across the evaporator coil increases with increasing frost accumulation and with increasing air velocity. As frost accumulates on the evaporator coil, the size of the air passages through the coil are reduced, resulting in an increase in the pressure drop through the coil and an increase in the air velocity through coil. Thus, it has been suggested that defrost initiation can be based either on the increase in pressure drop across the evaporator or on the increase in air velocity through the evaporator, both of which accompany an increase in frost accumulation.

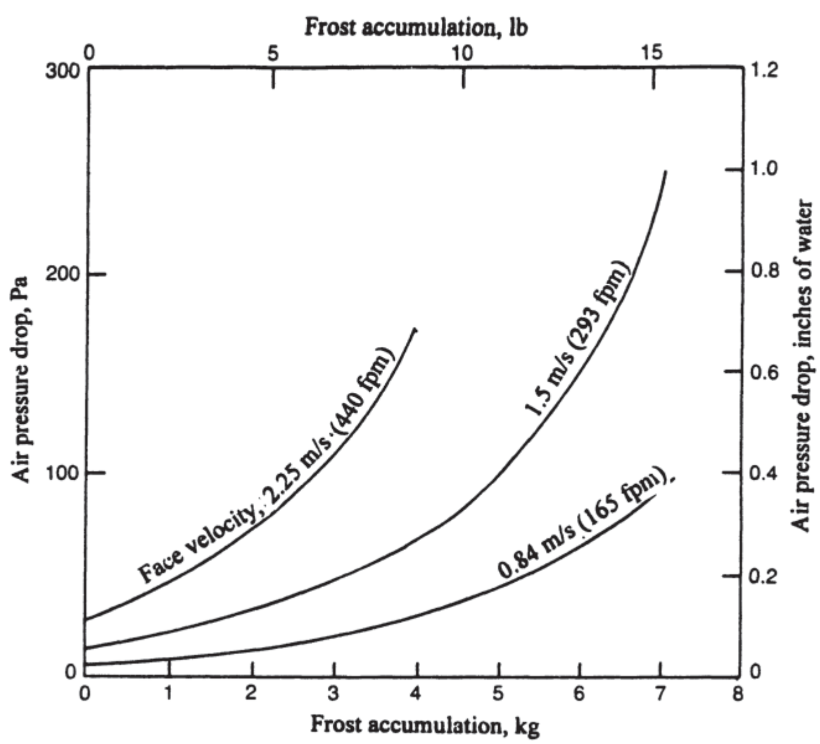

Figure 1. Effect of frost accumulation and air velocity on air pressure drop across an evaporator coil (Stoecker 1998).

5. Energy Use of Current Defrosting Strategies

In order to estimate the potential energy savings associated with implementing demand defrost strategies in supermarket refrigerated display cases, the energy consumption of the electric defrost systems for two types of frozen food display cases was determined. The display case types studied include following:

- Low temperature glass-doored reach-in case
- Low temperature coffin/island case

For each display case type listed above, the defrost strategy was identified and the energy consumption of the defrost strategy was obtained from manufacturers' data. Using this data, the energy required to melt the frost during one defrost cycle was determined. Next, the excess heat supplied by the defrost heater during one defrost cycle was estimated. Then, the energy required by the compressor to remove this excess heat was determined. Finally, the annual energy usage associated with the defrosting operation was calculated, which includes the direct electrical energy consumption of the electric defrost heater and the energy consumption of the compressor which is required to remove the excess defrost heat.

The energy consumption of defrost systems for medium temperature cases was not investigated since these types of cases typically employ off-cycle defrost. No significant energy consumption is associated with off-cycle defrosting. As previously noted, electric defrost heaters account for approximately 20% of the energy consumption of refrigerated display cases. However, in medium temperature applications, this energy could be saved through the use of off-cycle defrosting. Nevertheless, it should be noted that the energy consumption associated with off-cycle defrost is not equal to zero, since compressor and fan energy will be required to cool the display case and food products after each defrost cycle.

Low Temperature Glass-Doored Reach-In Case

The temperature and defrost specifications for a typical low temperature glass-doored reach-in case are as follows (Hussmann 2009):

- Evaporator temperature: -19°F (-28.3°C)
- Drain temperature: 41°F (5°C) (assumed)
- Rated display case load: 584 Btu/(hr·ft)
- Defrost water: 0.60 lb/(ft·day)
- Electric defrost power: 320 W/ft
- Suggested defrost schedule: one defrost per day, maximum of one hour in duration

First, the energy required to melt 0.60 lb/(ft·day) of frost, $\dot{Q}_{melt}$, is determined as follows:

$$\dot{Q}_{melt} = \dot{m}c_{p,f}\left(t_2 - t_1\right) + L_f\dot{m} + \dot{m}c_{p,u}\left(t_3 - t_2\right) \tag{1}$$

where $\dot{m}$ is the mass flow rate of water, $c_{p,f}$ is the specific heat of ice [0.502 Btu/(lb·°F) or 2.11 J/(g·°C)], $c_{p,u}$ is the specific heat of liquid water [1.00 Btu/(lb·°F) or 4.18 J/(g·°C)], L_f is the latent heat of fusion of water (144 Btu/lb or 334 J/g), t_1 is the initial temperature of the frost (-19°F or -28.3°C), t_2 is the freezing point of water (32°F or 0°C), and t_3 is the temperature of the condensate leaving the display case (41°F or 5°C). Thus, the energy required to melt 0.60 lb/(ft·day) of frost is 107 Btu/(day·ft) or 4.44 Btu/(hr·ft).

As specified by the display case manufacturer, the rate of heat supplied by the electric defrost heater is 320 W/ft or 1092 Btu/(hr·ft). Assuming that each defrost period is one hour in length, the defrost heater energy in excess of that required to melt the frost is:

$$q_{excess} = [1{,}092\ \mathrm{Btu/(hr \cdot ft)} - 4.44\ \mathrm{Btu/(hr \cdot ft)}]\left(\frac{1\ \mathrm{hr}}{\mathrm{defrost}}\right) = 1{,}088\ \mathrm{Btu/ft} \tag{2}$$

Since the defrost period is assumed to be one hour per day, the refrigeration system operates 23 hours per day. Thus, assuming that the excess heat, q_{excess}, must be removed by the refrigeration system over a 23 hour period, the additional heat load on the refrigeration system due to defrost, $\Delta\dot{Q}_{df}$, is:

$$\Delta\dot{Q}_{df} = \left(\frac{1{,}088\ \mathrm{Btu}}{\mathrm{ft}}\right)\left(\frac{1}{23\ \mathrm{hr}}\right) = 47.3\ \mathrm{Btu/(hr \cdot ft)} \tag{3}$$

Thus, the additional power required by the compressor, $\Delta\dot{W}_{comp}$, to overcome the heat added by the defrost can be estimated as follows:

$$\Delta\dot{W}_{comp} = \frac{\Delta\dot{Q}_{df}}{COP} \tag{4}$$

where $\Delta\dot{Q}_{df}$ is the additional heat added by defrost and *COP* is the coefficient of performance of the refrigeration system. The COP of the low temperature refrigeration system may be estimated using the procedure given in AHRI Standard 1200 (AHRI 2008). In this procedure, the adjusted dew point temperature of the low temperature refrigeration system is determined, which is 3°F (1.7°C) less than the rated evaporating temperature of the display case. In this instance, the adjusted dew point temperature would be −19°F − 3°F = −22°F. From AHRI Standard 1200, the coefficient of performance of the refrigeration system is estimated to be 1.96 (AHRI 2008). Thus, the additional power required by the compressor to remove the defrost heat is:

$$\Delta\dot{W}_{comp} = \frac{47.3\ \mathrm{Btu/(hr \cdot ft)}}{1.96} = 24.1\ \mathrm{Btu/(hr \cdot ft)} \tag{5}$$

Assuming that the compressor does not operate during the one hour defrost cycle, the additional annual energy consumption of the compressor which is required to remove the excess defrost heat is:

$$\Delta\dot{W}_{comp} = (24.1\ \mathrm{Btu/(hr \cdot ft)})\left(\frac{23\ \mathrm{operating\ hours}}{\mathrm{day}}\right)\left(\frac{365\ \mathrm{days}}{\mathrm{year}}\right) = 202{,}320\ \mathrm{Btu/(year \cdot ft)} \tag{6}$$

Thus, over the period of one year, the additional compressor energy consumption required to remove the excess defrost heat is estimated to be 59.3 kWh/(year·ft).

Assuming that each defrost period is one hour in length, the direct electrical energy consumed by the electrical defrost heater for one year is:

$$E_{df} = (320 \text{ W/ft})\left(\frac{1 \text{ hr}}{\text{defrost}}\right)\left(\frac{365 \text{ defrosts}}{\text{year}}\right) = 117 \text{ kWh/}(\text{year} \cdot \text{ft}) \tag{7}$$

Finally, the total electrical energy consumption for the electric defrost of a low temperature glass-doored reach-in case is estimated to be:

$$\begin{aligned} E_{total} &= E_{df} + \Delta \dot{W}_{comp} \\ &= 117 \text{ kWh/}(\text{year} \cdot \text{ft}) + 59.3 \text{ kWh/}(\text{year} \cdot \text{ft}) \\ &= 176 \text{ kWh/}(\text{year} \cdot \text{ft}) \end{aligned} \tag{8}$$

Thus, for the low temperature glass-doored reach-in case, it is estimated that the energy consumption associated with electrical defrost is 176 kWh/(year·ft). This energy consumption includes both the direct energy associated with operating the defrost heater and the energy consumed by the compressor to remove the excess defrost heat from the display case.

Low Temperature Coffin/Island Case

The temperature and defrost specifications for a typical low temperature coffin case are as follows (Hussmann 2010):

- Evaporator temperature: -20°F (-28.9°C)
- Drain temperature: 41°F (5°C) (assumed)
- Rated display case load: 550 Btu/(hr·ft)
- Defrost water: 1.7 lb/(ft·day)
- Electric defrost power: 455 W/ft
- Suggested defrost schedule: one defrost per day, maximum of one hour in duration

First, the energy required to melt 1.7 lb/(ft·day) of frost, $\dot{Q}_{melt}$, is determined as follows:

$$\dot{Q}_{melt} = \dot{m}c_{p,f}(t_2 - t_1) + L_f \dot{m} + \dot{m}c_{p,u}(t_3 - t_2) \tag{9}$$

where $\dot{m}$ is the mass flow rate of water, $c_{p,f}$ is the specific heat of ice [0.502 Btu/(lb·°F) or 2.11 J/(g·°C)], $c_{p,u}$ is the specific heat of liquid water [1.00 Btu/(lb·°F) or 4.18 J/(g·°C)], L_f is the latent heat of fusion of water (144 Btu/lb or 334 J/g), t_1 is the initial temperature of the frost (-19°F or -28.3°C), t_2 is the freezing point of water (32°F or 0°C), and t_3 is the temperature of the condensate leaving the display case (41°F or 5°C). Thus, the energy required to melt 1.7 lb/(ft·day) of frost is 308 Btu/(day·ft) or 12.8 Btu/(hr·ft).

As specified by the display case manufacturer, the rate of heat supplied by the electric defrost heater is 455 W/ft or 1553 Btu/(hr·ft). Assuming that each defrost period is one hour in length, the defrost heater energy in excess of that required to melt the frost is:

$$q_{excess} = [1{,}553\ \text{Btu/(hr} \cdot \text{ft)} - 12.8\ \text{Btu/(hr} \cdot \text{ft)}]\left(\frac{1\ \text{hr}}{\text{defrost}}\right) = 1{,}540\ \text{Btu/ft} \tag{10}$$

Since the defrost period is assumed to be one hour per day, the refrigeration system operates 23 hours per day. Thus, assuming that the excess heat, q_{excess}, must be removed by the refrigeration system over a 23 hour period, the additional heat load on the refrigeration system due to defrost, $\Delta\dot{Q}_{df}$, is:

$$\Delta\dot{Q}_{df} = \left(\frac{1{,}540\ \text{Btu}}{\text{ft}}\right)\left(\frac{1}{23\ \text{hr}}\right) = 67.0\ \text{Btu/(hr} \cdot \text{ft)} \tag{11}$$

Thus, the additional power required by the compressor, $\Delta\dot{W}_{comp}$, to overcome the heat added by the defrost can be estimated as follows:

$$\Delta\dot{W}_{comp} = \frac{\Delta\dot{Q}_{df}}{COP} \tag{12}$$

where $\Delta\dot{Q}_{df}$ is the additional heat added by defrost and *COP* is the coefficient of performance of the refrigeration system. Assuming that the coefficient of performance of the refrigeration system is 1.93, based on the procedures given in AHRI Standard 1200 (AHRI 2008), the additional power required by the compressor to remove the defrost heat is:

$$\Delta\dot{W}_{comp} = \frac{67.0\ \text{Btu/(hr} \cdot \text{ft)}}{1.93} = 34.7\ \text{Btu/(hr} \cdot \text{ft)} \tag{13}$$

Assuming that the compressor does not operate during the one hour defrost cycle, the additional annual energy consumption of the compressor which is required to remove the excess defrost heat is:

$$\Delta\dot{W}_{comp} = (34.7\ \text{Btu/(hr} \cdot \text{ft))}\left(\frac{23\ \text{operating hours}}{\text{day}}\right)\left(\frac{365\ \text{days}}{\text{year}}\right) = 291{,}307\ \text{Btu/(year} \cdot \text{ft)} \tag{14}$$

Thus, over the period of one year, the additional compressor energy consumption required to remove the excess defrost heat is estimated to be 85.4 kWh/(year·ft).

Assuming that each defrost period is one hour in length, the direct electrical energy consumed by the electrical defrost heater for one year is:

$$E_{df} = (455\ \text{W/ft})\left(\frac{1\ \text{hr}}{\text{defrost}}\right)\left(\frac{365\ \text{defrosts}}{\text{year}}\right) = 166\ \text{kWh/(year} \cdot \text{ft)} \tag{15}$$

Finally, the total electrical energy consumption for the electric defrost of a low temperature coffin case is estimated to be:

$$
\begin{aligned}
E_{total} &= E_{df} + \Delta \dot{W}_{comp} \\
&= 166 \text{ kWh/}(\text{year} \cdot \text{ft}) + 85.4 \text{ kWh/}(\text{year} \cdot \text{ft}) \\
&= 251 \text{ kWh/}(\text{year} \cdot \text{ft})
\end{aligned} \tag{16}
$$

Thus, for the low temperature coffin case, it is estimated that the energy consumption associated with electrical defrost is 251 kWh/(year·ft). This energy consumption includes both the direct energy associated with operating the defrost heater and the energy consumed by the compressor to remove the excess defrost heat from the display case.

The analysis performed above assumes that electric defrost is implemented in the refrigerated display cases. Laboratory testing has shown that the overall electrical energy use for hot gas defrost of low temperature refrigerated display cases can be less than 20% of that required by direct electric defrost (Palmer and Crompton 2003).

6. Defrost Control Strategies

The use of demand defrost strategies has been investigated in several applications including domestic refrigerators, heat pumps and commercial refrigerated display cases. The techniques to initiate and terminate defrost cycles which have been studied include the following:

- Time-temperature controlled defrost
- Air pressure differential or air flow rate across the evaporator
- Temperature difference between the air and the evaporating surface
- Air-side and refrigerant-side heat transfer comparison
- Refrigerant flow rate measurement
- Fan power measurement
- Optical or acoustic measurement of ice thickness
- Artificial intelligence-based defrost control systems.

A discussion of several of these demand defrost techniques is given below.

Time-Temperature Control

The most basic and commonly used defrost control strategy for supermarket applications is the timed defrost. The refrigerated display case evaporators are defrosted according to a predefined defrost schedule in which a timer both initiates and terminates the defrost cycle. Since this strategy is not based on the actual amount of frost present on the evaporator, it is possible that the defrost cycle is either insufficient in duration such that the frost is not completely removed during the defrost cycle or it is excessive in duration such that significantly more heating is supplied than that which is required to remove the frost.

The efficiency of the timed defrost strategy may be improved by using a temperature-controlled termination. In this technique, the defrost cycle is terminated when the evaporator temperature has reached a predetermined temperature, or when the defrost cycle has reached a predetermined duration, whichever occurs first. The temperature termination allows the defrost cycle to end earlier than that which would have occurred with only a timer. However, since the evaporator temperature is only used to terminate a defrost cycle, the possibility still exists that a defrost cycle will be initiated when none is required.

Time-Pressure Control

As an alternative to temperature-controlled termination, defrost may also be terminated based on pressure. In this technique, the defrost cycle is terminated when the evaporator pressure has reached a predetermined pressure deemed sufficient to melt all of the frost, or when the defrost cycle has reached a predetermined duration, whichever occurs first. The pressure termination allows the defrost cycle to end earlier than that which would have occurred with only a timer. However, since the evaporator pressure is only used to terminate a defrost cycle, the possibility still exists that a defrost cycle will be initiated when none is required.

Temperature Measurement

Borton and Walker (1993) discuss a demand defrost strategy that is based on the temperature difference between the display case discharge and return air. Their demand defrost controller measures the air curtain temperature at the outlet of the discharge and the inlet of the return to determine if defrost is needed. If the difference between these temperature measurements is greater than a predetermined set point for a sustained period of time, and a minimum amount of time has elapsed since the last defrost, then defrost is initiated. Furthermore, defrost is initiated if the elapsed time since the last defrost exceeds a specified maximum time between defrosts. The defrost cycle is terminated either on the basis of time or evaporator temperature (Borton and Walker 1991). The defrost controller was field tested in a supermarket with a sales area of 60,000 ft^2 (5,570 m^2), controlling the defrost of the low temperature display cases. Based on the results of the field testing at this supermarket, it was estimated that the demand defrost controller could reduce the annual energy consumption by 20,000 kWh for hot gas defrost systems and 62,000 kWh for electric defrost systems (including the energy savings of both the electric defrost heaters and the compressors).

Topper et al. (2001) describe a technique for demand defrost in which the air temperature within the refrigerated display case and the refrigerant temperature within the evaporator are measured. If the difference between the air temperature and the refrigerant temperature exceeds a predetermined threshold, then defrost is initiated. Since the rate of heat transfer between the air and the evaporator is reduced as ice builds up on the evaporator, the temperature of the air within the display case increases. Therefore, the temperature difference between the refrigerant and the air is indicative of frost formation on the evaporator. In the method described by Topper et al. (2001), a coefficient is used to modify the minimum temperature difference used to initiate defrost. For example, if doors are used on the display case, the time between defrost cycles may be extended if the frequency of door openings is low. Thus, the defrost threshold may be relaxed by modifying the value of the defrost coefficient.

Topper et al. suggested that the defrost cycle should be terminated based on refrigerant temperature exceeding a predetermined value or the defrost time exceeding a predetermined value (typically 45 minutes). The performance of this demand defrost system was not reported.

Airflow Measurement

Jarrett (1972) designed a fluid amplifier which can monitor the air pressure difference across the evaporator to detect the accumulation of frost on the evaporator and to initiate the defrost cycle. The fluid amplifier was tested in a domestic refrigerator, and it was shown that the device was capable of detecting the need for defrost based on the pressure difference across the evaporator. The original timed defrost controller installed in the domestic refrigerator initiated defrost every seven hours. With the fluid amplifier demand defrost controller, the interval between defrost cycles could be extended by three or four times that of the timed defrost interval when the door of the refrigerator or freezer was not opened and no loads were present within the refrigerator or freezer.

Hahn and Broyles (1968) utilized a technique in which the defrost cycle for a domestic refrigerator was initiated based on air-flow monitoring. Two separate and parallel air flow paths were created within the refrigerator: one air flow path contained the evaporator while the other air flow path (the reference channel) was clear of obstructions. The flow rate differential between these two flow paths was monitored by measuring the temperature of heated elements placed in each of the flow paths. As the air flow within the evaporator channel decreases due to frost formation, the temperature of the sensing element in the evaporator flow path increases. In addition, the air flow through the reference channel increases as the flow through the evaporator channel decreases. Thus, the temperature of the sensing element in the reference channel decreases. After a predetermined difference exists between the temperatures of the sensing elements, the defrost cycle is initiated. The defrost cycle is terminated when the temperature of the evaporator reaches a sufficiently high value to ensure that all the frost has been removed. Hahn and Broyles tested the demand defrost system in a domestic refrigerator both in the laboratory and in the field. They found that the system initiated defrost cycles as often as three times a day under high temperature and high humidity conditions, and as seldom as once in 15 days under low humidity and very low usage.

Humidity Measurement

Bell (1978) describes a humidity controlled technique used to initiate the defrost cycle for domestic refrigerator applications. A timing circuit was designed to vary the time between defrost cycles based upon the relative humidity in the refrigerated space. If the refrigerated space were maintained at 100% relative humidity, the time between defrosts was set to be 12 hours. As the relative humidity in the refrigerated space decreased, the time interval between defrosts increased. In experimental testing with a domestic refrigerator, it was found that the demand defrost system was capable of initiating defrost in 12 hours during severe usage and defrost could be delayed for several weeks under very light usage.

Refrigerant Mass Flow Rate

Lawrence (2004) and Lawrence and Evans (2008) describe a demand defrost technique in which the control system detects the variation in refrigerant flow through an evaporator to determine if defrost is needed. As frost builds on an evaporator, the amount of heat which can be removed by the evaporator decreases. When the frost accumulation has finally become too great, the thermostatic expansion valve which controls the flow of refrigerant through the evaporator is unable to maintain a stable flow of refrigerant through the evaporator. The expansion valve opens and closes rapidly, or "hunts", as it tries to maintain the proper superheat at the evaporator outlet. Lawrence and Evans developed an algorithm which determines the onset of this flow instability based on measuring the superheat at the exit of the evaporator.

The algorithm developed by Lawrence and Evans was tested in a laboratory setting using an 8.2 ft (2.5 m) low temperature coffin case with electric defrost. It was found that, on average, the demand defrost algorithm initiated defrost every 38.8 hours, whereas the display case manufacturer suggested that the case be defrosted every eight hours. Therefore, it was estimated that the annual defrost energy use of the 8.2 ft (2.5 m) coffin case, using the demand defrost algorithm, would be 538 kWh versus 1960 kWh for the standard defrost every 8 hours. This results in an electrical defrost energy savings of 73%.

Comparison of Air-Side and Refrigerant-Side Heat Transfer

Thybo et al. (2002) were able to determine the onset of evaporator icing in refrigerated display cases using a technique which compared the air-side and the refrigerant-side heat transfer. By measuring the temperature and pressure of the refrigerant entering and exiting the evaporator, as well as the refrigerant flow rate, the refrigerant-side heat transfer can be calculated. In addition, by measuring the temperature of air entering and exiting the evaporator, and using air flow rate data provided by the display case manufacturer, the air-side heat transfer can be calculated. Thybo et al. (2002) suggest that by monitoring the residual, i.e., the difference between the measured air-side heat transfer and the refrigerant-side heat transfer, faults in the refrigeration system can be detected. When the residual is significantly different than zero, then a fault has occurred in the refrigeration system. This methodology was tested on a coffin-type display case in a laboratory setting and it was found that it was possible to determine the onset of a refrigeration system fault such as evaporator coil icing or a malfunctioning evaporator fan.

Thermal Insulation Effect

Llewelyn (1984) briefly describes a demand defrost technique which is based on the thermal insulation effect of the frost layer. Two sensors are used in the system: one in intimate contact with the evaporator coil and one positioned in the outlet air stream from the evaporator. However, no information is provided on how the system operates or how well the system performs.

Optical Sensors

Paone and Rossi (1991) report on the use of fiber-optic sensors to determine ice thickness and to control the operation of the defrost cycle. Two types of fiber-optic sensors are discussed: reflection type sensors and transmission type sensors.

Reflection type sensors shine light on the ice surface and receive the reflected light from the ice surface. The intensity of the reflected light is proportional to the distance between the sensor and the ice surface. The output voltage of the sensor is proportional to the intensity of the reflected light, and thus, this voltage may be used to determine the distance between the sensor and ice surface, or the thickness of the ice. Reflection type sensors produce a continuous output between the minimum and maximum ice thickness. Reflection type sensors must be mounted perpendicular to the ice formation for proper operation.

Transmission type sensors consist of a separate light transmitting device and a light receiving device. The transmitter and receiver are mounted parallel to the evaporator surface and in line-of-sight of each other, at a certain distance above the evaporator surface. As ice grows, it eventually blocks the transmission of light from the transmitter to the receiver. The output voltage from the transmission type sensor is a step function indicating that the ice is either below or above the line-of-sight of the transducer and receiver.

Paone and Rossi (1991) noted that the output voltage of the reflection type sensor was strongly affected by the surface reflection coefficient of the ice surface. Since the ice surface may take on various textures depending on how the ice is formed, thereby leading to various surface reflection coefficients, uncertainties can exist in the measured ice thickness. On the other hand, the transmission type sensor generates an ON/OFF signal depending upon whether the ice has grown to a sufficient thickness to block the light traveling from the transmitter to the receiver. Thus, ice surface quality does not affect the output of a transmission type sensor.

During testing of a transmission type optical sensor in a domestic refrigeration application, Paone and Rossi (1991) noted that humidity condensed and ice formed on the lenses of the fiber-optic sensor heads. This could comprise the reliability of the sensor output. However, this problem was remedied by mounting a cylindrical duct on the fiber-optic head. The cylindrical duct reduced the convective motion near the sensor heads, allowing the humidity to diffuse along the length of the tube before it reached the sensor head. For the domestic refrigerator application, it was found that a duct of 4 mm in diameter and 30 mm in length was sufficient to eliminate ice formation on the sensor heads.

Paone and Rossi (1991) concluded that measuring ice thickness and controlling defrost cycles with a transmission type fiber-optic sensor was technically feasible in a domestic refrigeration application. However, the unit cost of the sensors, which was reported to be US$100 to US$150, would add substantially to the cost domestic refrigerators. Since the price of a typical domestic refrigerator can range from $400 to $800, an additional $100 to $150 for a transmission type fiber optic demand defrost sensor is economically unfeasible in that application. Furthermore, Paone and Rossi (1991) did not report on the long-term performance and reliability of the sensor in harsh environments such as that encountered in refrigerated display cases.

Byun et al. (Byun, et al. 2006) have investigated the use of photo-couplers to detect frost build-up on the evaporator coils of heat pumps. In their laboratory study, the evaporator coil was divided into nine zones and an infrared emitter and receiver were placed in the center of each of the nine zones, between the evaporator fins. Multiple photo-couplers were employed across the face of the evaporator to accurately detect the initiation and propagation of frost.

As compared to the standard timed defrost cycle, Byun et al. found that the photo-coupler defrost system increased the heating period of the heat pump by 7% to 9%. In addition, the defrosting period was reduced by 18% to 74% using the photo-coupler defrost system. While Byun et al. note that the photo-coupler defrost system was effective in laboratory studies, the system was not tested extensively in the field to determine its reliability.

Wang et al. (2010) describe the use of a micro-camera and image processing technology to determine the thickness of frost on a cold surface. The accuracy of the microscopic image system was reported to be 0.01 mm. The system was laboratory-based, and not optimized for field or commercial use.

Xiao et al. (2009) and Xiao et al. (2010) characterize the performance of a photoelectric device for determining frost layer thickness. It was found that the photoelectric device could accurately estimate frost height. A defrost control strategy was suggested, based on the use of photoelectric technology. While the system was effective in laboratory studies, the system was not tested extensively in the field to determine its reliability.

The Refrigeration and Thermal Test Center at Southern California Edison has tested an optical demand defrost technology in a medium temperature open vertical refrigerated display case (Mitchell 2005). The technology consists of a light emitting diode (LED) which transmits light through a fiber optic cable. The light output from the fiber optic cable is focused on a lens which reflects light back to the fiber optic cable. The lens is mounted near the fins of an evaporator so that frost accumulates on the lens, coincident with frost formation on the evaporator. The frost accumulation on the lens affects the amount of light which is reflected back to the fiber optic cable and when the intensity of the reflected light reaches a preset threshold, a defrost cycle can be initiated. During testing, it was noted that water droplet adhesion on the optical detector caused the optical demand defrost system to erratically initiate defrost cycles. In addition, at one point during testing, the defrost system failed to initiate defrost when the entire evaporator was frosted. Finally, the optical demand defrost system was unable to maintain the temperature within the refrigerated display case below acceptable levels. Thus, RTTC concluded that the optical demand defrost system was not reliable for supermarket refrigeration applications.

A commercially available optical frost sensor is available, shown in Figure 2 (New Avionics Corporation 2011). It is claimed that this device is capable of detecting various types of moisture including ice, snow, frost and condensation based upon optical opacity and optical refraction via its 3 mm diameter optical probe. An optional heating element to de-ice the optical sensor is available. The optical sensor is placed between any two evaporator fins to determine when the evaporator has frosted. The device then generates a control signal which is used by the refrigeration system to initiate a defrost cycle.

Figure 2. Commercially available optical ice sensor (New Avionics Corporation 2011).

Artificial Intelligence

Allard and Heinzen (1981) (1988) propose a demand defrost technique in which the time required to defrost the coil is monitored and the time periods between defrosting are adjusted accordingly. If the actual defrost time is shorter than a predetermined optimal time, then not enough frost was allowed to accumulate on the evaporator. Thus, the defrost controller increases the amount of time between successive defrost periods so that more frost will accumulate. On the other hand, if the actual defrost time is longer than the predetermined optimal time, too much frost accumulated on the evaporator. Thus, the defrost controller decreases the amount of time between successive defrost periods. The demand defrost controller was field tested in a domestic refrigerator and it was found that over an extended period of time, the controller had reduced the frequency of defrost by nearly a factor of four.

Working with Johnson Controls/Encore, EPRI developed a proprietary defrost control algorithm for refrigerated display cases that learns continuously from the current defrost behavior to schedule the next defrost (Hindmond and Henderson 1998). The method is sensorless and uses the computing power of the energy management system to perform the defrost scheduling calculations. Thus, new sensors are not required to be installed to use this system.

The demand defrost technology developed by Hindmond and Henderson was field-tested at two supermarkets. One supermarket, located in New Jersey, had a plan area of 33,000 ft^2 (3,070 m^2) and included 244 linear feet (74 m) of display cases and 863 ft^2 (80 m^2) of walk-in freezers serviced by a total of 123 kW of electric defrost. The remainder of the display cases and walk-ins at the New Jersey supermarket used off-cycle defrost. The other supermarket, located in Florida, had a plan area of 26,000 ft^2 (2,420 m^2) and included 236 linear feet (72 m) of display case and 1,705 ft^2 (158 m^2) of walk-ins serviced by hot gas defrost. The remainder of the display cases (160 ft or 49 m) and walk-ins (932 ft^2 or 87 m^2) at the Florida supermarket used off-cycle defrost.

At the New Jersey supermarket, the Hindmond and Henderson demand defrost controller was able to increase the time between defrosts from one day to three days. The electric defrost heater operation was reduced by 63% on average. It was estimated that if the demand defrost controller were installed on all the electric defrost cases in the supermarket, the total direct energy savings would be 25,000 kWh per year. By including the indirect savings associated with compressor energy use, the total savings was estimated to 38,000 kWh per year.

The results presented for the Florida supermarket were mixed. Hindmond and Henderson noted that a majority, but not all, refrigerated display case zones exhibited the expected behavior that defrost operation increases with increasing relative humidity. It was noted that perhaps the method of defrost termination, which was based on analog temperature sensors, was either not functioning properly or not optimally configured. Thus, additional testing of the demand defrost controller was planned to be performed at the Florida supermarket.

Datta and Tassou (2002) developed a demand defrost controller for refrigerated display cases based on artificial intelligence and inexpensive sensors such as temperature probes and a timer. Based on laboratory experiments performed on a medium temperature, multi-deck display case, Datta and Tassou found that the velocity of the air exiting the evaporator coil was the best indicator of frost accumulation on the coil. The velocity of the exiting air was found to decrease with increasing frost accumulation. In addition, Datta and Tassou found that the evaporator temperature as well as the entering and exiting air temperature at the evaporator decreased with increasing frost accumulation.

Datta and Tassou noted that robust velocity probes, such as hot-wire anemometers, are very expensive and thus are not feasible for use in demand defrost controllers for refrigerated display cases. Therefore, they proposed to use the ambient temperature and relative humidity, evaporator temperature, entering and exiting air temperature at the evaporator and the time between defrosts to as input to an artificial intelligence based demand defrost controller. While these quantities are not as good a predictor of frost accumulation as is the velocity of the air exiting the evaporator, the sensors for measuring these quantities are much less expensive.

Using a Multi-Layered Perceptron (MLP) artificial neural network model, a demand defrost controller was developed and tested in a laboratory setting. It was found that the demand defrost controller produced a defrost energy savings of 25% for ambient space conditions of 72°F (22°C) and 55% RH. In addition, defrost energy savings of 50% were achieved for ambient space conditions of 72°F (22°C) and 35% RH. For the medium temperature, multi-deck case studied, the number of defrost cycles per day was reduced from four at 72°F (22°C) and 65% RH to three at 72°F (22°C) and 45% RH, and to 2 at 72°F (22°C) and 35% RH. Furthermore, it was found that demand defrost had no adverse effect on product temperature as compared to timed defrost.

While the technique was successful in the laboratory, Datta and Tassou did not investigate the effectiveness of the demand defrost controller in a supermarket setting. They noted that other controllers, which are dependent on ambient space temperature and relative humidity, are being investigated for implementation in refrigerated display cases.

Other

For domestic refrigeration applications, Knoop et al. (1988) developed a methodology to estimate the time interval between defrosts based on the number and duration of refrigerator door openings. In this method, door openings and their duration are monitored. Then, a new time between defrosts is calculated based on the door opening duration times and the compressor run time. It was found that this technique could vary the defrost interval from 19 hours to 152 hours.

Bejan et al. (1994) derived theoretical equations to determine the optimal on/off sequence for operating a domestic refrigerator and its defrost system. These equations provide a means to theoretically determine the minimal power required by the refrigerator, while maintaining the prescribed temperature of the cold space and removing the frost build-up.

Verma et al. (2002) describe various design strategies which could be used to reduce the performance degradation due to frosting of display case evaporators. They show that the interval between defrosts could be dramatically increased by using variable speed evaporator fans to maintain constant airflow over the evaporator. In addition, fin staging was also shown to result in significant performance improvements, particularly at low air velocities and high inlet humidities where most of the frosting occurs near the front of the evaporator.

Liu et al. (2006) describe the use of an anti-frosting paint to effectively retard frost nucleation and decrease frost deposition rate on cold surfaces. For low air relative humidity, less than 60%, and cold surface temperature of 14°F (−10°C), the coated surface remained frost-free for over 3 hours while the uncoated surface was completely covered by a dense and thick layer of frost. While this technique does not eliminate frost formation, it does delay the formation of frost, thus potentially lengthening the duration between defrost cycles.

7. Discussion

The most common defrost methods used in supermarket applications each have their own advantages and disadvantages. Off-cycle defrost requires the least amount of energy to operate but it is limited in use to only medium or high temperature refrigerated display cases. In addition, the cost of implementation for off-cycle defrost is very low. Electric defrost has low initial cost, but the operating cost is relatively high. However, approximately 1% or more of the heat generated by the electric defrost heaters goes into melting the frost while the remaining excess heat is transferred to the air and food products within the display case. Compared to off-cycle and electric defrost, hot gas defrost can quickly defrost low and medium temperature display case evaporators. However, hot gas defrost can potentially damage refrigerant piping and evaporators through thermal shock. In addition, hot gas defrost has high installation costs, but its operating costs are lower than that of electric defrost. To minimize the impact of thermal shock associated with hot gas defrost, warm liquid defrosting or cool vapor defrosting may be used. However, these methods are not commonly used in supermarket applications.

Energy Use of Current Defrosting Strategies

The energy use associated with electric defrosting of low temperature reach-in display cases and low temperature coffin cases was estimated assuming that a timed initiation/termination defrost strategy was utilized. These energy estimates include the direct electrical energy consumption of the electric defrost heater as well as the additional energy consumption of the compressor which is required to remove the excess defrost heat. It was found that the electrical energy consumption associated with the electrical defrost of low temperature reach-in cases was 176 kWh/(year·ft). Furthermore, the electrical energy consumption associated with the electrical defrost of low temperature coffin cases was estimated to be 251 kWh/(year·ft).

Assuming that a typical 45,000 ft^2 supermarket contains 268 ft of low temperature reach-in cases and 128 ft of coffin cases (Westphalen, et al. 1996), the total electrical energy consumption associated with the electrical defrosting of these display cases would be approximately 79,300 kWh/year. Implementation of demand defrost strategies for refrigerated display cases has been reported to reduce defrost heater operation by 50% to 73% (Tassou and Datta 1999) (Lawrence and Evans 2008) (Hindmond and Henderson 1998). Thus, for a typical 45,000 ft^2 supermarket, the total annual electrical energy savings realized from the implementation of demand defrost would be between 39,650 kWh and 57,900 kWh. This agrees well with field data presented by Hindmond and Henderson (1998), in which they reported an estimated annual electrical energy savings of 38,000 kWh for a 33,000 ft^2 supermarket which implemented demand defrost.

Assuming an average cost of $0.103 per kWh for electricity (EIA 2011), the typical 45,000 ft^2 supermarket could save between $4,080 to $5,960 annually in electrical energy costs by implementing a demand defrost strategy for low temperature display cases. For a similar supermarket equipped with hot gas defrost, the savings is anticipated to be less than half of these values, and in fact, according to Palmer and Crompton (2003), could perhaps be less than 20% of these values.

Analysis of Defrost Control Strategies

A variety of defrost initiation and termination schemes have been developed for commercial and domestic refrigeration applications. Most of these demand defrost techniques lack the robustness required for supermarket environments and the systems are difficult to service and maintain. A successful demand defrost system for refrigerated display cases would be easy to install and maintain and would make use of simple, low-cost, robust sensors and controllers.

Time-Temperature Control

While it is not energy efficient, the timed initiation/termination defrost control strategy is most often used in supermarket applications because it has the lowest first cost as well as being simple, robust and easy to maintain.

Temperature Measurement

Demand defrost strategies based on the measurement of evaporator air inlet and outlet temperatures require the use of simple, durable temperature sensors. Since at a minimum, only two sensors are required, it is expect that these sensors can be easily installed within a refrigerated display case. Maintenance of these sensors would be minimal, however, sensor replacement may be difficult.

Airflow Measurement

The measurement of airflow requires relatively complex airflow sensors which may not be sufficiently robust for application in refrigerated display cases. The long-term reliability and durability of airflow sensors is expected to be low.

Humidity Measurement

Fluctuations in domestic refrigerator humidity levels are expected to be low and the overall humidity level would be relatively uniform with time, since, in domestic refrigeration applications, the frequency of usage and door openings is relatively low compared to that of commercial refrigerated display cases. Thus, demand defrost methods based on humidity measurement may work well only in low-use domestic refrigeration applications. Furthermore, the slow response time and relatively low accuracy, particularly at high humidity levels, of inexpensive humidity sensors may not provide reliable control in the high humidity environment of refrigerated display cases. However, the current trend in better humidity control within supermarkets, particularly in the areas near the refrigerated display cases, may be sufficient to overcome the weaknesses of humidity-based demand defrost strategies.

Refrigerant Mass Flow

Estimation of the stability of refrigerant flow through an evaporator, based on the measurement of superheat at the evaporator outlet, requires the use of a simple, durable temperature sensor. However, the temperature data must be analyzed by a control module to determine the onset of flow instability. This control module will increase the initial cost of this demand defrost system and may require training for proper installation and operation.

Comparison of Air-side and Refrigerant-Side Heat Transfer

The technique proposed by Thybo et al. (2002) to determine the onset of refrigeration system faults by comparing the heat transfer on the refrigerant and air sides of the evaporator requires multiple temperature and pressure sensors, as well as mass flow sensors. The installation and maintenance of these sensors would be difficult. In addition, a control module would be required to process the data. Thus, the initial cost of this system would be high. Due to the complexity of the system, the long-term reliability of the system would be low.

Defrost strategies based on simpler air-side heat transfer measurements could be feasible in commercial refrigeration applications. In a simpler system, a heat flux sensor coupled with temperature sensors that measure air temperature and evaporator fin temperature could be used to determine the thermal resistance of the frost layer as it develops on the evaporator surface. A sufficiently high thermal resistance could then be used to initiate a defrost cycle. The required temperature and heat flux sensors would be inexpensive and could be incorporated into an easily-installable device which mounts on the evaporator.

Optical Sensors

Optical sensors can accurately determine the quantity of frost accumulated on an evaporator in a specific location. However, multiple optical sensors would be required to accurately determine the accumulation of frost over the entire evaporator. The durability of the optical sensors is expected to be low in refrigerated display case applications. In addition, if multiple optical sensors are used, the complexity of the system would be high and the long-term reliability of the system would be low. As noted by the RTTC during testing of an optical demand defrost system, the failure of the system in a relatively clean laboratory environment casts doubt on the system’s ability to perform in a “dirty” supermarket environment (Mitchell 2005). If manufacturers’ were to overcome the reliability issues associated with optical demand defrost methods, it could be reasonably expected that optical sensors using LEDs, along with modern electronics, could be used to produce a low cost and commercially viable demand defrost system.

Artificial Intelligence

The success of an artificial intelligence based demand defrost strategy depends upon the complexity of the system. Rather complex artificial intelligence based demand defrost systems, such as that suggested by Datta and Tassou (2002), which require the use of several temperature and humidity sensors as well as a control module which analyzes the collected data, may not be commercially viable. The installation and maintenance of the numerous sensors would be difficult. In addition, the initial cost of the system would be high. Due to the complexity of the system, the long-term reliability of the system would be low. Refrigeration system installers and supermarket personnel may require training to properly install and operate this type of defrost system.

However, simpler artificial intelligence based defrost strategies which modify the time between cycles based on the duration of previous defrost cycles, such as that used by Hindmond and Henderson (1998), require only a control module which performs the required calculations and initiates and terminates defrost using a simple, durable temperature sensor. The temperature sensor and electronic controls for such a system are not inherently more complex than that required for simple time/temperature-termination defrost and they could conceivably be used to produce a low cost and commercial viable demand defrost system.

Summary

The most basic and commonly used defrost control strategy for supermarket applications is the timed defrost. The refrigerated display case evaporators are defrosted according to a predefined defrost schedule in which a timer both initiates and terminates the defrost cycle. Since this strategy is not based on the actual amount of frost present on the evaporator, it is possible that the defrost cycle is either insufficient in duration such that the frost is not completely removed during the defrost cycle or it is excessive in duration such that significantly more heating is supplied than that which is required to remove the frost.

In an effort to reduce the energy consumption and detrimental effects associated with timed defrost, the use of demand defrost has been attempted in supermarket refrigeration applications with little reported success. The demand defrost technologies have thus far been found to be unreliable in the rough environments found within refrigerated display cases. It has also been noted that demand defrost tends to work well when the display case and defrost system are new, however, over time, the case and the defrost sensor become dirty and the defrost system fails to work correctly.

Given the success of modern demand defrost controls in residential heat pumps and air-conditioners, it would appear that these technologies could be adapted to commercial refrigeration applications in an effort to reduce energy consumption associated with defrost. Demand defrost strategies applicable to supermarket refrigeration that appear to be robust, easy to install and low cost include air-side heat transfer measurement methods, optical sensor-based methods, and artificial-intelligence based methods. These methods make use of inexpensive and robust sensors (temperature sensors, heat flux sensors, LED optical sensors) and the required control electronics would be relatively straightforward to develop, resulting in a low cost defrost system. Nevertheless, at a minimum, it is suggested that refrigerated display cases should incorporate defrost controls which consist of timed initiation with temperature termination.

8. Next Steps

With input from Retail Energy Alliance members, a preferred defrost strategy will be identified and, based on this strategy, a demand defrost system suitable for supermarket refrigerated display cases will be designed. Limited field testing of the preferred defrost strategy will be performed in a supermarket environment.

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