# Efficient Refrigerated Display Cases - Can They Flex Their Power?

## Preprint

Grant Wheeler,[1] Omkar Ghatpande,[1] Ramin Faramarzi,[1] Alexander Bulk,[1] Juan Catano Montoya,[2] Diane Patrizio,[2] Frank Wallis,[2] Don Wiesmann,[2] Robert Nash,[2] and Suresh Shivashankar[2]

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# Efficient Refrigerated Display Cases – Can They Flex Their Power?

*Grant Wheeler, Omkar Ghatpande, Ramin Faramarzi, and Alexander Bulk, National Renewable Energy Laboratory*
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**ABSTRACT**

There is a growing need for effective and reliable demand reduction in buildings. Assets within commercial buildings that can shed and shift load during critical peak periods could benefit both utilities and building owners. Refrigerated display cases are widely used energy-intense critical equipment in supermarkets that could be leveraged for demand reduction. The National Renewable Energy Laboratory (NREL) previously demonstrated that refrigerated cases could provide up to 20 kW of demand reduction in a supermarket with simple controls leveraging the product thermal inertia. NREL further estimated the supermarket could reach 60 kW of demand reduction if medium-temperature cases could be leveraged, but those cases were not used due to concern from the supermarket owner and lack of control capabilities. This study addresses this key barrier by developing, integrating, and evaluating load shedding and shifting controls into a high-efficiency medium-temperature open vertical display case (OVDC).

This study shows that a medium-temperature OVDC, with some of the tightest tolerances for product temperatures, could reduce demand by 35% through permanent energy conserving measures. Load shift strategies could further reduce 42% load for 30 minutes and 30% load for 120 minutes temporarily while still maintaining product temperature. Strategies that did not leverage product temperature accounted for 6%–9% reduction in demand and were unaffected by duration. Although defrost control and pre-cooling minimally affected demand reduction, they are critical strategies to maintain product temperature.

## Introduction

Supermarkets can be a great resource for demand flexibility because of their high energy intensity (EIA 2012) and their pre-existing communication, monitoring, and control systems that can be leveraged. In a previous study (Deru 2016), the National Renewable Energy Laboratory (NREL) evaluated the potential of commercial refrigeration to provide demand reduction in an actual 45,591-ft$^2$ supermarket. This previous study estimated that an average supermarket could reduce power consumption by 60 kW for up to 2 hours by adjusting case discharge air temperature and the compressor lift. This study furthermore demonstrated 15 to 20 kW demand reductions were possible with only low-temperature non-ice cream cases. They determined that future research to develop and assess controls to enable medium-temperature cases to participate in demand response events was needed to realize the load flexibility potential of supermarkets.

This research focused on developing and assessing the impact of various load shed and shift strategies in medium-temperature open vertical display cases (OVDC), which have a larger presence in supermarkets and higher temperature vulnerability than low-temperature non-ice cream cases. Self-contained refrigerator cases feature all the components to cool products and dissipate heat in a single package. Likewise, an OVDC has some of the most stringent constraints for product temperature due to the large amount of infiltration. Evaluating a self-contained OVDC offers an opportunity for researchers to develop the most robust load flexibility controls for refrigerated cases.

The strategies included permanent demand reduction strategies through energy conserving measures (ECMs) as well as load shed and shift strategies that temporarily adjusted the case operation to reduce power consumption. The baseline self-contained OVDC was evaluated in a controlled environmental chamber using a modified version of the ANSI/ASHRAE Standard 72-2018 and FDA 2017 as guidelines (ANSI 2018; FDA 2017). The baseline OVDC was retrofitted with a novel-liquid-cooled condensing unit equipped with a variable compressor, electronic expansion valve, and advanced controls. These permanent ECMs were assessed in the same environmental chamber over 24 hours. Although the ECM results are highlighted in this study, a more detailed technical report is also available focusing only on the permanent ECM (Bulk 2022). This study further expanded on the permanent demand reduction strategies by developing, integrating, and assessing temporary load shed and shift strategies that leveraged the product thermal inertia and advanced controls to reduce demand for 30–120 minutes in the same medium-temperature OVDC.

## Test Hardware Description

### Refrigerated Display Case

The OVDC evaluated and shown in Figure 1 was an 8-foot long, 5-deck/4-shelf, open display merchandiser of standard type and model used in convenience store, supermarket, and restaurant markets.

Figure 1. Image of the refrigerator display case. *Photo by Alexander Bulk.*

The OVDC dimensions were 99.3 x 45 x 89.4 inches. The case had four shelves that were 96 inches long and 22 inches deep. Figure 1 also shows the case filled with “product.” Rather than use real product that is perishable, the team followed Ref: Bulk (2022) and used bottles of water for thermal inertia and “product simulators” to estimate the product core temperature. This case was retrofitted for the baseline and ECM with two different condensing units as shown in Figure 2. Table 1 further describes the physical hardware for the baseline and ECM. While the baseline system featured simple components and controls, the ECM contained the most advanced features found in a self-contained case.

Table 1. Baseline and ECM hardware

| Description | Baseline Case Hardware | Energy Efficient Case Hardware |
|---|---|---|
| Case Part Number | ORMC82MH | ORMC82MH |
| Condenser Type | Air-cooled fin-and-tube | Liquid-cooled coaxial tube with liquid control valve to regulate temperature across the condenser |
| Compressor Type | Fixed speed scroll | Variable speed scroll |
| Expansion Valve | Thermal | Electronic |
| Refrigerant | R-448A | R-448A |
| Rated Cooling [Btu/h] | 5,393 | 2,010 – 6,700 |
| Compressor Control | On-off cycling | Variable frequency drive |

Figure 2. Baseline air-cooled condenser (left) and high-efficiency liquid-cooled energy conserving condenser (right). *Photos by Alexander Bulk.*

**Experimental Setup/Instrumentation**

The OVDC was placed in a walk-in environmental chamber to ensure zone conditions including dry-bulb and dew-point temperatures as well as airflow across the front of the case were controlled. Table 2 shows the control points as well as the standard deviation across all experiments for each control point.

Table 2. Environmental and condenser conditions for all experiments

| Measurement | Target Control Value | Average Control Value | Standard Deviation |
|---|---|---|---|
| Zone Dry-Bulb Temperature [°F] | 75.2 | 74.9 | 0.59 |
| Zone Dew Point Temperature [°F] | 59.8 | 59.6 | 1.1 |
| Baseline Condenser Inlet Dry-Bulb Temperature [°F]* | 75.2 | 78.2 | 1.5 |
| Liquid Condenser Inlet Temperature [°F] | 80 | 79.5 | 0.8 |
| Velocity in Front of Case [fpm]** | ≤49 | ≤49 | NA** |

*Instantaneous measurements were all below 49 fpm.

Air temperatures and airflow requirements in the chamber followed a modified version of ANSI/ASHRAE Standard 72-2018 (ANSI 2018). Table 2 also reports the condenser inlet temperatures. The goal for the air-cooled baseline case was to match the zone temperature with the condenser inlet temperature. The zone temperature was cooler because it was affected by the cool air at the front of the case. NREL tried several different configurations in the chamber to minimize the difference between condenser inlet and zone temperature. Condenser inlet temperature for the liquid-cooled ECM was maintained at 80°F based on the guidance of Ref: Bulk (2022). Revenue-grade power meters were used to measure electrical power for the case input and subcomponents such as the compressor, condenser fan, evaporator fans, lighting, and baseline controller. The flowrate and pressure at the condenser were used to calculate hydraulic power. Condensate mass was measured throughout each experiment to verify equivalent latent conditions in the chamber. Measurements for evaporator superheat, compressor subcooling temperature differentials, or pump hydraulic power were calculated by the equations listed in Ref: Bulk (2022). The estimated condenser pump power was calculated from the hydraulic power assuming an 80% pump efficiency. Table 3 summarizes the various sensors used to measure performance of the OVDC.

Table 3. Sensors for measuring the OVDC performance

| Measurement Type | Quantity | Sensor Type |
|---|---|---|
| Product Simulator | 18 | 1/16" Type-T thermocouple probes |
| Internal Air Temp | 6 | Type-T surface temperature thermocouple |
| Component Temperatures | 7 | |
| Chamber Dry Bulb | 1 | |
| Refrigerant Temperatures | 7 | |
| Power Measurements | 6 | Revenue grade power meter, with split core current transformer |
| Refrigerant Pressure | 2 | 0 – 1,000 PSIG multimedia pressure transducer |
| Condensate Mass | 1 | 24"x24", 500 lb. capacity floor scale |
| Liquid-Loop Mass Flowrate | 1 | Coriolis meter |
| Chamber Dew-Point Temperature | 1 | Chilled-mirror dew-point hygrometer |

## Methodology

### Load Flexibility Strategies

This study attempted to leverage the advanced controls within the ECM to integrate load flexibility strategies into the same controller. In this study, "energy event" is defined as any time period when the case implements load flexibility strategies to respond to a request to shed or shift the load. Four advanced load shedding and shifting control strategies were developed, implemented, and evaluated in the local case controller to adjust load during an energy event. These strategies included:

**Strategy 1: Lighting Control**

The lighting control algorithm manages the case light operation and can turn off the lights when requested during an energy event. The lights will remain "off" until:

- The event timer has expired
- The digital input triggering the event is no longer present
- An alarm forces the case out of the event.

**Strategy 2: Reset Discharge Air Temperature Setpoint Control**

During the energy event, the algorithm can increase the setpoint to shed load and decrease the setpoint to pre-cool compared to the user-defined setpoint value. The energy event setpoint will be the new case setpoint during the event period. Once the energy event terminates, the discharge air temperature setpoint returns to the user-defined setpoint value. The algorithm also integrates alarms for extreme case air temperature limits, refrigerant pressures, and other standard sensor alarms to quit the energy event. The interface has an option for the user to modify the case air temperature limit alarms, and we had a default value of ±6°F during our experiments.

**Strategy 3: Reset Condenser Temperature Difference (TD) Setpoint Control**

A unique feature of the liquid-cooled condensing unit is the ability to adjust the conditions of the rejected heat loop in the water-cooled condenser. TD is defined as the temperature difference between the saturated condensing temperature and the inlet liquid temperature. Water flow rate is controlled to maintain the target TD by regulating a water valve. The manufacturer default TD is set to 25°F to balance efficient heat transfer with liquid flowrate. For this particular liquid-loop setup, we evaluated the net power saving potential by reducing the TD setpoint to 15°F during a load-shedding event. This effectively reduced the saturated condensing temperature as the inlet liquid temperature remained constant throughout all experiments. This algorithm also monitors critical system parameters and alarms to exit the energy event to avoid critical system failure.

**Strategy 4: Defrost Control**

While advanced defrost control did not directly affect power consumption during an energy event, it was critical in maintaining product temperature after an energy event. For load flexibility experiments, defrost control was terminated via a temperature sensor, reducing the average defrost duration from 32 minutes to 20 minutes for all load flexibility experiments. Furthermore, the algorithm also skipped a defrost cycle immediately following a load shed event. This was because the load shed events turned off the compressor for a small duration and maintained the evaporator coil temperature above freezing, removing any ice on the coil.

**Energy Efficiency Experiments**

Energy efficiency experiments were conducted to substantiate savings due to the ECM. The environmental conditions were controlled based on ANSI/ASHRAE Standard 72-2018 guidelines. Furthermore, the discharge air temperature setpoint was adjusted to match the average product simulator temperatures for the baseline and ECM. The final setpoint used for the baseline condensing unit was 34°F, and for the ECM was 33°F. Total and component power was collected across a 24-hour test period initiated by a defrost cycle. Daily energy consumption was calculated by integrating power data over each 24-hour test period.

## Load Flexibility Experiments

The load flexibility strategies were developed for load shedding and load shifting, which included pre-cooling before shedding load. The purpose of pre-cooling was to store energy within the product to improve demand reduction performance and protect product temperature. While pre-cooling can occur hours before a load shed event, this study only looked at load shift events where the pre-cooling and load shed were coincident. Table 4 shows the parameter ranges for the load flexibility experiments.

Table 4. Parameter ranges for load flexibility experiments

| **Load Flexibility Experiments** | | **Test Duration [min]** | **Discharge Air Temperature Setpoint [°F]** | **Condenser TD Setpoint [°F]** | **Light Status** | **Defrost Termination Method** | **Strategies** |
|---|---|---|---|---|---|---|---|
| Baseline | | 1,440 | 33 | 25 | On | Time | NA |
| Load Shed | | 30 – 120 | 38 | 15 | Off | Temperature | All |
| Pre-Cool | | 30 – 120 | 28 – 30 | 25 | On | | DAT Setpoint |
| Load Shift | Pre-Cool | 60 | 28 | 25 | On | | DAT Setpoint |
| | Shed | 30 – 120 | 38 | 15 | Off | | All |

Load flexibility experiments were conducted for durations of 30, 60, and 120 minutes. The maximum shed allowed was 120 minutes based on the results from Deru (2016).

The baseline and ECM experiments had cycles between defrost that provided similar trends for power consumption as well as product temperature. The product simulators reached a minimum temperature either within the first 10 minutes of the cycle or at the very end of the cycle and reached a maximum temperature around 90 minutes into each cycle. Based on this analysis of the cycles for the baseline and ECM experiments, the team decided to initiate load flexibility events 120 minutes after defrost initiation to ensure product temperature was not at the maximum value. All events were initiated at the same time to create comparable results. As load shift was a combination of pre-cooling and shed events, durations had to be determined for both the pre-cooling and shed event. Based on the experiments for pre-cooling, each pre-cooling event duration was set to 60 minutes by reducing the setpoint by 5°F. This was because the 60-minute pre-cooling experiment changed the average product temperature (and therefore stored energy in the product) without hitting the lower product temperature limit. The durations of the load shift events were 90, 120, and 180 minutes, including a 60-minute pre-cooling event followed by 30- to 120-minute load shed events. Each load flexibility experiment was recorded for a cycle before and after the event occurred. Condenser inlet temperature was maintained at 80°F, and all other experimental conditions followed the procedure used for the baseline and ECM experiments.

It was difficult to isolate the effect of the condenser TD setpoint control and the setpoint algorithm during experimentation. Therefore, a separate experiment was conducted to individually evaluate the condenser load flexibility shed strategy.

## Results

Figure 3 shows power consumption of the baseline, ECM, and two of the ten load flexibility experiments. Another eight load flexibility experiments were conducted to understand how setpoints and duration of the events could affect results. As shown in Figure 3, load shed events did not use any pre-cooling, whereas load shift events used 60 minutes of pre-cooling. The optimal pre-cooling duration and setpoint was determined by a set of experiments that varied discharge air temperature setpoint and pre-cooling duration to find the optimal settings. The same pre-cooling setpoint and duration were used for all load shift experiments.

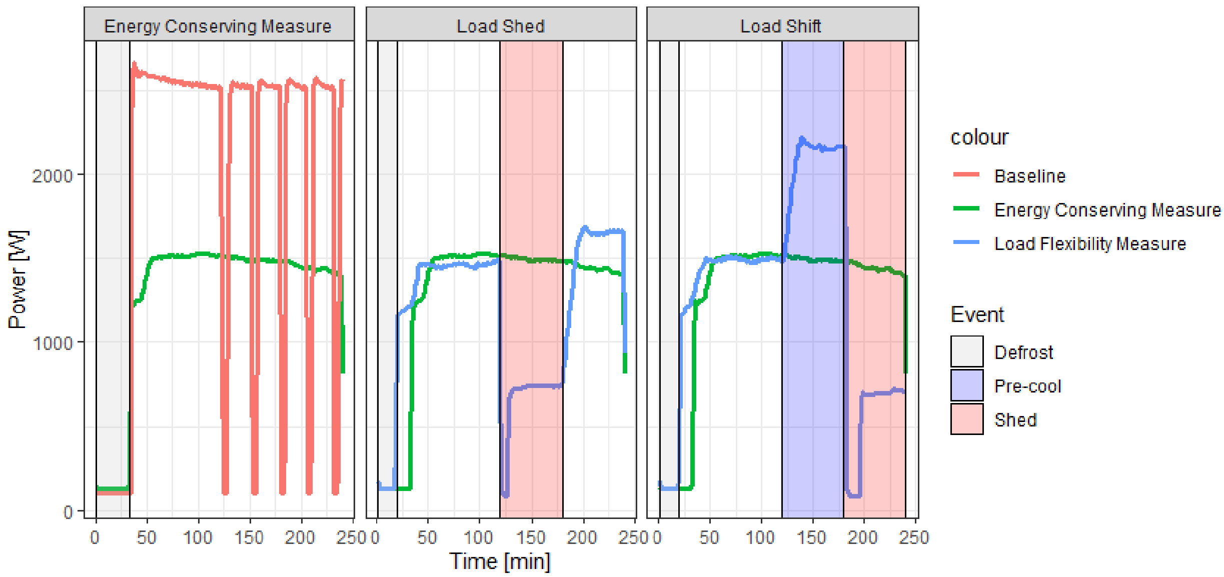


Figure 3. Power consumption of the baseline, ECM, and two load flexibility experiments

Figures 4 and 5 show the power and product temperature effects for all experiments. Figure 4 shows the ECM was able to reduce average power consumption. The load shed and load shift events were able to reduce power consumption temporarily compared to the baseline and the ECM. Figure 4 also shows that average power consumption during load shed and shift events was affected by the duration of the event. Pre-cooling helped reduce power consumption by an average 90 watts compared to load shed alone, but pre-cooling was less effective with longer duration shed events.

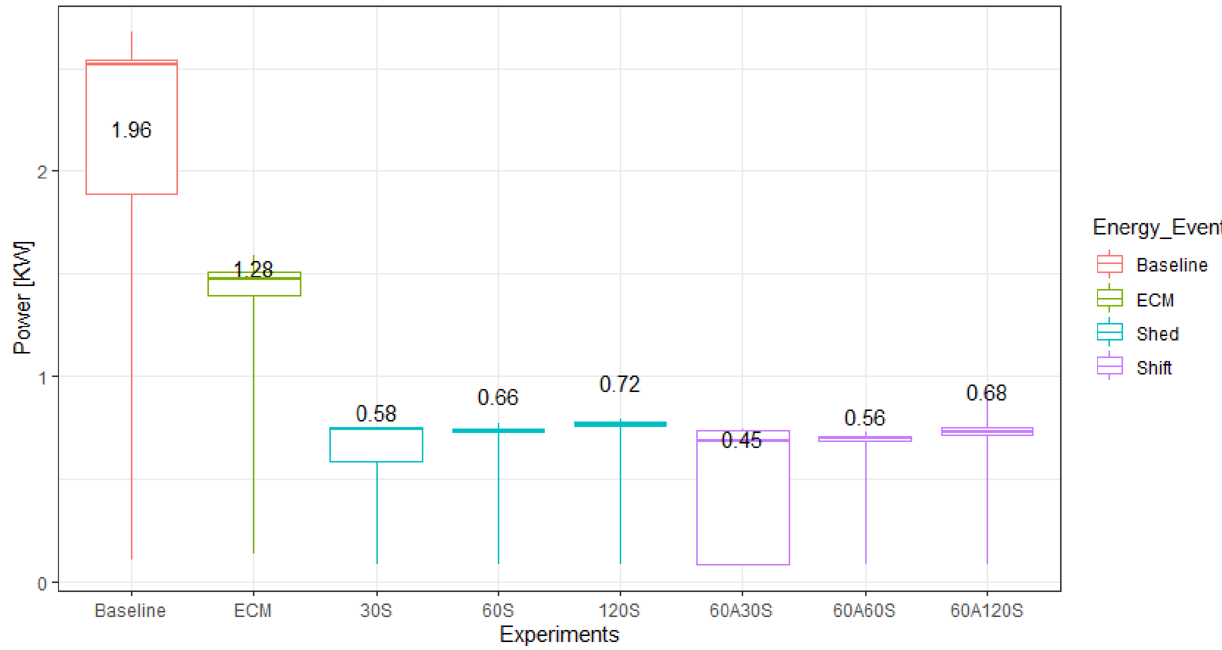


Figure 4. Average power consumption of an open medium-temperature case

Important trends with product temperature are shown in Figure 5. The maximum product temperature dropped by 0.8°F in the ECM experiment. This is likely because the variable speed compressor and advanced controls were able to keep the OVDC continuously conditioning the product, while the baseline duty-cycled the constant speed compressor. Product temperature also increased with event duration for the load shed experiments. Load shed with 120-minute duration exceeded the product temperature threshold of 41°F, suggesting that 2-hour events without pre-cooling is unadvisable for perishable products. If load-shed events were able to be initiated at a lower initial product temperature or if the defrost following the load shed event were skipped, two-hour events without pre-cooling might be possible, but this was not evaluated with the load shed experiments.

The product temperature in general maintained tighter tolerances with the load shift experiments, and product temperature did not increase with duration of the event. This could be because the 120- and 180-minute load shift experiments skipped defrost after shedding load. This provided more time to reduce the product temperature after a load shed event and prevented rising product temperatures that were seen with the load shed events. This indicates that defrost may be the driving force behind product temperature variation even for long-duration load shed or shift events. All load shift experiments maintained product temperature within 0.8°F of the baseline. Furthermore, Figure 5 shows that the load shift average product temperature remained lower than the baseline and the range of product temperatures was lower compared to the load shed experiments. This illustrates the importance of pre-cooling in order to balance the load shed event. Although the results shown here did not find the perfect balance, future work could adjust the balance and keep the product temperature variation the same as the baseline.

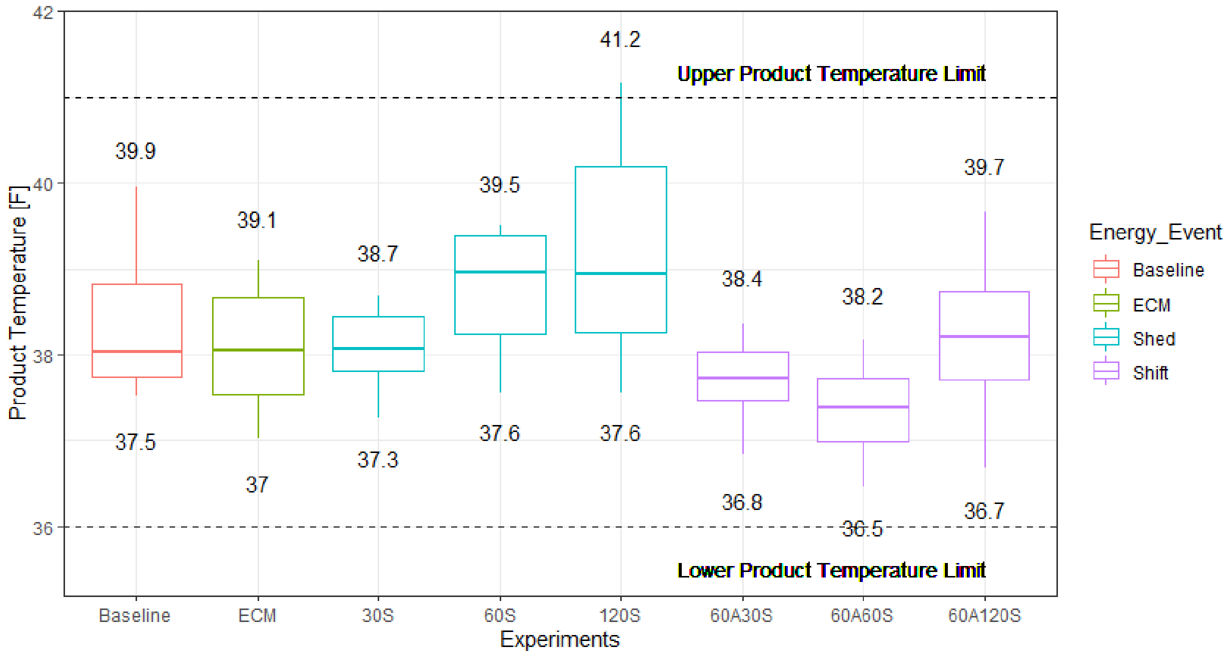


Figure 5. Product temperature ranges for all experiments

## Energy Conserving Measure Results

Table 5 shows detailed results for the ECM. Overall, the liquid-cooled condensing unit consumed 35% less daily energy than the baseline. The largest factor reducing energy consumption for the ECM was the lower saturated condensing temperature of the water-cooled system, resulting in a lower compressor lift. The compressor accounted for 87% of the total energy savings. The remainder of energy savings was mostly attributed to the condenser. Switching from a fan to a pump saved an estimated 10% energy savings.

Table 5. Energy and power performance of the ECM

| Case Type | Daily Energy Consumption [kWh/day] | Energy Savings [%] | Average Power [W] | Peak Power [W] | Peak Power Savings (%) | Average Product Temperature [°F] |
|---|---|---|---|---|---|---|
| Air-Cooled Baseline | 47.0 | N/A | 1,957 | 2,677 | N/A | 38.3 |
| Liquid-Cooled ECM | 30.7 | 35 | 1,281 | 1,587 | 41 | 38.1 |

Table 5 also compares the peak power consumption for both the baseline and ECM. The peak power reduction was 41%, indicating that advanced controls and components can further reduce peak power that could be important for demand reduction. This was further supported by an additional experiment in Ref: Bulk (2022) that matched the compressor lift of the baseline experiment. Although this experiment showed no energy savings, it still showed 7% power reduction for the ECM, supporting the theory that the advanced controls could play an important role for permanent demand reduction.

Because the ECM's variable speed compressor rarely turned off except during defrost, the continuous operation of the variable speed compressor required more defrost cycles than the baseline to prevent frost accumulation on the evaporator coil. This is an important distinction between the baseline and ECM unit controls. End users should consider increasing defrost frequency compared to constant-speed compressor systems that cycle frequently for zones with high humidity (the cases were tested at 55% relative humidity). Additional detailed results from this evaluation, including transient component power, air and product temperatures, refrigerant conditions, condensate production, etc., can be found in Ref: Bulk (2022).

### Load Flexibility Experimentation Results

A breakdown of the power consumption is provided in Table 6. While most of the power reduction was due to the discharge air temperature setpoint control, 8%–9% of the load shedding could be accomplished by leveraging controls that do not affect product temperature and are not dependent on duration (condenser TD and light control).

Table 6. Average power variation during load shed events

| Shed Duration | Baseline Power [W] | Power Variation [%] | | | | | Average Power Consumption [W] |
|---|---|---|---|---|---|---|---|
| | | ECM | Setpoint Shed | Condenser TD Shed | Light Shed | Total Shed | |
| 30 min | 1,957 | -35% | -28% | -6% | -2% | -70% | 580.0 W |
| 60 min | | | -23% | -7% | | -66% | 661.8 W |
| 120 min | | | -19% | -7% | | -63% | 721.0 W |

Pre-cooling was independently evaluated to optimize the duration and setpoint for load shift experiments. Two different discharge air temperature setpoints were evaluated. 28°F was the lowest suggested discharge air temperature setpoint by the manufacturer and was 5°F lower than the normal setpoint for the ECM. 30°F was a more moderate temperature change at only 3°F lower than the ECM setpoint. The lower discharge air temperature setpoint of 28°F increased the pre-cooling power consumption from 23%–27% up to 42% compared to the baseline. A 28°F setpoint with 60-minute duration was selected for all pre-cooling because it changed the average product temperature and stored energy but did not reduce product temperature below the lower product temperature limit of 36°F as shown in Figure 5.

Table 7. Average power variation during pre-cooling events

| Pre-Cooling Duration | Deviation From ECM Setpoint [°F] | Baseline Power Consumption [W] | Power Variation [%] | | Average Power Consumption [W] |
|---|---|---|---|---|---|
| | | | ECM [%] | Setpoint Add [%] | |
| 30 min | -3 | 1,957 | -35% | 23% | 1,732 |
| 60 min | -3 | | | 27% | 1,818 |
| 60 min | -5 | | | 42% | 2,095 |
| 120 min | -3 | | | 23% | 1,730 |

Table 8 shows the effect on power when load shift events were triggered. The load shift event was able to reduce 6%–8% more power than the load shed events with no pre-cooling. Similar to load shed, 6%–8% of the temporary demand reduction strategies could be applied that were independent of duration.

Table 8. Average power consumed during load shift events

| Shift Duration [min] | Baseline Power [W] | Power Variation [%] | | | | | Average Power Consumption [W] |
|---|---|---|---|---|---|---|---|
| | | ECM | Setpoint Shed | Condenser Shed | Light Shed | Total Shed | |
| 90 | 1,957 | -35% | -36% | -4% | -2% | -77% | 447 |
| 120* | | | -29% | -6% | | -71% | 632 |
| 180* | | | -22% | -6% | | -65% | 678 |

* Defrost after the energy event was skipped

Another factor that affected the load shift experiments was the defrost controls. The team added a defrost control strategy to skip the defrost immediately following the 120- (60A60S) and 180-minute (60A120S) load shift events. Figure 6 compares the condensate from the ECM and the load shift experiments. The ECM was used for comparison because it had the same frequency of defrosts as the load flexibility experiments.

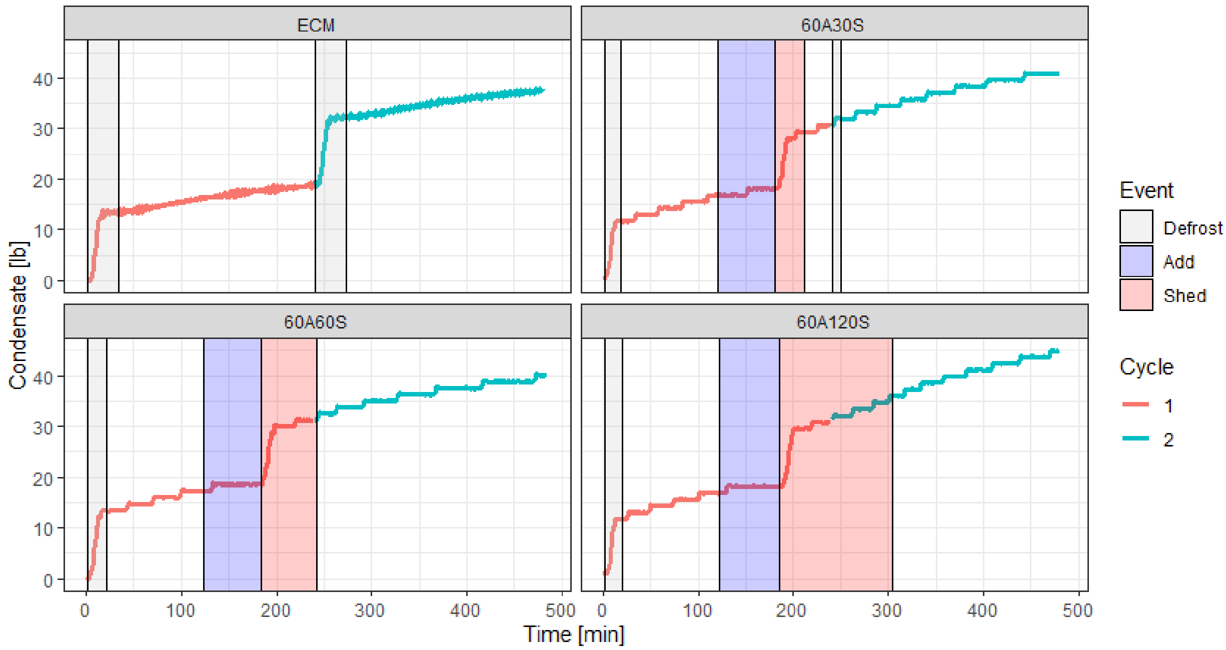


Figure 6. Condensate of the ECM and load shift experiments

Defrosts immediately after a load shift event resulted in significantly shorter durations. With the 90-minute (60A30S) load shift experiment, defrost duration was only ten minutes following the event, and furthermore, almost no condensation occurred during this shortened defrost. This led the team to hypothesis that defrosts immediately following a load shift or shed event were not needed. Therefore, the team skipped the coincident defrost after a load shift event as shown in Figure 6 for the 120- and 180- minute load shift experiments. The 120-minute shift experiment was able to reduce the average product temperature compared to the 90-minute load shift experiment, indicating that removing a defrost cycle can allow for more load shedding while still maintaining product temperature. The 180-minute shift experiment also reduced the maximum product temperature compared to the 120-minute load shed experiment, and still stayed under the baseline maximum product temperature. When comparing two cycles of condensate versus the ECM as shown in Figure 6, the total condensate for all three load shift experiments was very close to the ECM. This implies that skipping defrost had little to no effect for condensation rates yet had a profound effect on maintaining product temperature as discussed earlier.

A separate experiment was conducted to isolate the impact of condenser TD setpoint control. This experiment ran the ECM at manufacturer default setpoint of 25°F for an hour followed by an hour at 15°F setpoint. This experiment provided an estimated contribution of the condenser TD setpoint strategy. Table 9 shows the effects of this control strategy including increased liquid flowrate, increased pump power consumption, lower discharge pressure, and lower compressor power consumption. The net power savings for this strategy was 146 watts. Different liquid-loop setups could change the potential shed capability of this strategy. One key advantage of the condenser shed algorithm, however, is that it does not affect the product temperature.

Table 9. Results of condenser TD strategy for load-shed events

| Condenser TD Setpoint [°F] | Water Inlet Temperature [°F] | Saturated Condensing Temperature [°F] | Condenser Liquid Flowrate [gpm] | Compressor Power [W] | Calculated Pump Power [W] | Average Power [W] |
|---|---|---|---|---|---|---|
| 25 | 75.5 | 94.4 | 1.27 | 1,013.6 | 15.8 | 1,162.7 |
| 15 | 75.7 | 84.8 | 3.55 | 848.3 | 36.0 | 1,016.3 |
| Difference | 0.2 | 9.6 | 2.28 | -165.2 | 20.2 | -146.4 |

## Discussion/Conclusions

The results from this study show the potential to improve the energy efficiency and load flexibility of OVDCs. This study found that 35% energy savings can be achieved by switching from an air-cooled unit to a high-efficiency liquid-cooled condensing unit that utilizes a variable speed compressor, electronic expansion valve, and advanced controls. The features of the ECM technology that provide energy savings can be leveraged to integrated load flexibility controls. Four load flexibility strategies were developed, leveraging the advanced controls available with the high-efficiency liquid-cooled case. These strategies included discharge air temperature setpoint control, condenser TD setpoint control, light control, and defrost control.

Combining the permanent ECMs and all four strategies for load shift events resulted in an impressive 65% power reduction for a 120-minute event duration and up to a 77% power reduction for a 30-minute event duration. 6%–9% power reductions were possible using only condenser TD and light control that would have no effect on product temperature. Pre-cooling and defrost control minimally affected power consumption during load flexibility events, but were an important strategy to maintain product temperature.

As medium-temperature cases often condition products with very tight tolerances in temperature, the goal was to maintain product temperature within the same variation seen during normal operation. Due to improved defrost control, this OVDC was able to shed load for up to an hour while keeping product temperature within the same range as the baseline. Load shift experiments with pre-cooling actually reduced the average product temperature compared to the baseline due to the improved controls. This study showed load shift events of two hours were still possible if the variation of product temperature can be expanded slightly. Further optimization of pre-cooling and defrost control would likely make two-hour shed events possible without changing product temperature variation.

While this study quantified the change in power consumption by OVDCs using advanced control strategies to shed, and shift load, there is still important future work to apply these strategies. By implementing hierarchal control to determine when these strategies are available, and to manage the timing of defrost cycles with respect to events, power consumption could be further reduced while more effectively regulating product temperature. Furthermore, these control strategies must be coordinated between multiple refrigerator cases to provide significant building-wide demand reduction for more than two hours.

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