A NOVEL PCM THERMO SIPHON DEFROST SYSTEM FOR A FROZEN RETAIL DISPLAY CABINET

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ABSTRACT

An energy efficient method of defrosting the evaporator on a frozen retail display cabinet was developed and its performance compared with that of the existing electric defrost. The cabinet was modified so that either defrost system could be deployed, leaving the rest of the system operation untouched. Performance of the cabinet during EN23953 standard tests was compared.

Total energy consumption during the tests was 40% lower with the novel defrost. This was partly due to elimination of the use of electrical defrost power (which reduced direct electrical power by 39%). Since the system leads to lower liquid refrigerant temperatures at the expansion valve there is a saving in compressor power for the same refrigeration effect and as the defrost is quicker, the temperature excursions inside the cabinet are smaller, reducing the amount of heat which has to be removed after a defrost. The cabinet can also be run at a higher evaporating temperature, further reducing energy consumption.

1. INTRODUCTION

To maintain food at acceptable temperatures, both frozen and chilled refrigerated cabinets run their evaporative coils at temperatures less than 0°C. Because of this they need to defrost at regular intervals to remove any ice build-up. With chilled cabinets this can usually be achieved with an off-cycle (or passive) defrost, where the refrigerant flow is stopped and the evaporator allowed to warm naturally to above 0°C, melting the ice. With frozen cabinets this is not possible, as it would be extremely slow and cause the food to defrost.

The two most common defrost methods used in supermarket applications for defrosting frozen cabinets are:

1. Hot refrigerant gas from the compressor or receiver is diverted into the evaporator.
2. Resistive electric heater rods are used to heat the evaporator.

During a hot gas defrost, refrigerant gas is taken from the compressor and passed through the evaporator. With cool gas defrosts, the gas is taken from the receiver. In both cases the gas condenses in the evaporator giving up heat to melt the ice. Certain problems are associated with hot/cool gas defrosts. These include extra piping and valving, thermal shocks caused by rapid temperature changes which can cause pipes to leak and the need for head pressures to be high to force the gas through the pipes to the evaporator.

Electric defrost heaters use a significant amount of energy. Due to the inefficiency of getting heat from the defrost rods to all of the iced fins, much of this energy goes into the cabinet (overhead), rather than into melting the ice. Lawrence and Evans (2008) found the overhead to be around 85% of the energy for a 2.5 m frozen food well display cabinet at climate class 3 (temperature of 25 °C and relative humidity of 60%). This extra heat warms the product and needs to be removed by the refrigeration system. Therefore the defrost has direct electrical energy from the resistive heaters plus an indirect refrigeration energy required to remove the wasted heat. The cabinet often has to run at a reduced set point to allow for the increase in product temperature during the defrost, increasing refrigeration energy consumption.

Fricke and Sharma (2011) estimated the total electrical energy consumption for the electric defrost of a low temperature glass doored reach-in case to be 176 kWh/(year ft) or 577 $kWh.m^{-1}$ p.a. 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.

This paper describes a novel wax based phase change material (PCM) thermo siphon defrost system (Frigesco™) and presents results from trials that compare this to an electric defrost system. Energy savings for the novel defrost system are presented.

2. THE CABINET

The cabinet tested was a remote half glass door (HGD) and well frozen cabinet. The cabinet had two separate refrigeration and electrical circuits, one each for the HGD and well. The refrigeration circuits were fed from a common liquid line from a remote condenser unit operating on R404A refrigerant. The expansion devices were electronic expansion valves (EEVs).

The cabinet had an electric defrost system which consisted of a finned resistance heater element located upwind of each evaporator so that heat was transferred by forced convection from the element to the frosted coil. Six defrosts were programmed per day (one every 4 hours) for both the HGD and well sections with one hour separating the HGD and well defrosts. The electric defrost termination temperature was adjusted to a value which was previously shown to adequately defrost the evaporator without raising air temperatures any higher than required. This value was 7.0°C for the HGD and 14.0°C for the well section. The maximum defrost time was set to 60 minutes, such that the defrost always terminated on temperature.

3. NOVEL DEFROST SYSTEM

The novel defrost for the HGD section of the cabinet consisted of a heat exchanger (HE) placed within a tank containing a phase change material (PCM) (RT21, Rubitherm Technologies GmbH). The PCM was a wax (liquid saturated hydrocarbons) which melted at approximately 21°C. During normal running, liquid refrigerant from the condenser passed though the HE and melted the wax, sub-cooling the refrigerant before it passed into the cabinet evaporator (Figure 1a). During a defrost, valves were actuated such that the cold evaporator and the HE formed a closed loop (Figure 1b). The evaporator was now fed by refrigerant gas from the HE. This hot gas condensed in the evaporator, heating it. The liquid from the evaporator drained naturally (due to the higher height of the evaporator) to the HE, solidifying the PCM. The thermal capacity of the PCM was such that a temperature gradient was formed between the HE and the evaporator allowing a thermo siphon to exchange heat between the two. When the ice on the evaporator was melted and the PCM was solidified, the valves returned the system to normal operation. The PCM now started to melt again, and when melting was complete a defrost could again be activated.

The well section of the cabinet had the evaporator in the base and therefore it was not possible to put the HE low enough to create a thermo siphon. Instead an electric pump was fitted to pump the liquid refrigerant from the evaporator to the HE during a defrost.

The novel defrost had 3 benefits;

1. Eliminating the electrical consumption of the defrost heaters.
2. Sub-cooling the liquid from the condenser to the evaporator, reducing the refrigeration energy consumption
3. Reducing the heat introduced into the cabinet due to the electrical defrost.

The quantity of wax required to fully defrost both sections was estimated to be 10 kg. A clear acrylic container was built to house each of the HE's and the wax. The length of the defrost cycle was previously adjusted to allow the wax to fully solidify and thus exchange all its latent heat with the evaporator during the defrost. Previous experiments with view ports to the evaporator were used to confirm that the defrosts were fully melting the ice on the coil. The number of defrosts per day and timing during the test were kept identical to the electrical defrost test. The defrosts were terminated by time, with 15 minutes for the HGD and 20 minutes for the well defrost. It was found in previous tests that the melt water from the HGD evaporator re-froze as soon as it hit the evaporator tray. This did not happen with the electrical defrost test, as the extra heat from the electric defrosts was enough to raise the temperature of the tray to above 0°C. An electrical heater tape was therefore fitted to the tray. This was activated for the length of the HGD defrost (15 minutes).

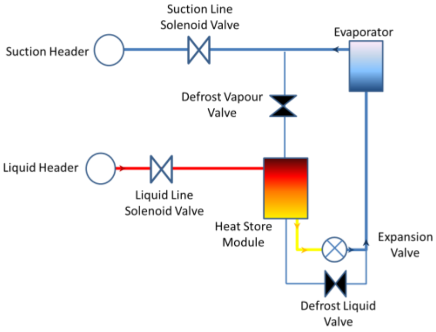

Figure 1a. Schematic of system on charge.

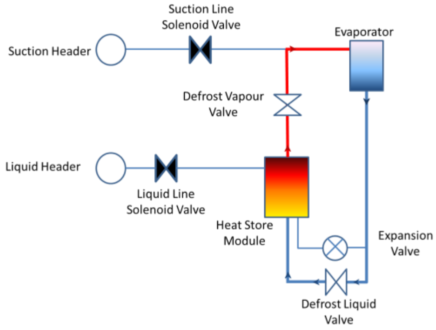

Figure 1b. Schematic of system during defrost.

4. METHOD

The cabinet refrigeration circuit and associated controls were modified in such a way that either an electric or novel defrost could be deployed, leaving the rest of the system operation untouched.

Tests with both the traditional and novel defrost system were carried out in a test room conforming to EN23953:2005 standards. During the test, the room conditions were maintained within climate class 3 (25°C and 60% RH).

The cabinet was loaded with standard ‘m’ packs (packs and loading as specified in EN23953:2005). Twelve measurement positions were sited on shelf 1, shelf 3 and the base of the HGD section and eighteen measurement positions were sited in the well. The temperature measurement packs on the shelves were placed at the edges and centre of the cabinet, at the front and rear of the shelves and at the bottom and top of the stack of packs. The temperature measurement packs in the well were placed at the edges and centre of the cabinet, at the rear, front and the middle of the shelves and at the bottom and top of the stack of packs. Each measurement pack had a calibrated ‘t’ type thermocouple (copper-constantan) inserted into the geometric centre of the pack.

A power meter (Northern Design, MultiCube) was connected with the stabilised mains electrical supply (230 V) to monitor and record electrical power consumption of all parts of the cabinet except the remote refrigeration system (lights, trim heaters, defrost heaters, controllers, solenoid valves, tray heaters). This power consumption is known as the direct electrical consumption (DEC).

The instantaneous heat extraction rate, Φ_n in kW, was calculated using eq. (1).

$$\Phi_n = m\,(h_{out}-h_{in}) \qquad (1)$$

Where m was the mass flow rate of the refrigerant, and h_{in} and h_{out} the enthalpies of the refrigerant at the entry and exit to the cabinet. Measuring the pressure and temperature at the exit from the cabinet and the temperature at the entry to the cabinet allowed h_{in} and h_{out} to be calculated.

The following sensors were used to measure the above parameters:

Temperature - measured to an accuracy of ±0.5°C using calibrated ‘t’ type thermocouple). The thermocouples were strapped tightly to the liquid and suction pipes, and the whole pipe insulated with 25 mm thick Armaflex for at least 150 mm on either side of the measurement point.

Pressure - measured to an accuracy of 0.25% of reading using a calibrated strain gauge type pressure transducer (Omega PX419).

Mass flow - measured using a calibrated Coriolis mass flow meter (Krohne Optimass) with an accuracy of ±0.1%.

The total heat extraction during a test, Q_{tot}, is defined as (eq. 2).

$$Q_{tot} = \sum_{n=1}^{n=N_{max}} \Phi_{n} \times \Delta t \qquad (2)$$

Where N_{max} is the number of measuring samples in 24 hours and Δt is the time between two consecutive measuring samples.

Heat extraction rate for a single cabinet installation in laboratory conditions (Φ_{run}), was calculated according to EN23953:2005 as shown in eq. (3).

$$\Phi_{run} = \frac{Q_{tot}}{t_{run}} \qquad (3)$$

Where t_{run} is the running time.

During all tests, temperatures of the 'm' packs, air temperatures in the cabinet, relative humidity and power were recorded every minute using a data logging system (Orchestrator software and Datascan measurement modules, Measurement Systems Ltd.). Data from sensors used to measure heat extraction rate were recorded at a 20 second interval using the same date logging system.

Before testing the cabinet was commissioned to achieve the best performance. The aim was to maintain all monitored ‘m’ pack temperatures as close as possible to the L3 temperature classification (the highest temperature of the warmest ‘m’ package must be equal to or lower than -12°C and the lowest temperature of the warmest ‘m’ package equal to or lower than -15°C) during the test period. The cabinet was run into the test and commissioned with the cabinet lighting on. To allow comparable maximum temperatures between the tests, both the evaporating pressure and set points were adjusted.

The Frigesco™ defrost required a higher liquid temperature than was used in the electric defrost tests. This was to allow sufficient melting of the wax between defrosts. The liquid temperature was therefore raised using a condensing pressure regulator, but was maintained within the EN23953:2005 specification of no more than 10°C higher than the test room temperature.

Once commissioning had been completed a test of temperature performance and energy consumption (according to EN23953:2005) was carried out over a 24-hour period. During tests the cabinet lights were switched on and the cabinet doors were opened cyclically for 12 hours during the test period. At the start of the opening cycle, each cabinet door was opened sequentially for 3 minutes. The doors were then each opened 6 times per hour for a total of 6 seconds. This was done using an automatic door opening mechanism. After the 12 hour door opening cycle was completed the lights were switched off for the remainder of the test.

The refrigeration electrical energy consumption (REC) was calculated according to EN23593:2005 for remote compression type refrigerating systems using the REC_{RC} method eq. (4).

$$REC_{RC} = Q_{tot} \times \frac{(T_c - T_0)}{0.34 \times T_0} \qquad (4)$$

Where REC_{RC} is the refrigeration electrical energy consumption for remote cabinets using compression-type refrigerating systems, T_c is the condensing temperature at 308.18 K (35°C) for European comparisons, T_0 is the refrigerant evaporating temperature in K and 0.34 is the Carnot efficiency of refrigerating systems used in commercial refrigeration.

The direct electrical energy consumption (DEC) was equal to the sum of the energy consumed by fans, lighting and accessories as described in EN23953:2005.

The total energy consumption (TEC) during the test is calculated from the DEC and REC as in eq. (4).

$$TEC = REC_{RC} + DEC \quad (5)$$

5. RESULTS

The mean temperature of all 'm' packs, the mean of all visible 'm' packs and the minimum and maximum 'm' pack temperatures for both the electric and Frigesco™ tests are shown in Figure 2 and 3 respectively. Compared to the electric defrost the Frigesco™ defrost tests had much smaller temperature swings on all 'm' packs. The average temperature difference (maximum minus minimum temperature of each pack) of all 'm' packs during the test was 7.9°C in the electric defrost test and 2.6°C for the Frigesco™ defrost test. The warmest pack in the electric defrost test varied between -23.5°C and -11.5°C and the warmest 'm' pack in the Frigesco™ defrost test varied between -13.2°C and -11.3°C during the course of the test. It should be noted that the warmest pack was not in the same position in both tests.

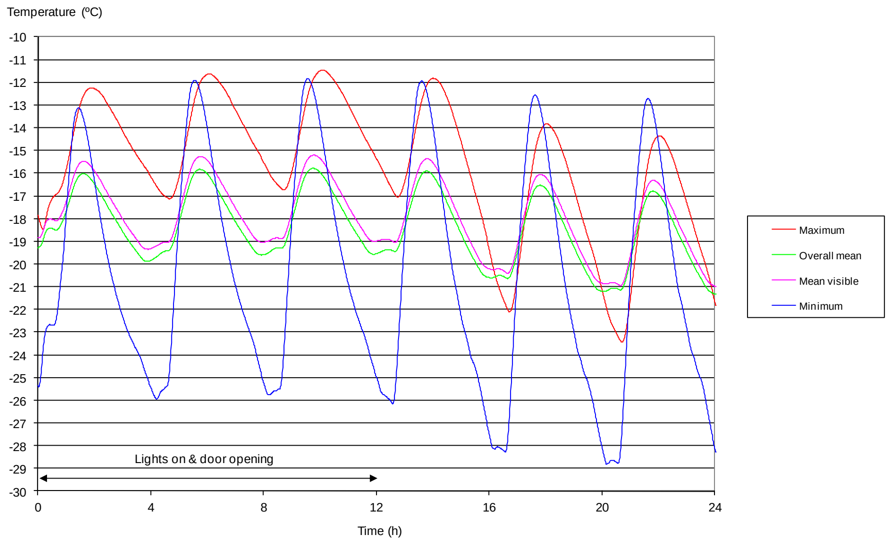

Figure 2. Overall arithmetic mean temperature of all 'm' packs, the arithmetic mean of all visible packs and the minimum and maximum 'm' pack temperatures with electric defrost.

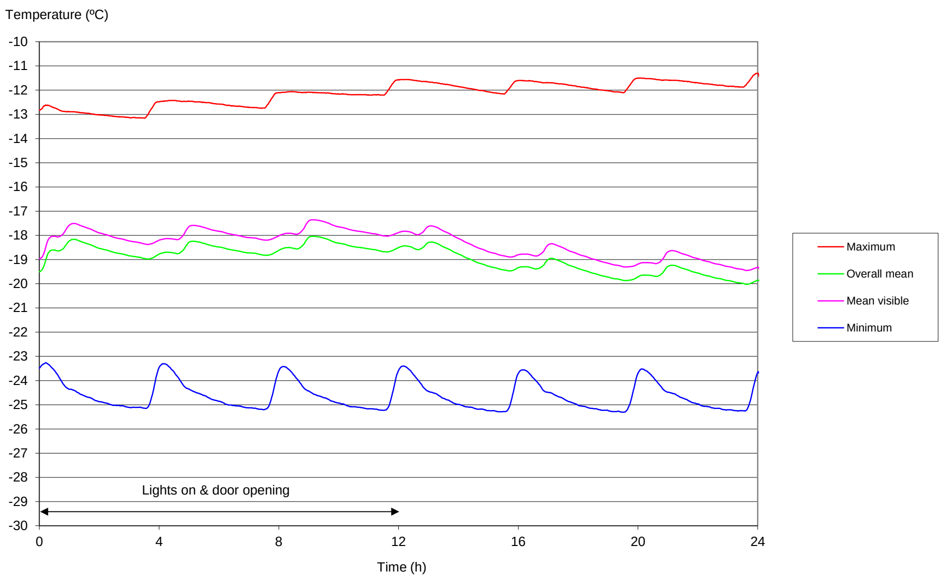

Figure 3. Overall arithmetic mean temperature of all 'm' packs, the arithmetic mean of all visible packs and

the minimum and maximum 'm' pack temperatures with Frigesco™ defrost.

During the course of both tests, the 'm' packs in the HGD were stable, with the exposed packs reducing in temperature when the lights were switched off. This was also the same for the well in the electric defrost test, however, for the Frigesco™ defrost test the packs increased in temperature. This was most probably due to defrost water freezing as it dropped off the evaporator and hitting the base of the well.

The energy consumptions during the tests are shown in Figure 4 and 5. The cabinet had a baseline power of 1200 W which was due to the trace heaters and fans. This increased to 1500 W when the lights were on. During the electric defrost test, power peaks (3700 and 4000 W) were caused by the electric defrost heaters for the HGD and well. During the Frigesco™ defrost test the only power peaks were caused by the tray heater in the HGD section.

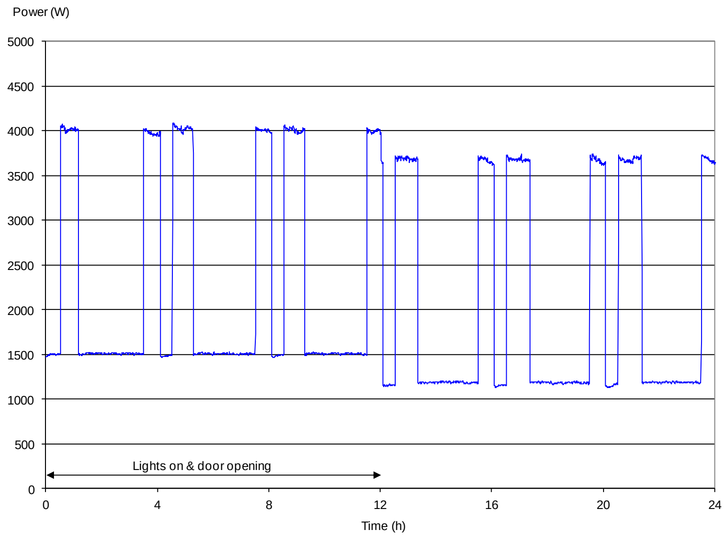

Figure 4. Energy consumed during the test with electric defrost.

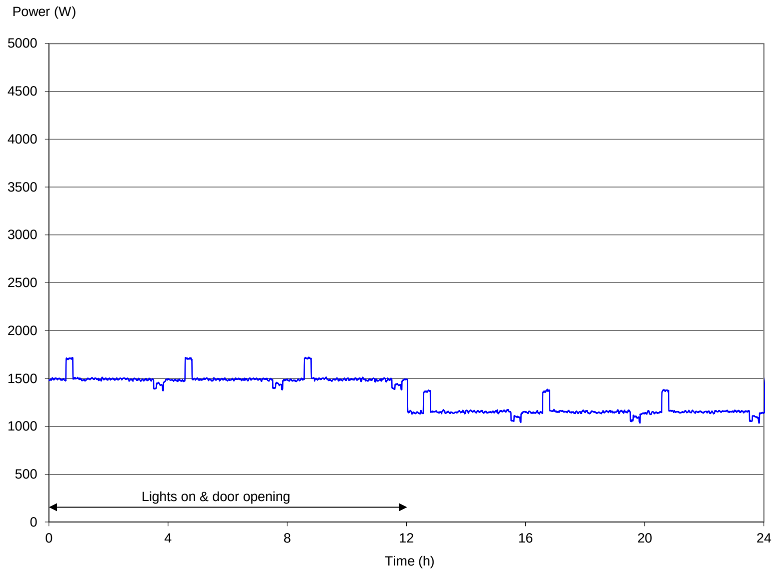

Figure 5. Energy consumed during the test with Frigesco™ defrost.

The energy consumed by the cabinet was 52.26 kWh/24h in the electrical defrost test and 31.87 kWh/24h during the Frigesco™ defrost test.

Figures 6 and 7 show refrigerant mass flow, high pressure liquid and low pressure saturated temperature, during the electric and Frigesco™ defrost tests respectively. The liquid temperature during the Frigesco™ defrost was increased from below 25°C to 30°C to allow effective melting of the wax between defrosts. The evaporation temperature was much lower in the electric defrost test (mean of -44°C) than the Frigesco™ defrost (mean of -32°C). This was because a lower evaporation temperature was required during the electric defrost test to maintain 'm' pack temperatures at the L3 condition. Mass flow of refrigerant was on average lower during the Frigesco™ defrost test (19 g.s-1 compared to 24 g.s-1), however there were peaks of up to 100 g.s-1 when the defrosts were activated.

The heat extraction rate calculated using the Φrun method was 2.74 kW for the electric defrost test and 1.98 kW for the Frigesco™ defrost.

The energy consumption values that were used to calculate TEC are shown in Table 1.

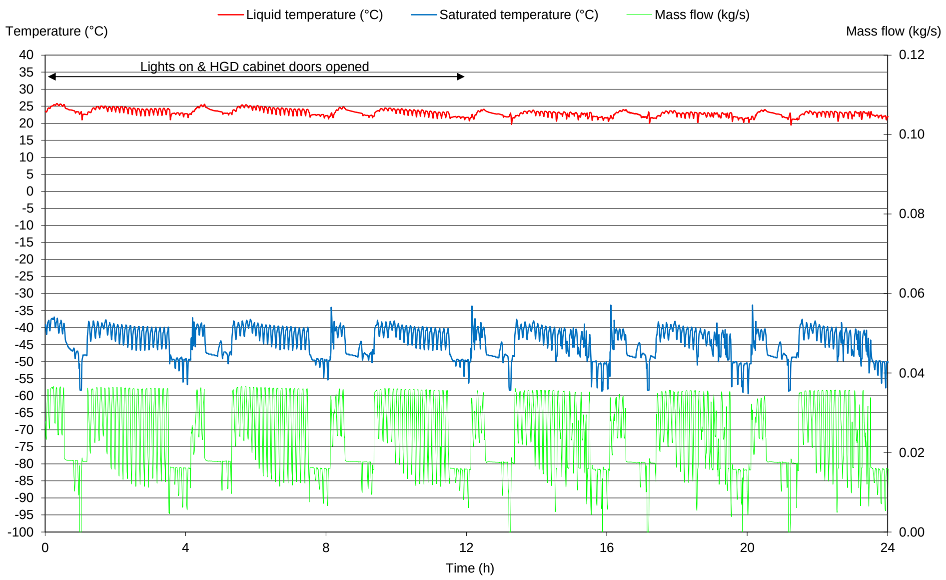

Figure 6. Refrigerant mass flow, high pressure liquid and low pressure saturated temperature, during the test with electric defrost.

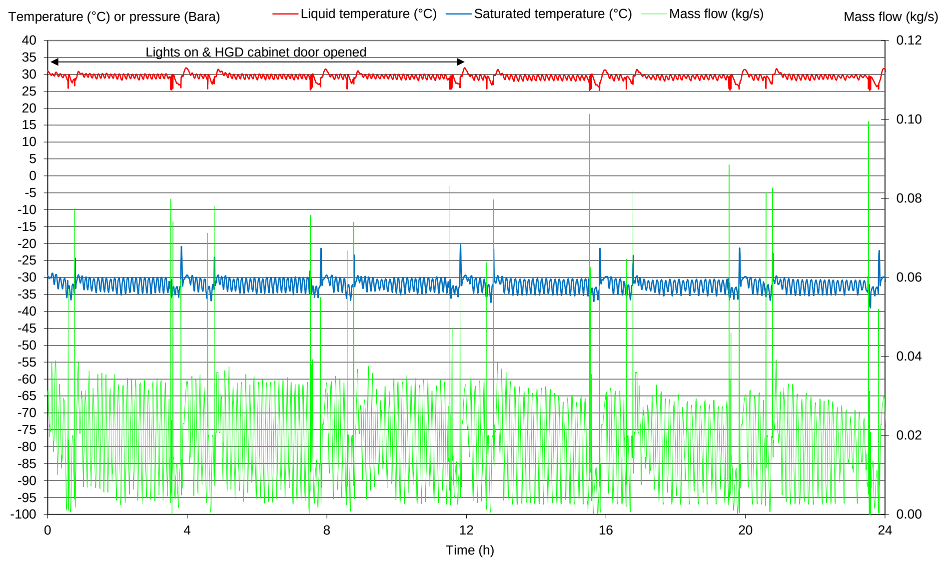

Figure 7. Refrigerant mass flow, high pressure liquid and low pressure saturated temperature, during the test with Frigesco™ defrost.

Table 1. Energy Consumption

	Electric defrost	Frigesco™ defrost
DEC (KWh/24h)	52.26	31.87
REC_{RC} (KWh/24h)	66.66	39.03
TEC (KWh/24h)	118.92	70.90

6. DISCUSSION

With electric defrosts the cabinet was unable to fully meet the L3 specification unless numerical rounding of 'm' pack temperatures was used. This was at an extremely low evaporating temperature of -44°C. With the Frigesco™ defrosts the cabinet was easily able to achieve the L3 specification, however, for a more realistic comparison with the electric defrost test the evaporating temperature was raised to give a similar maximum pack temperature.

The performance of the 2 defrost systems were therefore compared at close to an L3 classification.

Compared to electric defrosts the Frigesco™ defrosts reduced the TEC by 40%. The reduction in energy came from both the DEC and the REC. The DEC reduced by 39% due to the electric defrost heaters not being turned on. The REC reduced by 41% due to the:

1. reduced refrigeration load (Φ_{run} reduced by 28%) caused by the defrost heaters not putting heat into the cabinet;
2. free sub-cooling caused by recharging the thermal store;
3. increased evaporating temperature (from -44°C to -32°C) causing the refrigeration plant to run more efficiently.

An average electric defrost time of 43 minutes and defrost power of 2.5 kW equates to a heat load of 6.45 MJ per defrost. For the Frigesco™ defrost, assuming all wax solidifies and there is no sensible heat, a latent heat capacity of 134 kJ kg^{-1} and 10 kg of wax gives a heat load of 1.34 MJ per defrost. This shows that the Frigesco™ defrost only requires 20% of the heat of the electric defrost.

Temperatures were not stable in the well during the Frigesco™ defrosts test. This was due to icing. The Frigesco™ defrost appeared to be melting the ice on the evaporator in the well, however, the water then appeared to be freezing as soon as it hit the base of the well. Therefore ice built up during the course of the test, raising pack temperatures. This was not the case for the electric defrost which appeared to warm the base sufficiently to allow the defrost water to drain. Ideally a heater mat should be placed in the base of the well to prevent ice build up. In the HGD section the defrost tray heater was energised for the duration of the Frigesco™ defrost (15 minutes), this allowed the defrost water to drain away and the HGD temperature to remain stable during the test.

Based on an estimate of 4.8 million low temperature (freezer) cabinets in the world, saving 48 kWh/day (difference between the energy for the electric and Frigesco™ defrosts in this report) would provide a total annual saving of 8.4×10^{10} kWh (84 TWh).

7. REFERENCES

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