2014

A Low Carbon Defrost System

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ABSTRACT

A new defrost system is described which is virtually energy-free and has the additional advantage of minimizing temperature excursions in the frozen food during and after defrost. This novel defrost system has been tested in a frozen food retail display cabinet and a frozen food walk-in store. In both instances the defrost was normally carried out using electric resistance heaters. The test procedures are described and the test results are presented. In both tests it was demonstrated that the new defrost system saves virtually all the energy used by the conventional electric defrost systems.

1. INTRODUCTION

The air coils of direct expansion freezer systems must be periodically defrosted to maintain performance, and this incurs an energy penalty. Firstly the extra energy needed to melt ice on the finned heat exchanger is usually supplied by direct electrical heating or indirectly via hot has from the compressor, and secondly extra compressor work is needed to rechill components of the system which are incidentally warmed during defrost. One consequence of defrost is to increase the design capacity of the compressor over that strictly necessary to provide the cooling load. The design capacity is equal to the cooling load divided by (24-n.t) where n is the number of defrosts in 24 hours and t is the duration of each defrost. Any reduction in (n.t) is desirable. The total amount of energy needed to perform a successful defrost is

$$Qt = Qm + Qa + Qc + Qp \tag{1}$$

Where Qm is the energy needed to raise the ice from the operating temperature of the aircoil to 0^0C and then to melt it, Qa is the energy which ends up in the circulating air, Qc is the energy which is used to heat up the metallic components of the air coil to above 0^0C, and Qp is the energy which is unavoidably wasted in heating up the the frozen product in the freezer, which is clearly an undesirable consequence of defrost.

The total energy cost of defrosting may be as high as 30% of the total refrigeration energy use and in many cases only about 20% of the energy consumed in a defrost goes to melting ice (Qm), leaving an energy overhead of 80% which has to be removed by the refrigeration system following a defrost, so existing defrost systems are fundamentally inefficient heat transfer processes, (Fricke and Sharma, 2011, Lawrence and Evans, 2008).

The authors now describe a new low temperature defrost system (Davies and Campbell, 2013) which requires virtually no extra energy and which greatly reduces the temperature rise of the freezer contents during defrost since the energy applied to the aircoil is well directed and rapid and at low temperature. This flash defrost system was applied to a frozen food retail cabinet and shown to reduce total energy consumption by 40%, (Foster et al, 2013) and has also been applied to a walk-in frozen food store. It will shortly be applied to an air source heat pump. The concept and implementation are simple. A heat store is introduced into the refrigeration circuit at a point after the condenser unit so that heat in the warm liquid leaving the condenser is collected and stored for use during a defrost. This has two benefits. First the heat which would otherwise be wasted is harvested and put to later use for defrosting, and second the resulting subcooling of the liquid arriving at the expansion device has a beneficial effect on the overall system efficiency. In fact the subcooling gain effectively pays for the post-defrost rechilling effort. Thus with no extra energy needed for defrost and little extra energy needed for re-chilling the whole defrost process is virtually energy free. A collateral advantage of the flash defrost system is that it operates at a lower temperature than electric defrost systems and thus eliminates steaming effects associated with high temperature defrost systems.

2. FLASH DEFROST

The way in which this is achieved can be best explained by reference to Figure 1 which shows a simplified schematic of a remotely connected freezer system with flash defrost components added (three valves and a heat store).

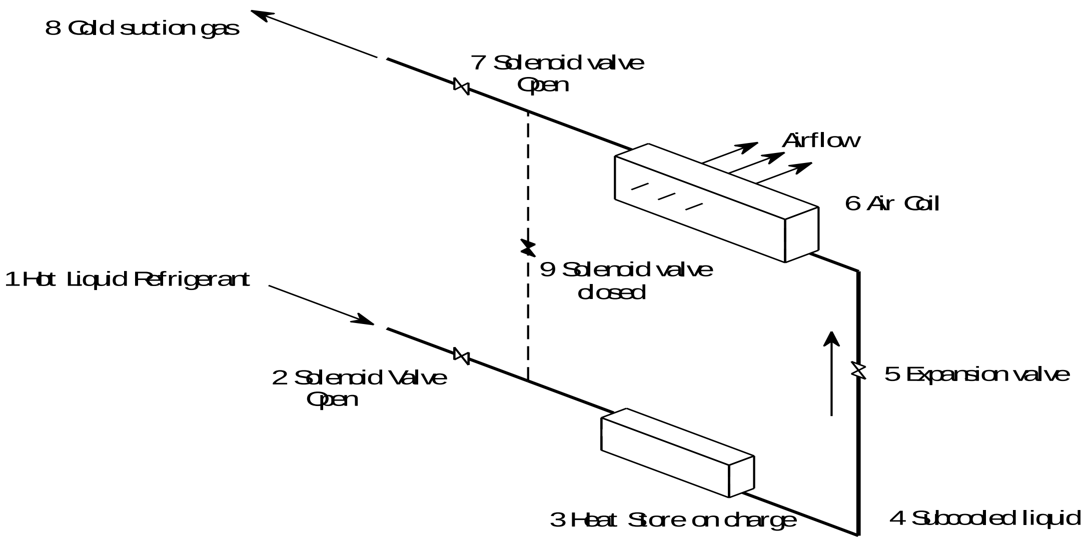

Figure 1: Components of the flash defrost system

2.1 Normal operation

Hot liquid (1) from the condensing pack passes through an open solenoid valve (2) and the heat store (3). The heat store consists of a finned coil immersed in a bath of phase change material (PCM), in this case with a melting point of 15C. Heat is absorbed by the (solid) wax until it is all melted and there is a resulting subcooling of the liquid emerging from the heat store which diminishes with time as shown in Figure 2.

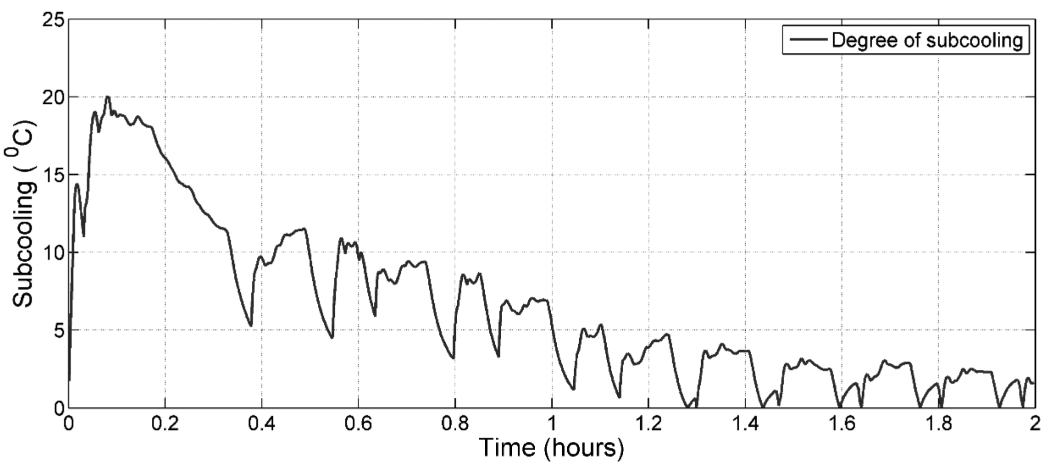

Figure 2: Subcooling of the liquid as the heat store charges

The heat store is sized according to the defrost duty required. In the applications described in this paper the defrost module was capable of storing 1.5MJ and took approximately 2 hours to fully charge. The approximate amount of

energy needed to raise the aircoil and ice from -30C to +1C was 600kJ. Thus the heat store was easily capable of providing the energy to meet the sensible and latent heat requirements of a defrost.
The subcooled liquid leaving the heat store (4) then passes to an expansion valve (5) after which the wet vapour passes through the evaporator (6), the spent dry vapour then returning to the suction manifold (8) via the open solenoid valve (7).

2.2 Defrost operation

When a defrost is called for the stored heat is delivered to the air coil by the simple expedient of closing valves (2) and (7) and opening valve (9) creating the closed loop shown in Figure 3.

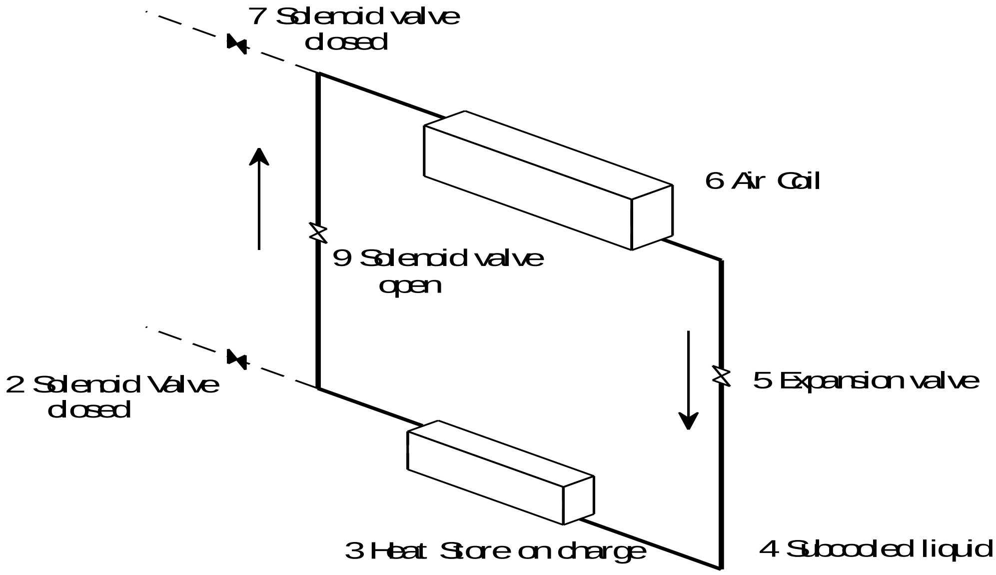

Figure 3: Closed loop connecting the heat store to the aircoil

When the defrost valve (9) is opened the low pressure evaporator is connected to the high pressure heat store and liquid immediately flashes over to the evaporator where condensation and heating occurs, the condensate returning by gravity to the heat store where it boils, the process being repeated until the heat store is exhausted and the ice on the air coil melted. This typically takes less than 10 minutes. After defrost valve (9) is closed and valves (2) and (7) opened the system returns to normal operation as the heat store is recharged ready for the next defrost.

3. EXPERIMENTAL TEST METHODS

3.1 Retail display case

A commercial frozen food display case (conventional electric defrost) which had glass doors on the upper half and an open well below (SPG Geneva, LULT 1-4 HILITE-2) was characterized in an environmental chamber before and after fitting the flash defrost module. The cabinet was remotely connected to a condensing unit operating on R404A and had two separate refrigeration and electrical circuits, one each for the HGD and well.
The cabinet refrigeration circuit and associated controls were modified in such a way that either an electric or flash defrost could be deployed, leaving the rest of the system operation untouched.
Tests with both the traditional and flash defrost systems 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 equation (2).

$$\Phi_n = m\,(h_{out}-h_{in}) \tag{2}$$

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:

$$Q_{tot} = \sum_{n=1}^{n=N_{max}} \Phi_n \times \Delta t \tag{3}$$

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 equation (4).

$$\Phi_{run} = \frac{Q_{tot}}{t_{run}} \tag{4}$$

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 data 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 flash 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 equation (5).

$$REC_{RC} = Q_{tot} \times \frac{(T_c - T_0)}{0.34 \times T_0} \quad (5)$$

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 equation (6).

$$TEC = REC_{RC} + DEC \quad (6)$$

3.2 Walk-in cold room

There is an ANSI/AHRI Standard 1251 test protocol which is used in the USA to evaluate the performance of walk-in cold rooms. As yet there is no equivalent European standard in force. This lists all the required test conditions and instrumentation needed to characterise the thermal performance of a walk-in cold store and it requires two separate environmental chambers which control the environment of both the cold room and the condensing pack.
The objective of this study was to make a direct comparison of the energy costs of running the cold room with a standard defrost system and with the new flash defrost system whilst simulating real operating conditions. We did not try to establish the absolute thermal performance of the cold room along the lines of the above mentioned ANSI test protocol but rather to compare the performance of two defrost systems when the coldroom was maintained at similar conditions.
To this end the experimental conditions such as internal room humidity and thermal load were created by means of an internal 3kW steam generator and a 2kW electric room heater with thermal inertia (stock load) being provided by means of three 200 litre drums of ethylene glycol. The fan heater was regulated at 70% of the rated output and the steam generator regulated at 30% of the rated output. Both units were run for 75% of the testing period. This was meant to provide a consistent simulation of practical operating conditions created by door openings and loading/unloading stock and create a realistic and consistent degree of ice loading on the air coil.
The condenser pack was located on the external wall of the laboratory and thus exposed to variations in atmospheric temperature, so condensing pressure was controlled to give reasonably consistent warm liquid feed to the heat store for both the standard defrost tests and the flash defrost tests. The minimum time between standard defrosts was limited by the controller to 4 hours. The minimum time between flash defrosts was limited by the charge rate of the heat store and was 2 hours.
A commercial cold store (ISARK) measuring 2.2m(W)x2m(H)x2m(D) fitted with a ceiling mounted Searle evaporator (model NS 43-6L) was connected to a 3kW Copeland condensing unit (model MC-H8-ZF13KE-TFD) via an Alco EX4 electronic expansion valve. The refrigerant was R404A. The standard circuitry was adapted in such a way that the flash defrost system could be deployed by means of strategically placed valves, as shown in the schematic diagram, Figure 4. The three extra valves are given the same numbering as those in Figure 1. When operated in the conventional mode with electric defrost the warm condensate flowed from the condensing unit through a solenoid valve (2), the heat store (3), an expansion valve (5), the evaporator (6), a solenoid valve (7), finally returning to the compressor. When a defrost was initiated by the controller (every 4 hours) the compressor was turned off and the embedded resistance heaters and tray heater turned on for 45 minutes. Total electrical power consumption was measured using an ISKRA digital power meter (model MT171-D2A51-V12G12-KO).

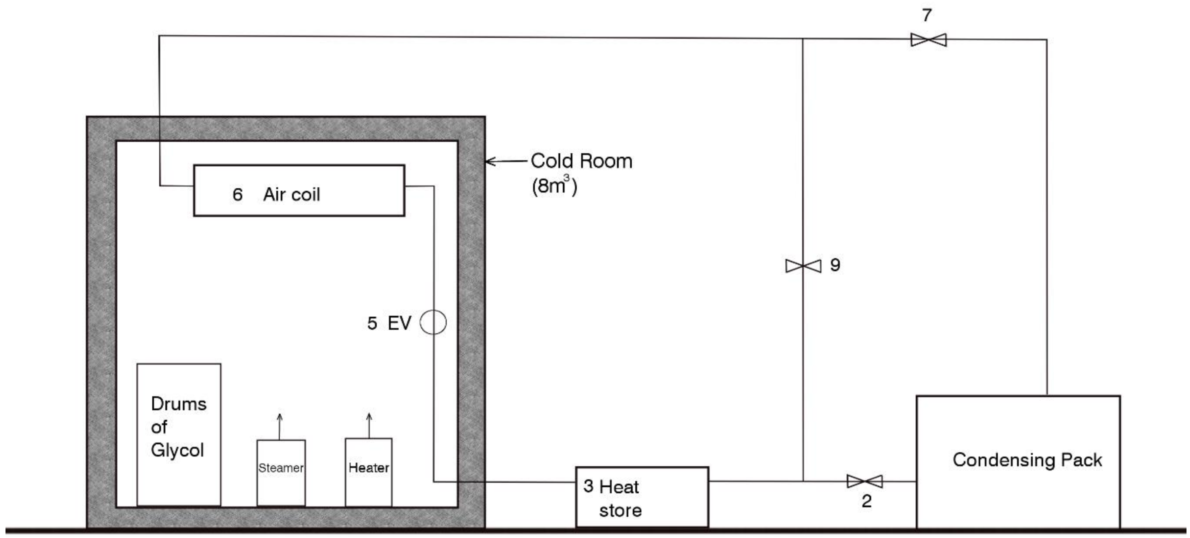

Figure 4: Main elements of the test equipment

Apart from defrost energy consumption another important effect of defrost is the temperature rise of the stored product. To compare the product temperature history during a defrost cycle a tub of ice cream was placed in the volumetric centre of the room and a thermocouple embedded in the centre of the tub.

4. EXPERIMENTAL RESULTS

4.1 RDC tests

4.1.1 Energy consumption: The direct, refrigeration and total electrical energy consumption is shown in Table 1. It can be noted that the total energy saving was thus 40%.

Table 1: Daily energy consumption

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

4.1.2 Product temperature: Because the flash defrost system operates at a low temperature the evaporator coil never rises above 10C so therefore the cabinet and its contents likewise are not subjected to large temperature swings compared with the electric defrost system. This is well illustrated by Figure 5 which shows the averaged recorded core temperatures of all the instrumented m-packs over a series of 6 defrost cycles.

4.2 Walk-in room tests

4.2.1 Energy consumption: For the purpose of comparing the energy performance of both systems a series of 4 consecutive and typical defrost cycles with intervening periods of refrigeration were selected and analyzed for power consumption. The results are shown in Figure 6 where two flash defrosts were performed in the same period as a single electric defrost.

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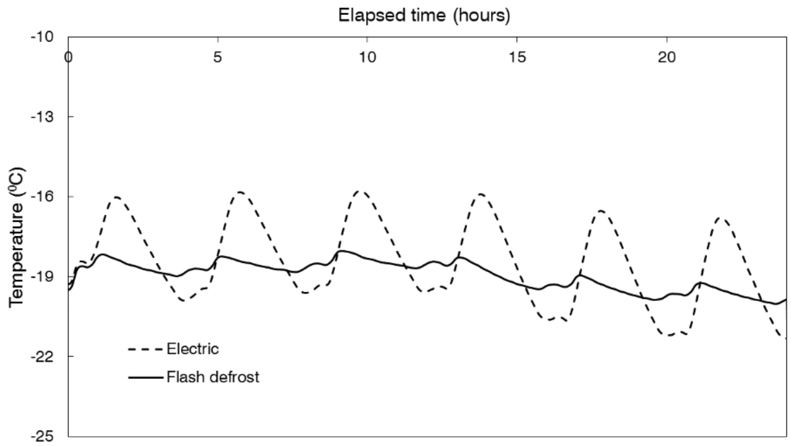

Figure 5: Core temperatures of m packs during and after electric and flash defrosts

Over the period of 4 hours the average electrical power consumption of the refrigeration unit when using the standard electric defrost system was 2.5kW, which is significantly higher than the 2.2kW being used prior to defrost.
By contrast the refrigeration system used an average of 2kW over the same period when the flash defrost system was deployed, which is actually less than the 2.1kW being used prior to the start of defrost. In other words energy is saved by flash defrosting. The optimum frequency of defrosting has yet to be determined.

Table 2: Daily energy consumption

WALK-IN tests	Electric defrost	Flash defrost
TEC (KWh/24h)	360	288

Under the experimental conditions described above the energy saving is 20%. Allowing for seasonal variations the savings will rise in warmer weather (the tests were carried out in January 2014 when the average ambient temperature at the test site was around 7C). A power spike is visible in Figure 6 during the flash defrost and this was caused by the electric heater used to warm the drain pan. This power spike could be reduced or possibly even eliminated by modifying the drain pan design.

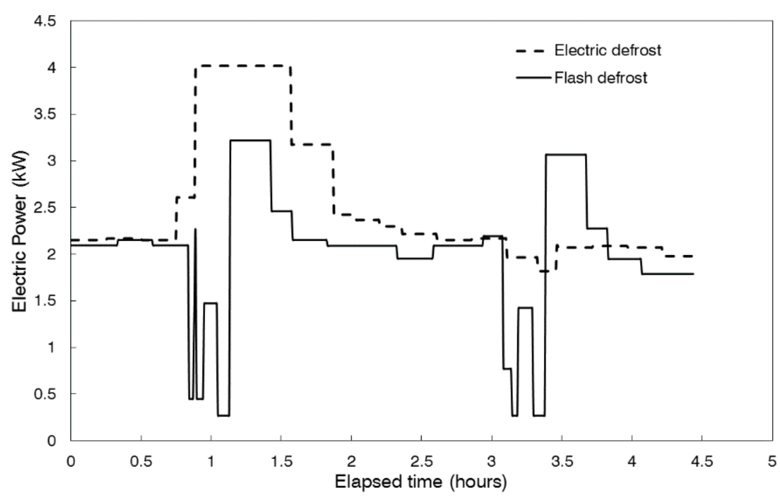

Figure 6: Comparison of the power consumption profiles averaged over 4 defrost cycles for both the electric and flash defrosts

4.2.2 Product temperature: Again because the flash defrost occurs at a low temperature compared with the electric defrost, the room and its contents did not heat up as much, as exemplified in Figure 7.

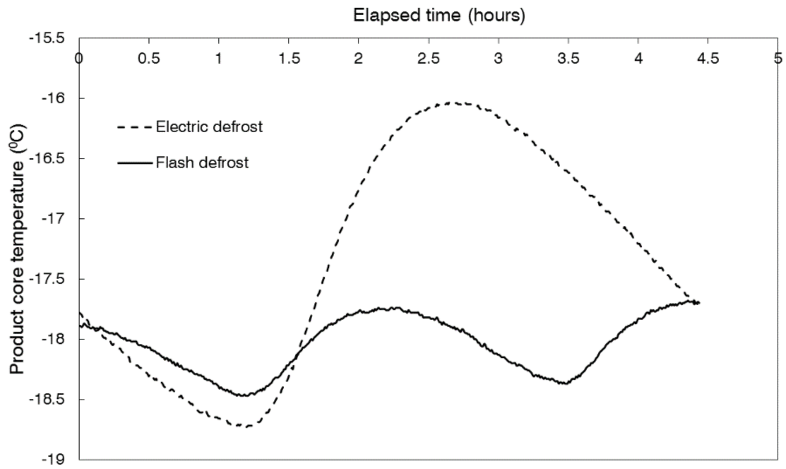

Figure 7: Temporal variations in ice cream tub core temperature for both defrosts

5. DISCUSSION

Both the comparisons between electric defrost and flash defrost described above were made using the same defrost module retrofitted to standard commercial refrigeration circuitry i.e. a heat store was inserted in the liquid line from the condenser and three solenoid valves were used to create an isolated defrost flow loop connecting the heat store to the aircoil so that trapped refrigerant was used to transfer stored heat to the aircoil by a process of boiling and condensation.

5.1 RDC tests

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 flash 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 flash 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:

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

5.2 Walk-in cold room tests

The tests described in this paper were not conducted under rigorously controlled environmental conditions such as those used in the RDC tests. However the test conditions were sufficiently constant for both the electric defrost tests and the flash defrost tests that a reasonable comparison of performance can be made.

- When the flash defrost system was used the overall refrigeration power consumption fell by around 20% and the speed and effectiveness of the process greatly reduced the deviations of the product temperature from the ideal level and, because the defrost was achieved at a low temperature, "steaming" was eliminated.
- A significant additional safety benefit of the flash defrost system is that high voltage power can be eliminated from the air coil in any system employing electric defrost.

5.3 Evaporator temperature

Since the product temperature deviations during flash defrost are much smaller than those measured during the high temperature electric defrosts it is suggested that this will allow the evaporator to be operated at a generally higher temperature than usual, thus leading to even greater reductions in overall power consumption when flash defrost is used.

6. CONCLUSIONS

What is clear from the experimental work carried out on the retail display cabinet and the walk-in cold store is that:

- Flash defrost eliminates the direct use of electrical power for defrost
- Flash defrost limits the temperature rise in frozen food during defrost
- Flash defrost reduces the compressor power used to re-chill the system after a defrost
- Flash defrost allows more frequent and shorter defrosts
- Flash defrost creates the opportunity to raise the evaporator temperature
- Flash defrost creates the opportunity to reduce the size of the evaporator and/or reduce the compressor capacity

7. REFERENCES

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