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HEAT EXCHANGER FROSTING PATTERNS WITH EVAPORATING R404A AND SINGLE PHASE SECONDARY REFRIGERANT

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ABSTRACT

The paper presents experimental results and a comparative analysis of frosting and defrosting of the same heat exchanger under different conditions. It was first used as an evaporator for R404A (in DX mode) and then as a heat exchanger with single-phase secondary refrigerants at low temperatures (-15°C to -30°C, for frozen food and ice cream) in the 8 ft single deck display case. Results reveal more uniform frosting of the heat exchanger when operated with single-phase secondary refrigerant (potassium formate). More uniform frosting results in less reduction in air-flow in refrigerating mode, faster defrost and reduced heat load due to inefficient defrost. These are just some of the reasons for better performance of the display case in indirect refrigeration mode.

INTRODUCTION

An ongoing project at the University of Illinois Air Conditioning and Refrigeration Center (ACRC) is focused on issues related to use of secondary refrigerant for supermarket refrigeration at low temperatures (evaporating temperatures as low as -35°C). Experimental program is focused on display case performance. A system simulation has also been developed. The same state of the art, single deck, low temperature display case, supplied by one of the sponsors, is first tested in baseline mode with R404A evaporating in the evaporator. The same evaporator is later converted into a heat exchanger by removing the TXV, distributor and suction line heat exchanger. Defrost in the baseline mode used a 3kW electric heaters while in tests with secondary loop defrost was done with the warm coolant. Experimental results demonstrated that the same display case operated better when refrigerated by secondary fluid (potassium formate and potassium acetate so far) than with R404A. More details about the performance and the test procedure could be found in Hrnjak (1997a), (1997b), Terrell, Mao, Hrnjak (1997) and Mao, Terrell, Hrnjak (1998). Additional elements needed for analysis in this paper are given in the following paragraph. The focus of this paper is on one of the reasons for better performance: difference in frosting and defrosting of the same coil when used as an evaporator for R404A and heat exchanger for potassium formate.

COMPARISON OF THE DISPLAY CASE PERFORMANCE WHEN OPERATING WITH DIFFERENT REFRIGERANTS

Tests are conducted according to the procedure described in ANSI/ASHRAE Standard 72 - 1983 "Method of testing open refrigerators for food stores" at the Laboratory for Commercial Refrigeration, ACRC, University of Illinois. The display case under the test is placed in environmental chamber and exposed to conditions described in the Standard. The display case is filled with test packages and dummy packages. After repeatable conditions occur, the recorded data for a 24-hour period is treated as one test level (defined by Standard). Repeatability of test conditions is determined by ± 0.2 °C difference in package temperatures at the beginning and end of the 24 hour period. Package temperatures generally take longer to reach steady state compared to other parameters (air and refrigerant temperatures). Adequate refrigerant flow in baseline tests to have minimum superheat for stable operation is supplied as demanded by the case. This is achieved by changing the suction pressure and proper adjustment of the thermoexpansion valve to obtain maximum flow rate and maintain stable superheat signal. More details could be found in Hrnjak, Terrell and Mao (1996, 1997).

The schematic of the display case is shown in Figure 1. It shows the location of the test packages (with thermocouples) and dummy packages along with thermocouples in the air ducts of the display case. The positions of the thermocouples on the heat exchanger are shown in Figure 2. Note that heat exchanger shown is with headers (for secondary refrigerant) but it is the same unit used in baseline tests. The only

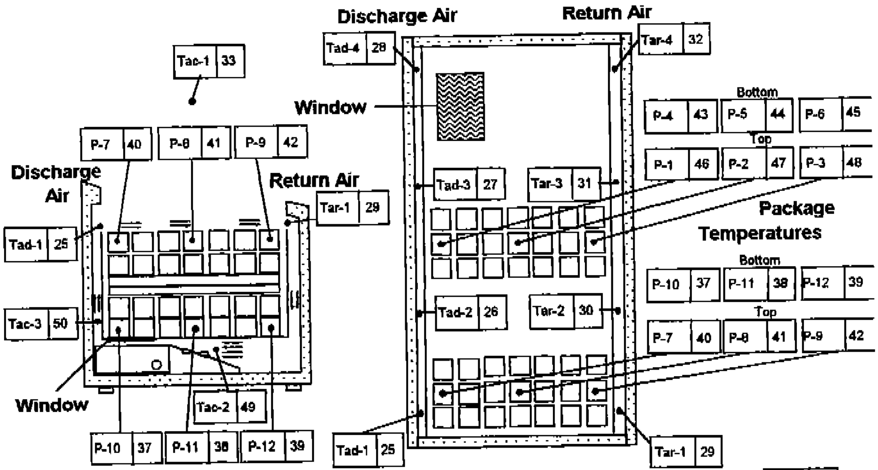


Fig. 1. Position of the test packages in the display case.

difference is that the header replaces distributor and that the suction line heat exchanger used with R404A is eliminated in tests with secondary fluids.

Approach described here is to use existing state of the art display cases, run the baseline tests with refrigerant and oil as in conventional operation, and then compare it to operation when served with single phase secondary refrigerant. Two steps in testing display case with secondary refrigerant are taken:

1. Same heat exchanger as evaporator substituting distributor with the inlet header and
2. Modified heat exchanger that is more suited to single phase secondary refrigerant (fin and tube spacing, circuiting, etc.).

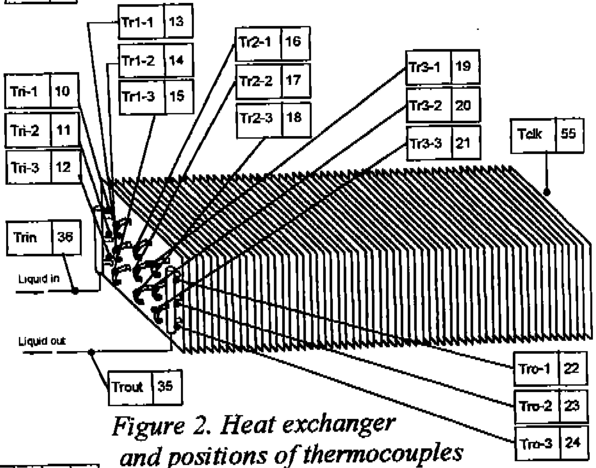


Figure 2. Heat exchanger and positions of thermocouples

Data shown here are the part of the first step. Heat exchanger surface when operating with secondary refrigerant is reduced by removing suction line heat exchanger used in baseline tests.

One key issue is the choice of comparison criteria. Our approach is to compare performance based on product temperature because the purpose of the display case is to maintain product temperature at required level. Even more, we think that the temperature of the warmest test package should be the criterion.

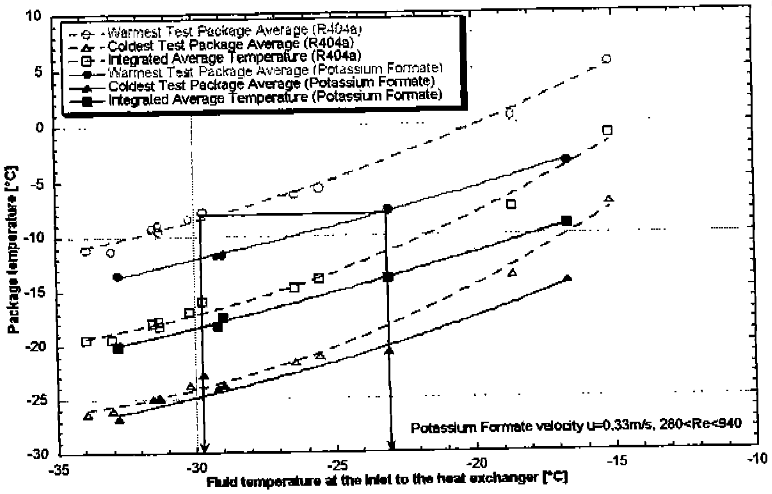


Fig. 3. Package temperatures as a function of the refrigerant inlet temperature to the heat exchanger for conventional (baseline) and indirectly refrigerated display case

The standard prescribes presentation of three package temperatures: the coldest test package average (average temperature of the coldest package in the test period), the warmest test package average and integrated average. The coldest test package is usually at the bottom of the display case (P4), right above the evaporator (heat exchanger), while the warmest package is on the top (P8 or P2), see Figure 1.

Figure 3 shows the performance of the display case when operating with R404A and with potassium formate as the secondary refrigerant. Package temperatures are plotted against the refrigerant temperature at the inlet to the heat exchanger. Three lines are shown for each refrigerant: coldest, average and the warmest package temperatures. Dashed lines represent performance in baseline mode, while solid lines represent performance with the secondary refrigerant (potassium formate). The diagram shows that the same product temperature could be achieved by significantly higher temperature of the secondary refrigerant at the inlet to the coil. For example, to maintain frozen food product temperature at -8°C (warmest test package average) evaporation temperature of R404A should be -29.5°C. At the same time the coldest package is at -25°C. The same average temperature of the warmest product could be achieved with potassium formate at the inlet of the coil at only -23°C. Difference of 6.5°C could be used in chiller.

Natural question is WHY. We have identified several reasons but at this time we will shed some light on differences in frost formation on the coil only.

FROSTING

It is observed that the heat exchanger in both cases (R404A and secondary fluid) accumulate similar quantities of frost for the same conditions (Figure 4 a and b). Accumulated frost is plotted at the left (a) as a function of the difference in absolute humitities or moisture contents in the environmental air and saturated air at the temperature of the cold surface. Since surface temperatures are relatively low, saturation moisture content is almost insensitive to temperature (almost horizontal line in the psyhrometric chart), so the surface temperature has no significant influence and just absolute humidity of the outside air could be used. Diagram (b) on right in Figure 4 reveals that relative humidity could be used as the good parameter over the range used in this study.

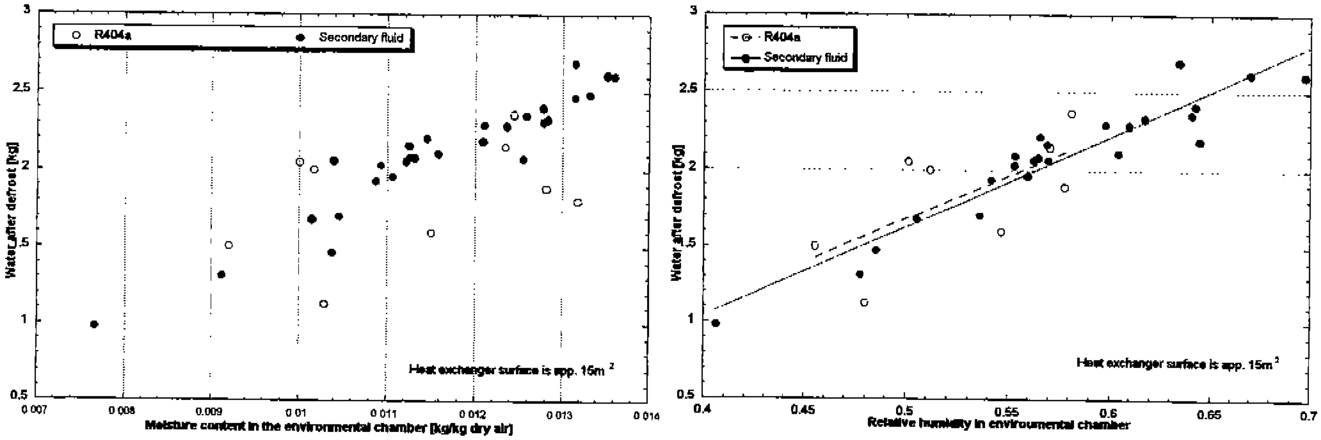


Fig. 4. Frost collected from the same heat exchanger when operated with R404A and potassium formate as a function of moisture content (a) and relative humidity (b) of air in the environmental chamber

The frost formed on the heat exchanger surface when potassium formate was used as the refrigerant was significantly more uniform. It is illustrated by the photos in the Figure 5. It is evident that the trailing edge of the evaporator (R404A) that has fin density 4fpi accumulates much more frost than leading edge (air inlet). The experiment was not designed to measure actual frost thickness but we have determined the change in air-flow across the evaporator (heat exchanger) over the 24h period. Since heat exchanged on the heat exchanger is:

$$Q = m_a * \Delta h_{air} = m_r * \Delta h_{ref}$$

air mass flow rate m_a is determined based on measured refrigerant flow rate m_r and enthalpy difference on air Δh_{air} and refrigerant Δh_{ref} sides. Measurements with anemometer confirmed numbers shown. Reduction in air flow in 24 h for two typical baseline tests (R404A) for two relative humidities are shown in Figure 6 (a) and for secondary refrigerant (potassium formate) in figure 6 (b), for three relative humidities of air in environmental chamber. Note that there are two pairs of very close humidities app. 47% and 57% for baseline and indirect refrigeration tests. The third with secondary fluid is for much more humid air.

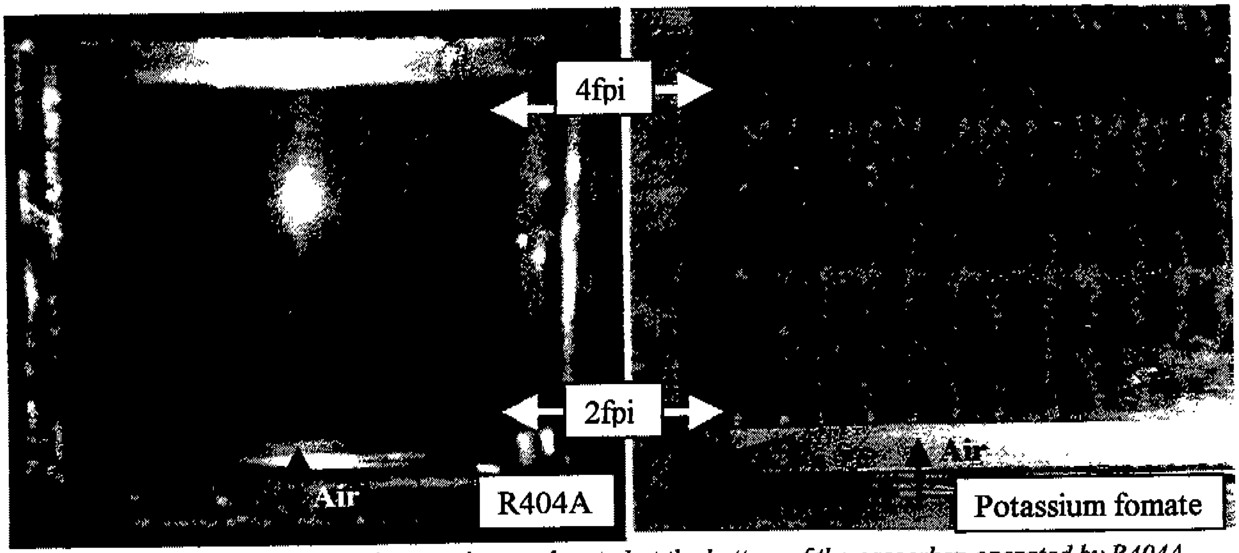


Fig. 5. Top view to the same heat exchanger located at the bottom of the case when operated by R404A (left) and potassium formate (right). Air flow indicated by the arrow. In the case of R404A coil frost is accumulated at the trailing edge reducing the air flow rate

Greater scatter in baseline graphs is due to variation in exit superheat and refrigerant flow. Graphs show the same air flow after the defrost and greater reduction in air flow for baseline (R404A) tests. Figure 7 shows direct comparison of R404A and potassium formate tests at almost identical operating conditions. The graphs show and influence of environmental conditions (humidity) and that the indirectly cooled coil experience initially faster reduction of air-flow (due to pressure drop i.e. frost) and then much less change in the rest of 24 h refrigeration period. Increase in air-flow is due to imperfect experiment. One of explanations for the faster frosting could be found in Figure 8. It shows the difference in defrosting and pull-down for DX and indirectly refrigerated modes.

Two tests are chosen with almost identical refrigerant inlet temperatures (app. -30°C) to the heat exchanger. Solid lines are for tests with secondary refrigerants and dashed for baseline tests. Lines with more intense change are air temperatures in and out of the heat exchanger. Other lines are temperature

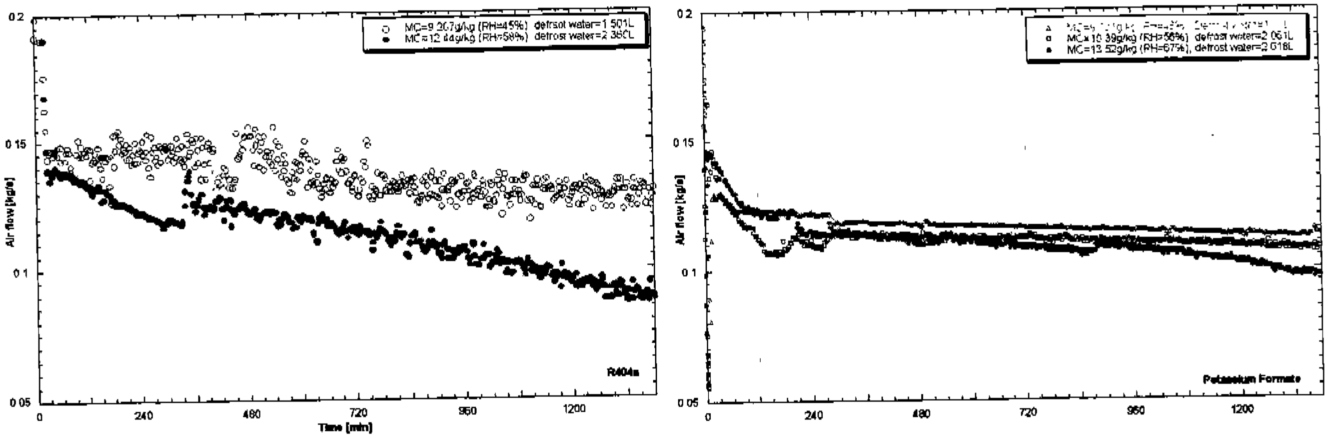
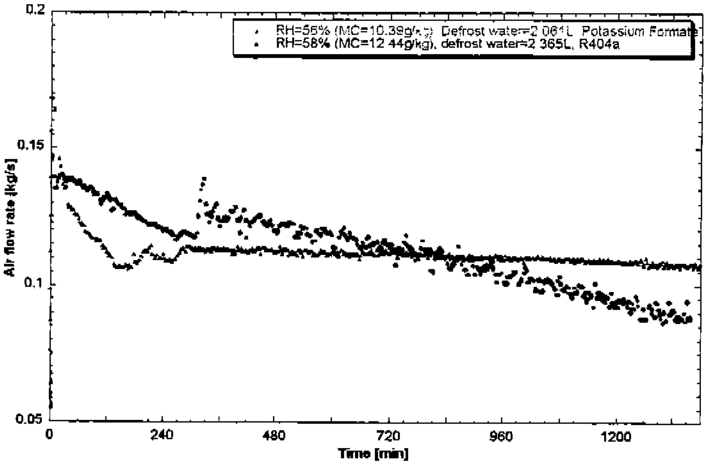


Figure 6. Reduction in air flowrate due to frost when display case is refrigerated conventionally (DX evaporator) - (a) and indirectly, with potassium formate (b)



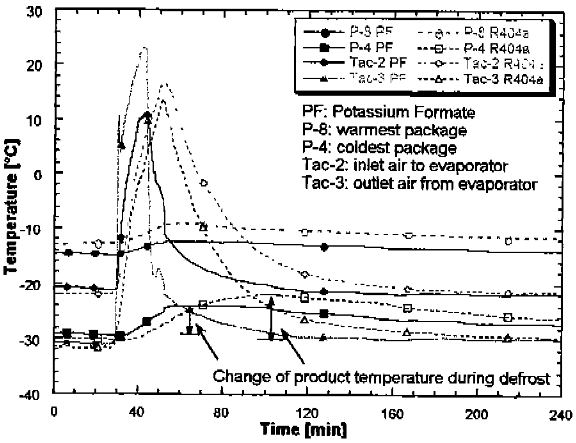
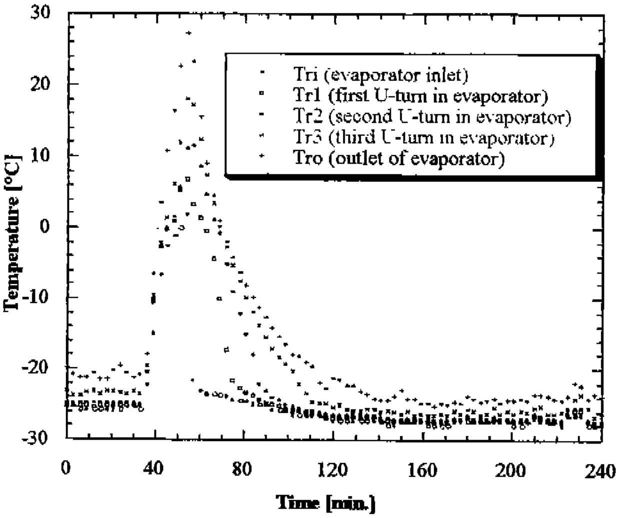


Figure 7. Different reduction in air-flow due to nonuniform frosting in conventional (DX evaporator) and more uniform indirectly cooled (with potassium formate)

Figure 8. Air and product temperatures during defrost when display case is refrigerated conventionally (DX evaporator) and indirectly (with potassium formate)



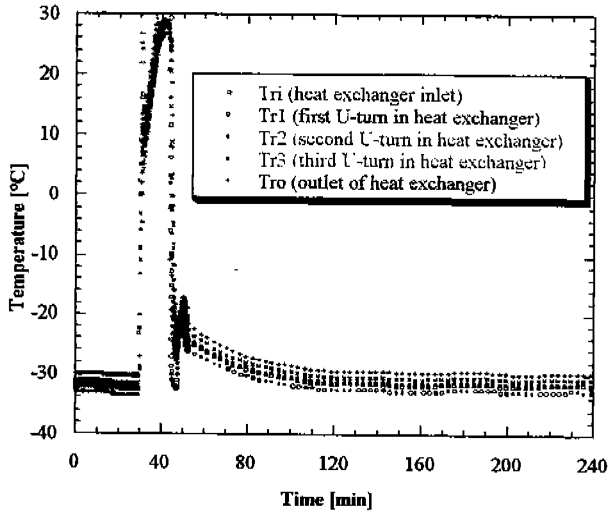


Figure 9. Refrigerant temperatures in the evaporator when in baseline DX (R404A) mode

Figure 10. Secondary refrigerant temperatures in the heat exchanger when served by secondary refrigerant

profiles for the warmest (P-8) and the coldest (P-4) test package. The locations are shown in Figure 1. This graph reveals that defrost is finished much faster with secondary fluid (the peak that defines moment when heating is reversed in refrigeration occurs earlier). The temperature in the center of the coldest package is being changed by approx. 8°C in DX defrost while with secondary refrigerant is much less - only 4.8°C mode (indicated by arrows). Graph also shows that the pull-down period in tests with secondary refrigerant are much faster (solid lines reach close to steady state in 65min (110-42) vs. 160min (168-52) in DX mode. This is the consequence of faster defrost and better location of the heat source. Some reasons for this are shown in figures 9 and 10. These two graphs show the change in refrigerant temperatures in baseline (Figure 9) and with secondary refrigerant mode (Figure 10) along the heat exchanger: at the inlet to heat exchanger T_{ri}, in the first T_{r1}, second T_{r2}, third T_{r3} U bend, and at the exit T_{ro}. The heat exchanger has three passes, each eight 5/8" tubes 2 m long in staggered arrangement. The heat exchanger is cross flow, overall counter flow (see Fig. 2 for details and positions of thermocouples).

Figure 9 shows that the superheat in steady operation before defrost was approx. 5°C (difference between T_{ri} and T_{ro}). After defrost almost whole heat exchanger is filled with vapor, even evaporation pressure is pulled down very quickly. It is visible that it takes long time to gradually fill the whole evaporator with two-phase refrigerant. Naturally, operating temperature in most of the evaporator, exit pipes in particular, is higher than it could be. Consequently heat flux at the inlet at the refrigerant inlet (where fins are dense) is much higher. This is the reason why there is much more and fluffier frost in this zone. Heat flux at the exit is low because heat transfer coefficient and temperature difference is low. Figure 10 shows how quick is the temperature drop in the indirectly refrigerated coil. That is the reason why the frost builds so much faster than with R404A. The same diagram reveals very uniform temperature glide in secondary refrigerant coil. This is the reason, along with the constant heat transfer coefficient at the refrigerant side and in time why frosting is so uniform. It should be noted that the greatest local humidities occur just after defrost when evaporator and surrounding surfaces are wet and this is the time when coil with secondary refrigerant has good performance.

Consequently, defrost of the coil with secondary refrigerant is much quicker. We have additional information but we do not have space to elaborate on this issue. We will provide these information in communications that follow. Reduction of defrost time has several positive effects: shorter defrost reduces the heat input into the display case and consequently it reduces the load in refrigeration mode, increases time available for refrigeration, etc.

CONCLUSIONS

Test results shown in Figure 3 show that the performance of the display case refrigerated with potassium formate at low temperatures is better than in the baseline mode (using the same heat exchanger as R404A evaporator). It is because the same product temperature can be achieved with higher temperature of secondary refrigerant than R404A.

Frost formed on the surface of the heat exchanger in indirectly refrigerated mode is more uniform. It is demonstrated by the photographs and by faster reduction of air-flow for the same water after defrost.

Defrost and pull-down is faster and product temperature (measured in the center of the test package) undergoes much smaller temperature change.

More uniform frosting allows for greater fin density. Additionally, more uniform frost results in a smaller reduction of air flow as defrost time is being approached, thus increasing both air side heat transfer by increasing temperature difference compared to operation in DX mode.

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