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Fault Detection and Diagnostics for Commercial Coolers and Freezers

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ABSTRACT

Most of the previous diagnostics research for vapor compression equipment has been performed for packaged air conditioners and chillers. This paper describes application of a decoupling-based diagnostic technique that was originally developed for air conditioners to equipment used in walk-in coolers and freezers. Testing was performed on a small, restaurant-style walk-in cooler and a small walk-in freezer for faulted and un-faulted conditions. The data was then used to characterize how the fault features respond to faults and to evaluate the performance of the decoupling-based diagnostic technique.

1. INTRODUCTION

In general, HVAC&R systems are not well maintained [Proctor and Downey (1995), Cowan (2004), Li and Braun (2007a)] because of the relatively high cost of service and low cost of energy. Recently, a diagnostic method was developed for vapor compression equipment that handles multiple-simultaneous faults [Li and Braun (2007b)] through the use of decoupling features [Li and Braun (2007c)]. Decoupling features are parameters that are uniquely influenced by individual faults and are insensitive to variations in ambient conditions. For example, air mass flow rate through the condenser is a feature that is strongly influenced by the level of fouling and condenser fan problems but is nearly independent of other faults that can occur for air conditioning systems that incorporate fixed-speed fans.

In developing decoupling features, it is important to utilize low cost sensors, such as temperatures. These low-cost measurements are used in simple models as virtual sensors to infer other system measurements. For example, as described by Li and Braun (2007c) condenser air flow can be estimated using an energy balance with air and refrigerant-side measurements. For this energy balance, the refrigerant flow is estimated using a compressor map as a virtual sensor. Furthermore, virtual evaporating and condensing pressure sensors utilize surface mounted temperature measurements at locations where saturated conditions exist and property relations to estimate saturation pressures. The virtual and physical measurements are used to determine the decoupling features for diagnostic purposes. When a decoupling feature deviates significantly from its normal value then a fault is indicated (e.g., low condenser air flow for fouling or fan problems).

The decoupling-based FDD method was originally developed for air conditioning (AC) systems. Although the vapor compression equipment used for commercial refrigerators and freezers are very similar to those used for air conditioning, operation occurs over a different range of temperatures and the systems utilize different refrigerants. In addition, commercial refrigeration equipment typically utilize liquid-line receivers which are not generally employed for air conditioners. In the current paper, the decoupling-based FDD method is applied to equipment used in small-scale walk-in coolers and freezers. Faults were artificially introduced in the laboratory and the performance of the diagnostic method was evaluated. A more detailed presentation of the evaluation is presented by Wichman and Braun (2007).

2. WALK-IN COOLER AND FREEZER EXPERIMENTS

Walk-in cooler and freezer units were tested within psychrometric chambers to allow control of the condenser air inlet conditions. Figure 1 shows a picture of the cooler unit and walk-in cabinet. The walk-in cooler and freezer experiments utilized the same refrigerated space but with different refrigeration equipment. The cooler system utilized R-22 as the refrigerant, whereas the freezer unit employed R-404A. Both systems were equipped with a

TXV expansion valve and a liquid line receiver. The receiver provides a volume for liquid refrigerant to collect after it exits the condenser. This volume keeps the refrigerant exiting the condenser in a saturated liquid state during operation unless the unit is overcharged to the point where the receiver is completely filled with liquid refrigerant. When the receiver is full, then additional charge added to the system will back up in the condenser and lead to subcooling of the refrigerant exiting the condenser under steady operating conditions. The liquid line receiver is shown in Figure1.

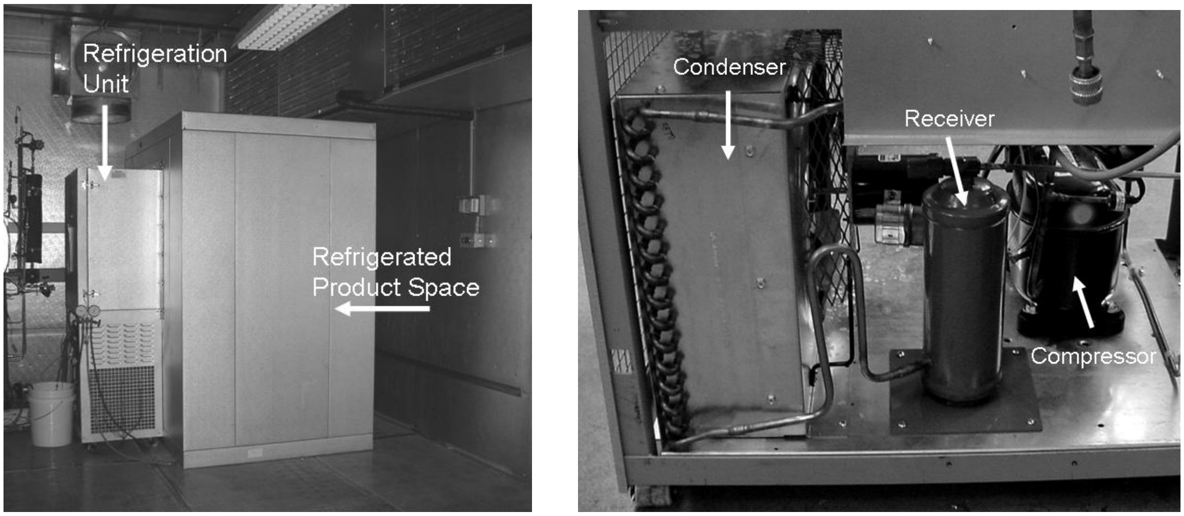

Figure 1: Walk-in cooler inside the psychrometric chamber.

Figure 2 shows a schematic of the refrigerant cycle depicting the methods used for simulating faults and the measurements taken. Refrigerant undercharge, refrigerant overcharge, liquid line restriction, compressor valve leakage, condenser fouling and evaporator fouling were considered. Compressor valve leakage is meant to include any fault within the compressor that leads to a loss in volumetric efficiency and refrigerant flow rate. A leaky compressor valve allows high pressure refrigerant to flow back to the low pressure side of the system which lowers the volumetric efficiency of the compressor and lowers the mass flow rate of the system. To simulate a loss in compressor volumetric efficiency, a bypass line with a flow control valve was added around the compressor which can be opened to allow refrigerant to flow from the high pressure side of the system to the low pressure side. Heat exchanger fouling in vapor compression equipment can be characterized as a decrease in airflow across the coils. Previous work [Pak et al. (2005) and Yang et al. (2007)] has demonstrated that the primary effect of air-side heat exchanger fouling is an increased pressure drop leading to a reduced air flow rate. Fouling was simulated for both the condenser and evaporator by connecting fan speed controllers to control the air flow rates across the heat exchangers. During operation, a vapor compression system can experience clogging of the filter dryer which restricts the flow through the liquid line. In a system with a fixed orifice expansion device, a liquid line restriction can lead to a reduced mass flow rate. The walk-in cooler tested uses a TXV which can compensate for the pressure drop incurred for moderate restrictions and keep the refrigerant flow rate relatively constant. For severe restrictions, the TXV will saturate, opening fully and act like a fixed orifice. A flow control valve was added to the liquid line which was partially closed to simulate this fault.

For the cooler, each individual fault was simulated at three different ambient conditions (T_{cai}). Five fault levels were tested and characterized by percent of nominal cooling capacity. The nominal cooling capacity was determined in the un-faulted condition or 0^{th} fault level test. Fault levels were chosen so that the degradation in cooling capacity would occur in even increments with the maximum degradation depending on the fault type. The compressor valve leakage and liquid line restriction faults degraded cooling capacity by over 50%, and undercharging the system degraded capacity around 20%. Slowing the heat exchanger fans over the test range degraded the capacity by only 10%. Overcharging the refrigerant had very little effect because of the presence of a receiver. Four combinations of multiple faults were tested for the cooler. For these tests, the system was undercharged by 50% and four other faults were applied to the system, all at maximum fault levels defined by the single fault tests.

Based on knowledge gained during testing of the walk-in cooler, a smaller test matrix was employed for the freezer.

Only one ambient condition was tested. The overcharging tests on the cooler showed that a liquid line receiver prevents overcharging from being a fault that affects performance of the system. Therefore, no overcharging tests were performed on the freezer. Multiple fault tests were run on the freezer combining evaporator fouling with the other four faults. One of the concerns with a freezer is ice accumulation and distinguishing it from evaporator fouling. To gather data on this phenomenon, an ice accumulation test was performed.

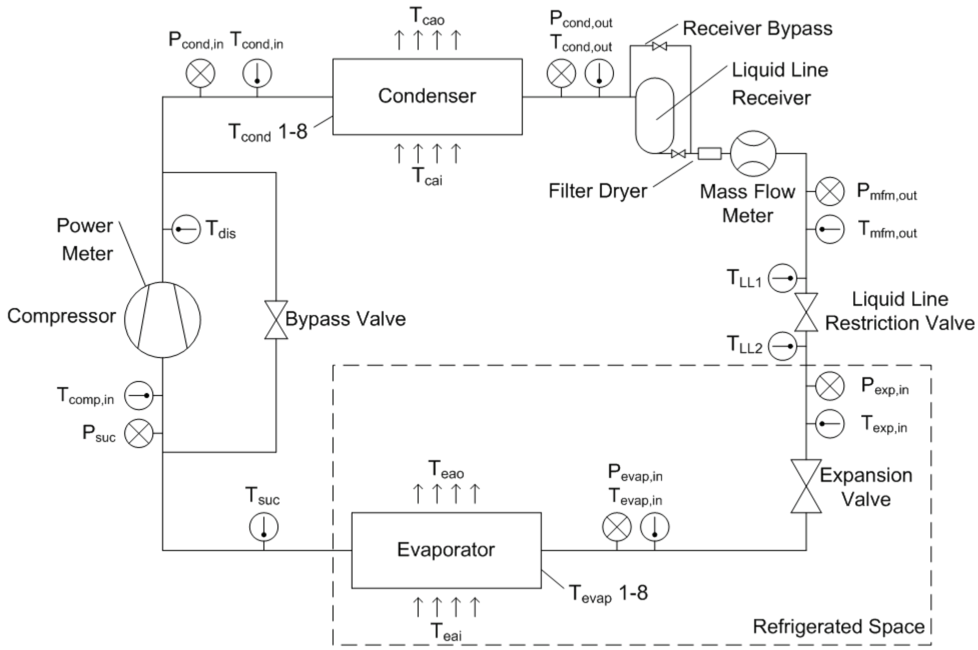

Figure 2: Cooler cycle diagram with added instrumentation.

3. DECOUPLING FEATURES

The decoupling features are based on the work presented by Li and Braun (2007c) and rely on the use of virtual sensors to achieve low cost with a requirement for only temperature sensors. Table 1 presents the decoupling features used to diagnose each fault along with the necessary temperature measurements and virtual sensors to evaluate the features for each fault. Table 2 describes the measurements and models used for the virtual sensors.

As compressor valve leakage (or a similar fault) develops the volumetric efficiency of the compressor decreases. This decreases the refrigerant mass flow rate, which in turn, decreases the discharge enthalpy. In order to detect this type of fault, a simple model is used to estimate the nominal discharge temperature (T_{dis}) from the compressor. This expected value is then compared to the measured T_{dis}. The normal discharge enthalpy is calculated using a steady-state energy balance on the compressor including power input, heat loss, and enthalpy change of the refrigerant flow stream. The refrigerant flow, power consumption and heat loss are estimated using virtual sensors as outlined in Table 2.

A liquid line restriction fault is meant to represent a dirty filter dryer. In a typical air conditioning system, there is usually about 15°F of condenser subcooling. This makes it difficult to use a temperature drop across the filter dryer (ΔT_{ll}) as a fault indicator because it would require a large pressure drop to get the refrigerant to change phase and generate a large enough ΔT_{ll} for detection. However, for systems with a liquid line receiver, the refrigerant at the condenser exit is a saturated liquid. Therefore, it requires a very small pressure drop in the liquid line to get the refrigerant to change phase. For detection of a liquid-line restriction, using two temperature measurements across the filter dryer is adequate since a change in temperature can be directly correlated to pressure drop.

Condenser fouling occurs as a result of dirt and debris, whereas evaporator fouling is meant to represent a dirty filter or a frost accumulation. The primary impact of any of these fouling types is a reduction in air flow. In order to detect fouling faults, virtual sensors for air volumetric flow rate are employed. The air flow rates are determined using energy balances on the condenser and evaporator using temperature and virtual measurements. The effect of moisture removal is neglected for the evaporator since the humidity ratios and moisture removal rates are low at the low temperatures associated with cooler and freezer applications.

The difference between the superheat at the evaporator exit and the subcooling at the condenser exit is used as the decoupling feature to detect high or low refrigerant charge. This feature is incentive to charge until the liquid-line receiver is either empty or full. When the system is undercharged to the point where the receiver is empty, there should be two-phase refrigerant in the liquid line. This causes the TXV to fully open and lose control of the superheat. Undercharging the system further should cause superheat to increase while subcooling should remain approximately equal to zero. At the other extreme, when the receiver is completely full then refrigerant will back up in the condenser and additional charge will cause an increase in the condenser subcooling. However, the superheat should remain relatively constant for overcharging. Since superheat only changes for low refrigerant charge and subcooling only varies for severe overcharging, the simple decoupling feature is reasonable

Table 1: Fault decoupling features and measurement requirements

Fault	**Decoupling Feature**	**Temperature Measurements**	**Virtual Measurements**
Compressor Valve Leakage	T_{dis}-$T_{dis,normal}$	T_{dis}, T_{suc}	P_{suc}, $P_{cond,in}$, $\dot{m}_{ref}$, $\dot{W}_{comp}$, $\dot{Q}_{comp,loss}$
Liquid Line Restriction	$T_{LL,1}$-$T_{LL,2}$	$T_{LL,1}$, $T_{LL,2}$	-
Condenser Fouling	$\dot{V}_{ca}$	T_{cai}, T_{cao}, T_{dis}, $T_{cond,out}$	$P_{cond,in}$, $P_{cond,out}$, $\dot{m}_{ref}$
Evaporator Fouling or Frost Accumulation	$\dot{V}_{ea}$	T_{eai}, T_{eao}, T_{suc}, $T_{cond,out}$	P_{suc}, $P_{cond,out}$, $\dot{m}_{ref}$
Low or High Refrigerant Charge	T_{sh}-T_{sc}	T_{suc}, $T_{cond,out}$	P_{suc}, $P_{cond,out}$

Table 2: Virtual sensors measurement and modeling requirements

Virtual Sensor	**Temperature Measurements**	**Virtual Measurements**	**Model**
P_{suc}	$T_{evap,in}$	-	Saturation pressure for refrigerant evaluated at the refrigerant temperature entering the evaporator ($T_{evap,in}$). Assumes negligible pressure drop across the evaporator. Insulated surface temperature measurement is sufficient.
$P_{cond,in}$, $P_{cond,out}$	T_{cond}	-	Saturation pressure for refrigerant evaluated at the temperature of a return bend within the two-phase section of the condenser (T_{cond}). Assumes negligible pressure drop across the condenser. An insulated surface temperature measurement is sufficient. For the cooler and freezer in this study, the fifth return was found to work well for the condenser.
$\dot{m}_{ref}$	T_{suc}	P_{suc} , $P_{cond,in}$,, $\dot{W}_{comp}$, $\dot{Q}_{comp,loss}$	Compressor performance map for refrigerant flow rate in terms of inlet pressure (P_{suc}) and temperature (T_{suc}) and outlet pressure ($P_{cond,in}$). Alternatively, an overall energy balance is employed when a compressor leakage fault has been identified.
$\dot{W}_{comp}$	$T_{evap,out}$	P_{suc} , $P_{cond,in}$,	Compressor performance map for power in terms of inlet pressure (P_{suc}) and temperature (T_{suc}) and outlet pressure ($P_{cond,in}$). The power is relatively insensitive to a compressor leakage fault.
$\dot{Q}_{comp,loss}$	T_{suc}, T_{dis}, T_{amb}	-	An empirical correlation for compressor heat loss rate.

4. FAULT FEATURE CHARACTERISTICS

In this section, individual fault features are presented as a function of percent capacity degradation associated with different individual faults. The cooling capacity of the 0th fault level was taken as a baseline value for determining percent capacity degradation. Cooling capacity degradation was chosen as a general indicator of the severity of fault because it is more sensitive to fault level than efficiency degradation. Furthermore, for refrigeration equipment, lost cooling capacity could mean the loss of valuable refrigerated or frozen product, which is more important than lost efficiency. Only sample results are presented in this section that highlight particular performance characteristics and problems. The fault features were calculated for two cases: 1) using all of the measured data and 2) using temperature sensors only with virtual sensors.

4.1 Compressor Valve Leakage

Figures 3 and 4 show the effects of capacity degradation due to compressor valve leakage on discharge temperature residuals for the walk-in cooler and freezer. This fault feature increases with fault level for both systems with either real or virtual sensors. However, the discharge residual is much less sensitive to capacity degradation for the cooler than for the freezer. The small dependence of discharge temperature residual on capacity degradation for compressor valve leakage fault with the cooler is problematic because this feature also depends on condenser fouling. This effect may be due to an inadequate heat loss model for the compressor. The compressor heat loss is much more significant for the cooler application than for the freezer application because of higher suction pressures and temperatures. Therefore, model errors have a more significant effect on discharge temperature for the cooler.

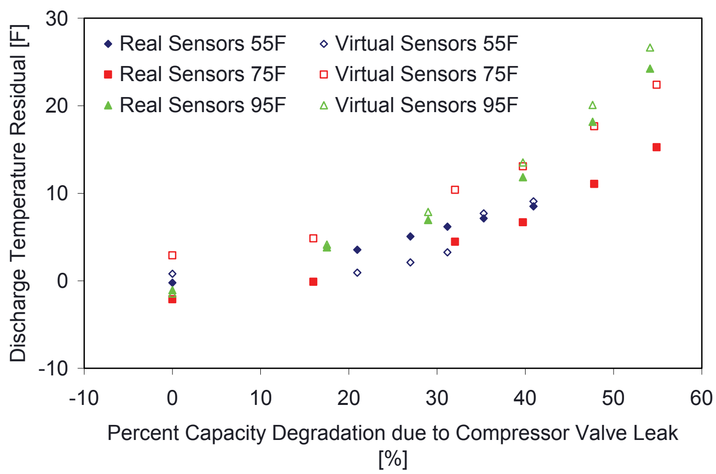

Figure 3: $T_{dis,residual}$ vs. % capacity degradation due to compressor valve leakage for the walk-in cooler.

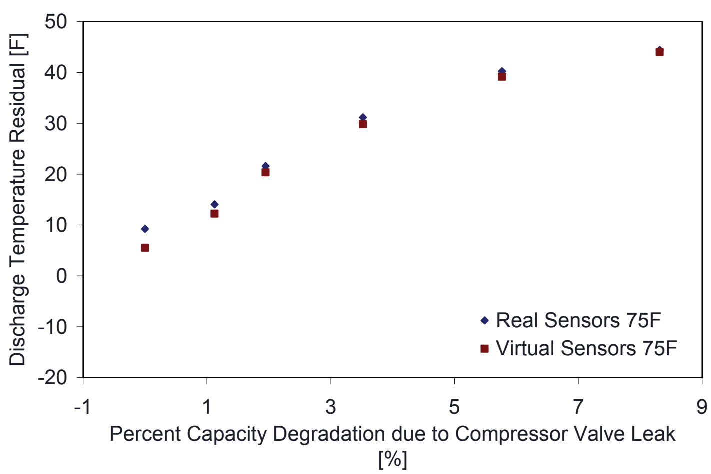

Figure 4: $T_{dis,residual}$ vs. % capacity degradation due to compressor valve leakage for the walk-in freezer.

The compressor valve leakage fault also caused the feature for low refrigerant charge to increase at high fault levels for the walk-in cooler. As the compressor flow is reduced, the TXV must open to maintain the target superheat. At severe fault levels, the TXV saturates open and the superheat increases. This could potentially lead to a false alarm for low charge for capacity degradations greater than about 40%. However, this may not be a problem because the compressor fault would normally be identified at lower fault levels before the charge feature was affected. Furthermore, false alarms could be avoided for individual faults because the diagnostic feature for compressor valve leakage would take precedence. In other words, if the compressor temperature discharge feature exceeded a threshold for this fault then the refrigerant charge feature would be ignored. However, under some circumstances it may not be possible to remotely diagnose both low refrigerant charge and compressor valve leakage if they were simultaneously present. In this case, a technician might need to visit the unit and use a sight glass to determine whether the refrigerant charge were low prior to deciding whether to replace the filter drier.

4.2 Condenser and Evaporator Fouling

Figures 5 and 6 show the impacts of condenser and evaporator fouling level on virtual condenser and evaporator air flow rates. These features are very sensitive to the level of fouling and decrease by about a factor of two for about a 5% degradation in cooling capacity. Very similar results were obtained for the freezer. Furthermore, these features were insensitive to the other faults considered.

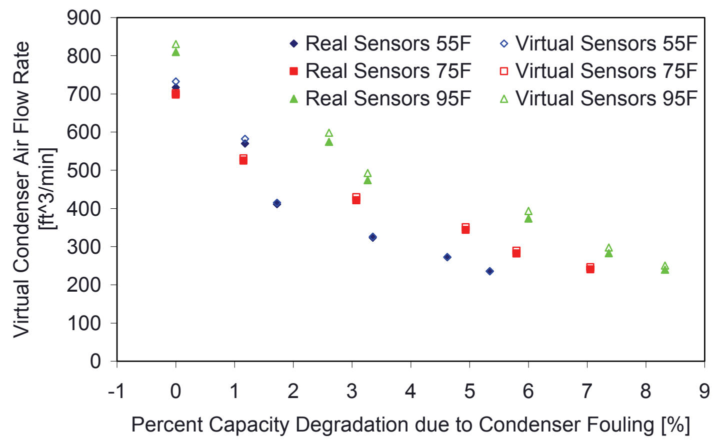

Figure 5: Virtual condenser air flow rate vs. % capacity degradation due to condenser fouling for walk-in cooler.

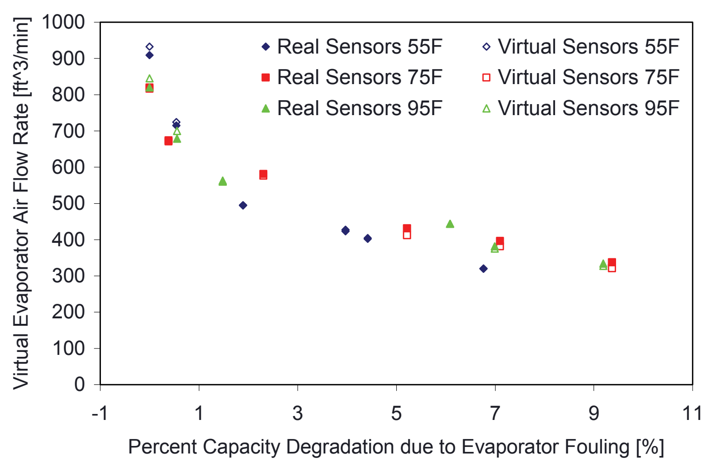

Figure 6: Virtual evaporator air flow rate vs. % capacity degradation due to condenser fouling for walk-in cooler.

One of the issues for the walk-in freezer is to be able to distinguish evaporator fouling from ice accumulation on the heat exchanger prior to a defrost cycle. To characterize the ice buildup, an ice accumulation test was run by introducing a moisture source inside of the freezer compartment. Figure 7 shows the output from the virtual evaporator air flow rate sensor over time during the ice build up. This is a good indicator of the frost accumulation and could be used as part of a "smart" defrosting scheme to determine the need for defrosting. Although not shown in this figure, the virtual evaporator air flow feature returned to a normal value of about 1200 cfm after a defrost cycle. As a result, evaporator fouling and ice accumulation could easily be distinguished within a fault detection system. After a defrost cycle and when steady state conditions are achieved, the evaporator air flow rate should return to a normal, un-faulted value. If the evaporator were fouled, then a defrost cycle would not return the virtual evaporator air flow indicator to normal and a fault could be flagged.

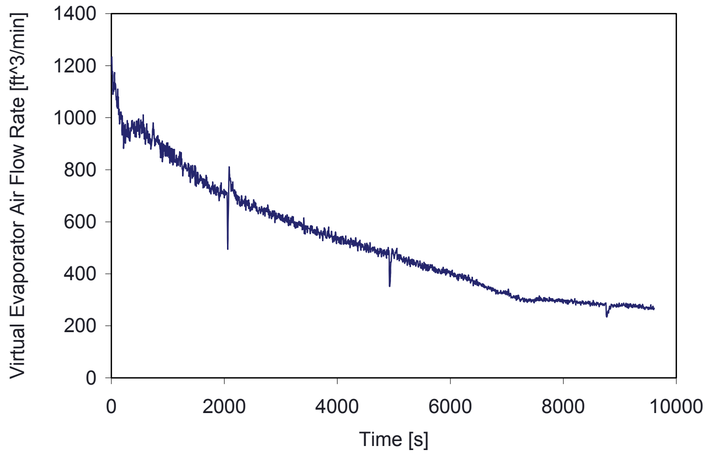

Figure 7: Virtual evaporator over the course of the ice accumulation test.

4.3 Liquid Line Restriction

Figure 8 shows the effect of capacity degradation due to liquid line restriction on the liquid line temperature difference for the cooler. This fault feature increases significantly with fault level for all three ambient conditions. However, the impact is less at lower ambient temperatures due to a lower pressure ratio for the system. For the same fault level, the pressure drop across the restriction is larger for higher ambient temperatures, which increases the temperature drop across the restriction. Very similar results were obtained for the freezer.

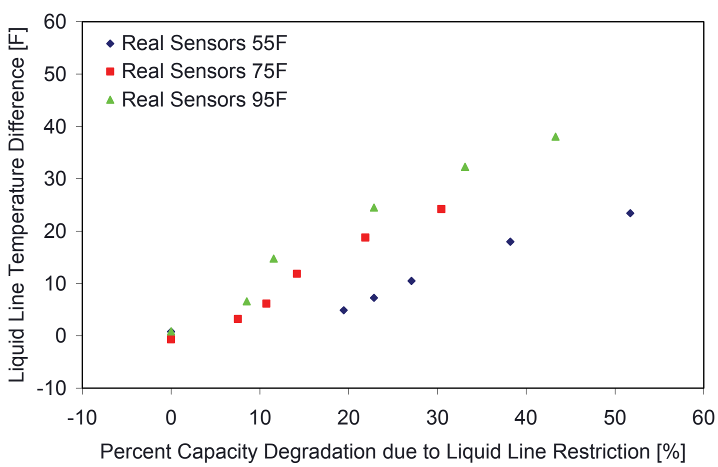

Figure 8: Liquid line temperature difference vs. % capacity degradation due to a liquid line restriction for the walk-in cooler.

The liquid line restriction also caused the feature for low refrigerant charge to increase. This occurs because of an interaction with the TXV. As the refrigerant flow is reduced with a liquid line restriction, the TXV must open to maintain the target superheat. At a sufficient fault level, the TXV saturates open and the superheat increases. Although the refrigerant charge feature is sensitive to liquid line restriction, false alarms can be avoided for individual faults because the diagnostic feature for liquid line restriction would take precedence. In other words, if the liquid line feature exceeded a threshold for this fault then the refrigerant charge feature would be ignored. However, it may not be possible to remotely diagnose both low refrigerant charge and a liquid line restriction if they were simultaneously present. In this case, a technician would need to visit the unit and use a sight glass to determine whether the refrigerant charge were low. A liquid line restriction did not cause changes in other fault features that would lead to false alarms.

4.4 Refrigerant Charge

Figure 9 shows the effect of refrigerant charge level on capacity degradation for the walk-in cooler. Overcharging the system has very little effect on performance because of the liquid line receiver. There is a small impact of very high charge levels at low ambient temperatures at the point where the receiver becomes full of refrigerant. Reduced charge does have an impact on cooling capacity once the charge is less than about 80% of the nominal charge. At this point, the liquid line receiver is empty and the TXV saturates at a fully open position. This leads to an increasing superheat and fault feature with decreasing charge as demonstrated in Figure 10. Similar results were obtained for the freezer. Low or high refrigerant charge did not have a significant effect on other fault features and would not lead to false alarms. Although it is not possible to detect system overcharging for these systems, this is not a problem because overcharging does not impact system performance.

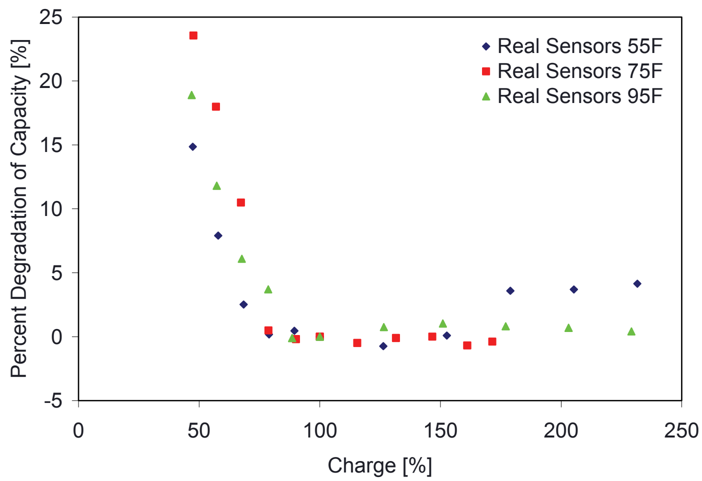

Figure 9: Percent capacity degradation as a function of charge for the walk-in cooler.

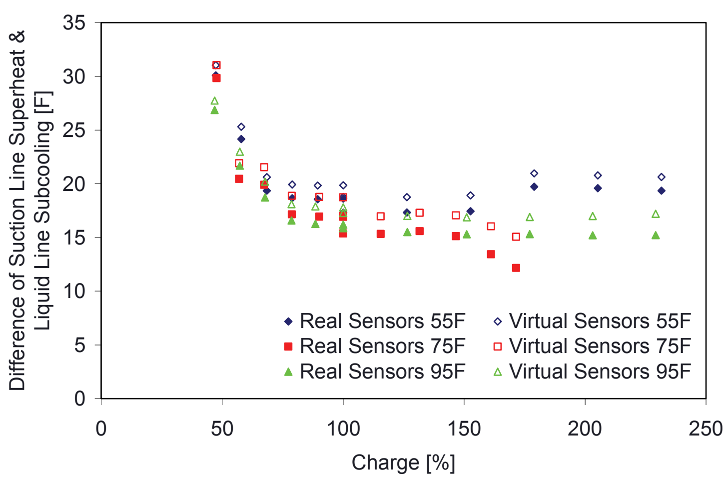

Figure 10: Difference in T_{sh} and T_{sc} as a function of percent nominal charge for the walk-in cooler.

5. OVERALL DIAGNOSTIC PERFORMANCE

Fault features determined using data from the experiments were used along with fault thresholds to determine the levels at which faults could be detected and to identify false alarms. Thresholds for each of the decoupling features were chosen to correspond to a 5% degradation in cooling capacity. Virtual sensors were used for this evaluation to represent actual implementation of the decoupled diagnostic method. Tables 3 and 4 give results for fault detection sensitivity. For the single fault tests on both the walk-in cooler and freezer there were no missed faults. The diagnostic method was able to detect compressor valve leak, condenser fouling, and liquid line restriction at the first fault level implemented on the cooler. Liquid line restriction was detected at the first level on the freezer as well.

Table 3: Fault levels where the algorithm could first diagnose individual faults for the walk-in cooler.

Fault	Ambient Temperature [F]	Fault Level	Degraded Capacity [%]
Compressor Valve Leakage	55	1st	21.0
Compressor Valve Leakage	75	1st	16.0
Compressor Valve Leakage	95	1st	17.5
Condenser Fouling	55	1st	1.2
Condenser Fouling	75	1st	1.2
Condenser Fouling	95	1st	2.6
Evaporator Fouling	55	2nd	1.9
Evaporator Fouling	75	3rd	5.2
Evaporator Fouling	95	3rd	6.1
Liquid Line Restriction	55	1st	19.4
Liquid Line Restriction	75	1st	7.5
Liquid Line Restriction	95	1st	8.5
System Undercharge	55	4th	7.9
System Undercharge	75	3rd	10.5
System Undercharge	95	3rd	6.1

Table 4: Fault levels where the algorithm could first diagnose individual faults for the walk-in freezer.

Fault	Ambient Temperature [F]	Fault Level	Degraded Capacity [%]
Compressor Valve Leak	75	3rd	3.5
Evaporator Fouling	75	3rd	3.0
Liquid Line Restriction	75	1st	22.5
System Undercharge	75	4th	11.9

6. CONCLUSIONS

In general, the decoupling features developed for compressor valve leakage, condenser fouling, evaporator fouling, liquid line restriction faults, and refrigerant charge should work well for diagnostics applied to vapor compression systems used in walk-in coolers and freezers. However, it was found that the refrigerant charge feature is not completely decoupled from liquid line restriction and compressor valve leakage faults at high fault levels. Systems that utilize a liquid line receiver and TXV are insensitive to charge until the system becomes starved and the TXV saturates open. A saturated TXV leads to an increase in superheat which is used to indicate low refrigerant charge. However, the TXV can also be saturated open when refrigerant flow is reduced significantly due to a high level of compressor valve leakage or a severe liquid line restriction.

Although the refrigerant charge feature is sensitive to liquid line restriction and compressor valve leakage faults, false alarms can be avoided for individual faults because the diagnostic features for these other faults work well and would identify the appropriate fault in the absence of low charge. However, it is not possible to identify multiple fault combinations of low refrigerant charge and either compressor valve leakage or liquid line restriction. Furthermore, it is not possible to determine overcharging of refrigerant with this feature unless the charge is severely overcharged to the point where the receiver is full. For systems with liquid line receivers and TXVs, it may make sense to employ a low-cost level sensor in the receiver. The normal charge level could be correlated with operating conditions and used to decouple charge from other faults.

There is also a need to develop a better model for estimating heat loss in order to improve estimates of the normal compressor discharge temperature under all conditions. This should eliminate an indication of compressor value leakage when condenser fouling is present.

Evaporating frosting tests were also implemented and the evaporator fouling feature was found to be a reliable indicator. This feature could be used as part of a "smart" defrosting scheme to determine the need for defrosting. A threshold could be determined that balances tradeoffs between improved cycle efficiency and defrost energy. This could lead to reduced defrost cycles for situations where the evaporator is not exposed to significant moisture (e.g., infrequent door openings) and increased defrost cycles for cases with high indoor box moisture levels.

NOMENCLATURE

$\dot{m}_{ref}$	refrigerant mass flow rate	$P_{cond,in}$	condenser refrigerant inlet pressure
$P_{cond,out,}$	condenser refrigerant outlet pressure	P_{suc}	compressor inlet pressure
$\dot{Q}_{comp,loss}$	compressor heat loss rate	T_{amb}	compressor ambient temperature
T_{cai}	condenser air inlet temperature	T_{cao}	condenser air outlet temperature
T_{cond}	representative refrig. condensing temp.	$T_{cond,out}$	condenser refrigerant outlet temperature
T_{eai}	evaporator air inlet temperature	T_{eao}	evaporator air outlet temperature
$T_{evap,in,}$	evaporator refrigerant inlet temperature	T_{dis}	compressor discharge temperature
$T_{dis,normal}$	normal compressor discharge temperature	$T_{LL,1}$	temperature at inlet of filter drier
$T_{LL,2}$	temperature at outlet of filter drier	T_{sh},	superheat at evaporator outlet
T_{sc}	subcooling at condenser outlet	T_{suc}	compressor inlet temperature
$\dot{V}_{ca}$	virtual condenser air flow rate	$\dot{V}_{ea}$	virtual evaporator air flow rate
$\dot{W}_{comp}$	compressor power		

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