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Decoupling features for diagnosis of reversing and check valve faults in heat pumps

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ABSTRACT

Recently, a decoupling-based (DB) fault detection and diagnosis (FDD) method was developed for diagnosing multiple-simultaneous faults in air conditioners (AC) and was shown to have very good performance. The method relies on identifying diagnostic features that are decoupled (i.e., insensitive) to other faults and operating conditions. The current paper extends the DB FDD methodology to heat pumps. Heat pumps have all the same faults as occur for air conditioners with additional faults associated with components that accommodate heating mode, including reversing valve leakage and check valve leakage. Decoupling features were developed for these additional faults and laboratory evaluations were performed to evaluate diagnostic performance. It was found that check valve leakage could be detected and diagnosed before the heating capacity degradation reached 5% for a system with a fixed orifice expansion (FXO) device and 3% for the same system retrofit with a thermal expansion valve (TXV). Furthermore, the feature for check valve leakage is very insensitive to other faults and operating conditions. The decoupling feature for reversing valve leakage could successfully detect and diagnose faults for a TXV system before the heating capacity degraded 6% and was also insensitive to other faults and operating conditions. However, this feature did not work well for a system with an FXO in heating mode because the refrigerant exiting the evaporator and entering the reversing valve was typically a two-phase mixture. Fortunately, it was possible to diagnose this particular fault at many operating conditions in cooling mode for the system with an FXO.

Pompes à chaleur : diagnostic des anomalies de robinets d’inversion et des clapets anti-retour

Mots clés : Pompe à chaleur ; Procédé ; Détection ; Anomalie ; Robinet inverseur ; Soupape ; Fuite ; Frigorigène

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Nomenclature

A	Opening of the TXV and leaky check valve combination [m^2]
A_{FXO}	FXO throat area [m^2]
A_{LCV}	Opening of the leaky check valve [m^2]
A_{TXV}	TXV throat area [m^2]
$A_{TXV,0}$	TXV offset adjustment parameter [m^2]
AC	Air conditioner
AMB	Ambient temperature [°C]
C	Discharge coefficient
C_p	Specific heat [$J\,kg^{-1}\,K^{-1}$]
DB	Decoupling based
$DF_{LCV,FXO}$	Decoupling feature for check valve leakage faults in FXO systems
$DF_{LCV,TXV}$	Decoupling feature for check valve leakage faults in TXV systems
DF_{LRV}	Decoupling feature for reversing valve leakage faults
EXV	Electronic expansion valve
FDD	Fault detection and diagnosis
FXO	Fixed orifice
K_{TXV}	TXV Proportional gain [$m^2\,K^{-1}$]
K_{VCC}	VCC plant proportional gain [$K\,m^{-2}$]
LMTD	Logarithmic mean temperature difference
$\dot{m}_{comp}$	Mass flow rate through the compressor [$kg\,s^{-1}$]
$\dot{m}_{cycle}$	Mass flow rate through the cycle [$kg\,s^{-1}$]
$\dot{m}_{leak}$	Mass low rate leaking from the high side to the low side [$kg\,s^{-1}$]
$P_{dis,comp}$	Compressor discharge pressure [Pa]
P_{down}	Expansion device downstream
P_{evap}	Evaporating pressure [Pa]
$P_{suc,comp}$	Compressor suction pressure [Pa]
P_{up}	Expansion device upstream pressure [Pa]
$T_{dis,coil}$	The reversing valve low side inlet temperature [°C]
$T_{dis,comp}$	Reversing valve high side inlet temperature [°C]
T_{sh}	Actual superheat [K]
$T_{sh,o}$	TXV superheat threshold [K]
$T_{sh,sp}$	Superheat set point [K]
$T_{suc,coil}$	Reversing valve low side inlet temperature [°C]
$T_{suc,comp}$	Temperature of the reversing valve low side outlet [°C]
TXV	Thermostatic expansion valve
UA	Product of overall heat transfer coefficient and surface area [$W\,K^{-1}$]
VCC	Vapor compression cycle
Greek letters	
ρ	Refrigerant density [$kg\,m^{-3}$]

1. Introduction

HVAC&R systems often do not function as well as expected due to faults introduced during initial installation or during routine operation. For example, numerous case studies conducted by various independent investigators (Proctor and Downey, 1995; Li and Braun, 2006) concluded that more than 50% of the packaged air conditioning systems in the field were improperly charged due to improper commissioning or refrigerant leakage. Estimates of energy savings associated with correcting the refrigerant charge faults alone range from 5% to 11% (Cowan, 2004). Faults found very common in HVAC&R systems can be divided into three groups: (1) refrigeration cycle; (2) distribution system; and (3) sensor, control and economizer faults. Among these three groups of faults, refrigeration cycle faults are the most difficult and expensive to diagnose.

With growing realization of the benefits, a lot of research on automated FDD (AFDD) for HVAC&R systems has been done during the past two decades as summarized by Dexter et al. (2001), Li (2004) and Katipamula and Brambley (2005a,b). For vapor compression air conditioning equipment, most of the methods presented in the literature (Grimmelius et al., 1995; Stylianou and Lau, 1996; Rossi and Braun, 1997), utilize differences between measurements and model predictions (residuals) of state variables to perform fault detection and diagnostics. Although these methods have good performance for individual faults (Breuker and Braun, 1998; Li and Braun, 2003), they do not handle multiple-simultaneous faults. In addition, these methods require measurements over a wide range of conditions for training reference models, the development of which can be time consuming and cost-prohibitive.

To handle multiple-simultaneous faults, Li and Braun (2007a) formulated model-based FDD techniques in a general mathematical way (see Eq. (1)) and found that the methodology of decoupling is the key to handling multiple-simultaneous faults. As illustrated in Eq. (2), the decoupling methodology transforms a complicated multiple-input and multiple-output FDD problem into a finite number of simple single-input and single-output problems. That is, a fault indicator, termed the decoupling feature, is uniquely related to a single fault and independent of the impacts of other faults and driving conditions. Consequently, multiple faults can be handled.

$$\begin{bmatrix} \text{variable } 1 \\ \text{variable } 2 \\ \vdots \\ \text{variable } i \\ \vdots \\ \text{variable } n \end{bmatrix} = \begin{bmatrix} f_{11}(\bullet) & f_{12}(\bullet) & \cdots & f_{1i}(\bullet) & \cdots & f_{1n}(\bullet) \\ f_{21}(\bullet) & f_{22}(\bullet) & \cdots & f_{2i}(\bullet) & \cdots & f_{2n}(\bullet) \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ f_{i1}(\bullet) & f_{i2}(\bullet) & \cdots & f_{ii}(\bullet) & \cdots & f_{in}(\bullet) \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ f_{n1}(\bullet) & f_{n2}(\bullet) & \cdots & f_{ni}(\bullet) & \cdots & f_{nn}(\bullet) \end{bmatrix} \times \begin{bmatrix} \text{fault } 1 \\ \text{fault } 2 \\ \vdots \\ \text{fault } i \\ \vdots \\ \text{fault } n \end{bmatrix} \quad (1)$$

where 'variable i' represents a certain state variable of the diagnosed system (e.g. suction superheat); 'fault i' represents a certain fault of the diagnosed system (e.g. refrigerant leakage); and $f_{ij}(\bullet)$ denotes the function relationship between 'fault j' and 'variable i'.

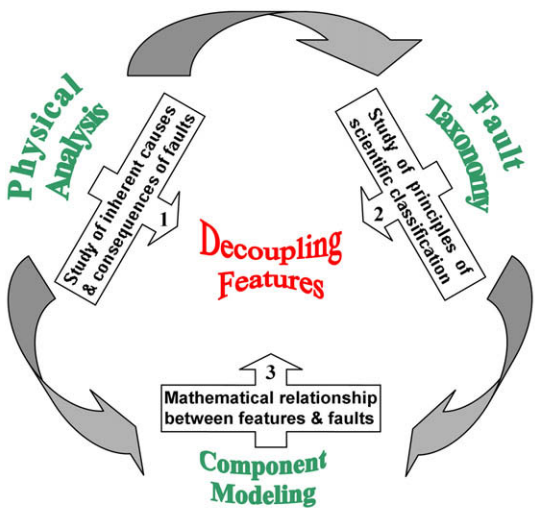

Fig. 1 – Illustration of the physical/conceptual decoupling methodology.

$$\begin{bmatrix} \text{feature } 1 \\ \text{feature } 2 \\ \vdots \\ \text{feature } i \\ \vdots \\ \text{feature } n \end{bmatrix} = \begin{bmatrix} f_1(\cdot) & & & & \\ & f_2(\cdot) & & & \\ & & \ddots & & \\ & & & f_i(\cdot) & \\ & & & & \ddots \\ & & & & & f_n(\cdot) \end{bmatrix} \begin{bmatrix} \text{fault } 1 \\ \text{fault } 2 \\ \vdots \\ \text{fault } i \\ \vdots \\ \text{fault } n \end{bmatrix} \quad (2)$$

where ‘feature *i*’ represents a decoupling feature for ‘fault *i*’ and denotes the function relationship between ‘fault *i*’ and ‘feature *i*’.

In order to apply the decoupling methodology to non-critical HVAC&R systems with low costs, methodologies of physical decoupling were developed by Li and Braun (2007a). As illustrated in Fig. 1, three approaches were proposed to obtain decoupling features, including fault taxonomy, physical analysis, and component modeling. By definition, taxonomy is ‘‘the study of the general principles of scientific classification’’ (Merriam-Webster). Essentially FDD is a scientific branch of pattern recognition or classification so fault taxonomy is the fundamental of FDD and contributes greatly to the decoupling of faults. For instance, low and high refrigerant charge faults, classified as exclusive faults, can never occur simultaneously and are naturally decoupled. Physical analysis involves identification and isolation (decoupling) of the source impact of each fault. For example, non-condensable gas (for a positively pressurized system) and refrigerant overcharge can only be introduced when the unit is serviced so they can be decoupled from developmental faults which develop during routine operation. Component modeling is used to mathematically isolate (or decouple) the impact of the fault directly associated with the modeled component from that of other faults and driving conditions. For example, a compressor component model estimates the normal value of the discharge line temperature according to its measured driving conditions on which other faults may have impacts. Consequently, the residual, the difference between estimated and measured compressor discharge line temperatures is a unique function of the compressor valve leakage fault and decoupling is achieved. In this manner, the necessity of a cost-prohibitive overall system model for decoupling is eliminated and the decoupled features are determined using virtual sensors that incorporate models and low-cost measurements (Li and Braun, 2007b). The models are simple and obtainable from information and data readily available from equipment manufacturers and do not require extensive training.

The DB FDD method was originally developed for cooling-only air conditioning (AC) systems. Generally speaking, an air conditioner is a heat pump operating in cooling-only mode so faults common in air conditioners should be common in heat pumps as well. These kinds of faults include indoor heat exchanger fouling, outdoor heat exchanger fouling, refrigerant undercharge, refrigerant overcharge, liquid line restriction, compressor valve leakage, and non-condensable gas. However, from the perspective of FDD, a heat pump (HP) is significantly different from a cooling-only AC system: (1) it includes additional components such as check valves and reversing valves to accommodate operation in heating mode and thus more involved faults; (2) its design is a compromise between cooling and heating modes and thus some non-optimal operating conditions such as two-phase refrigerant entering compressors, uncommon to cooling only systems, can be very common to HP systems; and (3) it runs at a larger range of operating conditions and thus more difficult to achieve robustness. The current paper focuses on development and evaluation of decoupling features for leaky check and reversing valves. These faults are relatively common for heat pumps and can have a significant effect on performance. The proposed features are evaluated over a wide range of operating conditions in terms of sensitivity and robustness using laboratory measurements. A separate paper will present a holistic evaluation of DB FDD for a heat pump system.

2. Decoupling features for check and reversing valve leakage

2.1. *Development of check valve leakage feature*

In heat pumps, check valves are used to disable or enable expansion devices for heating and cooling modes. A check valve can be either integrated as internal or external to the expansion device. However, from a functionality standpoint, the check valve and expansion device can be treated as a combination placed in parallel with each other (see Fig. 2(a)). As shown in Fig. 2(b), if the pressure acting on the check valve is positive, the check valve will open (be enabled) and the expansion device will be bypassed (disabled). As shown in Fig. 2(c), if the pressure acting on the check valve is negative or less than a threshold, the check valve will close (be disabled) and the refrigerant will be throttled through the expansion device.

During operation, the check valve can become leaky or be unable to close fully due to the presence of contaminants even if the pressure acting on it is negative. As shown in Fig. 2(d), if the check valve cannot close fully, part of the refrigerant flow will go through the check valve. From the perspective of fault taxonomy (Li and Braun, 2007a), check valve leakage is a component-level fault. According to the DB FDD

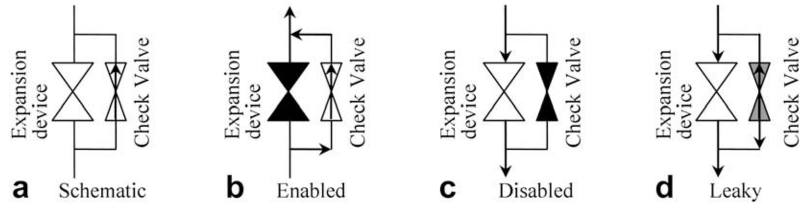

Fig. 2 – Illustration of the combination of the check valve and expansion device for various modes.

methodology (Li and Braun, 2007a), decoupling features could be obtained through component modeling. There are two types of expansion devices used in heat pumps: fixed orifices (FXO) and variable-throttling-area valves (e.g., TXV). Systems with different types of expansion devices react differently to check vale leakage so the decoupling feature development is different.

2.1.1. *Systems with a fixed expansion orifice (FXO)*

For a system with an FXO, a leaky check valve acts together with the fixed orifice to throttle the refrigerant flow. The combination of a leaky check valve and fixed orifice can be treated as a combined throttling device which can be modeled as (Li and Braun, in press)

$$C(A_{FXO} + A_{LCV}) = \frac{\dot{m}_{cycle}}{\sqrt{\rho(P_{up} - P_{down})}} \tag{3}$$

where, C is discharge coefficient, A_{FXO} is the FXO throat area, A_{LCV} is the opening of the leaky check valve, $\dot{m}_{cycle}$ is the refrigerant mass flow rate, ρ is refrigerant density, P_{up} is the upstream pressure, and P_{down} is the downstream pressure. Eq. (3) can be rearranged as

$$DF_{LCV,FXO} = \frac{A_{LCV}}{A_{FXO}} = \frac{\dot{m}_{cycle}}{[CA_{FXO}]\sqrt{\rho(P_{up} - P_{down})}} - 1 \tag{4}$$

$DF_{LCV,FXO}$ is the ratio of the leaky check valve opening to the FXO opening and can serve as a decoupling feature for check valve leakage faults in FXO systems.

2.1.2. *Systems with a TXV*

In a similar fashion, the TXV and check valve combination can be modeled using Eq. (5).

$$\frac{A_{LCV}}{A_{TXV}} = \frac{\dot{m}_{cycle}}{[CA_{TXV}]\sqrt{\rho(P_{up} - P_{down})}} - 1 \tag{5}$$

where, A_{TXV} is the TXV throat area. However, unlike A_{FXO}, A_{TXV} varies with both operating conditions and faults. For example, the TXV opening can compensate for leakage caused by the check valve to a certain degree. That is, the ratio of the leaky check valve opening to the TXV opening is a function of both the leaky check valve opening and the TXV opening. Consequently, it cannot serve directly as a decoupling feature for check valve leakage for this type of system. However, it does not mean that the component modeling method adopted in FXO systems cannot be used to obtain the decoupling feature for TXV systems. The very reason is that a TXV has an additional input, the superheat, which has not been taken into account in the models described by Eq. (4) or (5).

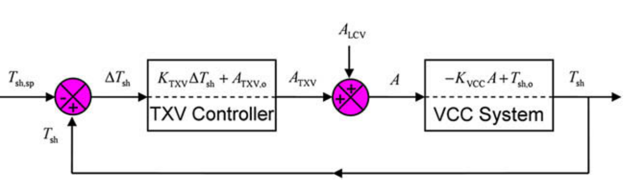

Fig. 3 – Steady-state control block diagram for a TXV system.

From the control point of view, the TXV and leaky check valve combination can be represented by a control block diagram as illustrated in Fig. 3. In this diagram, the vapor compression cycle (VCC) is the controlled plant, the superheat (T_{sh}) is the controlled variable, the TXV is the controller, and the leaky check valve opening is the plant disturbance. At steady-state, the VCC system can be linearized as

$$T_{sh} = -K_{VCC}A + T_{sh,o} \tag{6}$$

where K_{VCC} is the plant proportionality gain, A is the actual TXV opening, and $T_{sh,o}$ is the superheat threshold preset by the TXV spring where the TXV is fully closed. The TXV can be represented by a proportional controller as

$$A_{TXV} = K_{TXV}\Delta T_{sh} + A_{TXV,o} \tag{7}$$

where K_{TXV} is the controller proportional gain, ΔT_{sh} is the superheat error signal, and $A_{TXV,o}$ is the offset adjustment parameter for the TXV controller. According to the diagram, we can obtain

$$\begin{cases} \Delta T_{sh} = T_{sh} - T_{sh,sp} \\ A = A_{TXV} + A_{LCV} \end{cases} \tag{8}$$

where $T_{sh,sp}$ is the superheat set point. At the design condition, the actual superheat T_{sh} is equal to its setpoint, that is, $\Delta T_{sh} = 0$, and

$$T_{sh,sp} = -K_{VCC}A_{TXV,o} + T_{sh,o} \tag{9}$$

Combining Eqs. (6), (7), (8) and (9) leads to

$$A_{LCV} = \frac{K_{TXV}K_{VCC} + 1}{K_{VCC}}(T_{sh,sp} - T_{sh}) \tag{10}$$

Eq. (10) provides a method to calculate the opening of the leaky check valve. However, although K_{TXV} and K_{VCC} are constants, they are not readily available. A decoupling feature independent of K_{TXV} and K_{VCC} is desired. To this end, a critical check valve leakage opening is defined at the point where the system superheat goes to zero ($T_{sh} = +0$) using Eq. (10):

$$[A_{LCV}]_{T_{sh}=+0} = \frac{K_{TXV}K_{VCC} + 1}{K_{VCC}}(T_{sh,sp} - 0) = \frac{K_{TXV}K_{VCC} + 1}{K_{VCC}}T_{sh,sp} \tag{11}$$

This critical condition is significant because at this condition the TXV is on the verge of completely losing the capacity to compensate for the check valve leakage fault and regulating the flow properly. Any fault level more severe than this value can lead to: (1) a detrimental condition of two-phase refrigerant entering the compressor and (2) significant system performance degradation. Consequently, this critical condition can serve as a criterion against which the severity of the check valve leakage fault can be evaluated. To this end, Eqs. (10) and (11) are combined to obtain the following decoupling feature for check valve leakage:

$$DF_{LCV,TXV} = \frac{A_{LCV}}{[A_{LCV}]_{T_{sh}=+0}} = \frac{T_{sh,sp} - T_{sh}}{T_{sh,sp}} \quad (12)$$

$DF_{LCV,TXV}$ is a unique function of the check valve leakage fault level and can be calculated with a measurement of T_{sh} and manufacturer's information for $T_{sh,sp}$. It should be pointed out that this feature may work poorly if it is directly extended to systems using electronic expansion valves (EXV) for which the superheat set point ($T_{sh,sp}$) could have a very low value such as 0.5 °C. In such case, either sensors of high accuracy should be used or the algorithm should be modified. One possible low cost solution for this could be using the valve position signal fed back from the controller as an indicator for check valve leakage diagnostics.

2.2. *Development of reversing valve leakage feature*

In heat pumps, a reversing valve switches the direction of refrigerant flow through the heat exchangers to allow heat pump operation in either heating or cooling mode. The following factors may affect the development of a decoupling feature for reversing valve leakage.

(1) Leakage can occur across the valve slide that separates low and high pressures sides of the system. Similar to check valve leakage, reversing valve leakage is a component-level fault and its decoupling feature could be obtained through component modeling. As shown in Fig. 4, leakage can occur (a) from the high side inlet to the low side outlet, (b) from the high side outlet to the low side outlet, (c) from the high side inlet to the low side inlet, and (d) from the high side outlet to the low side outlet. As the ultimate result of leakage through any of these paths, the flow of refrigerant in the cycle will be less than the flow produced by the compressor, and more fortunately, as shown in the subsequent section, the four leakage scenarios can be taken into account in one development procedure.
(2) Heat transfer can occur across the valve due to significant temperature differences between the high and low pressure sides. This is an internal heat transfer process.
(3) Heat loss occurs from the valve body to the ambient. However, as demonstrated in Section 4.2.2.2, heat transfer between low pressure side of the valve body and the ambient is negligible whereas heat loss from the high side of the reversing valve body to the ambient environment is significant in heating mode. This is because the low side surface temperature is very close to the ambient temperature under almost all conditions and the high side surface temperature can be considerably higher than the ambient in heating mode.

Assuming that the refrigerant vapor has a constant specific heat, the inlet and outlet refrigerant states are vapor, and the external heat loss only occurs between the high pressure side of the reversing valve and the ambient, then a steady-state energy balance on the reversing valve for any of the cases depicted in Fig. 4 leads to

$$\dot{m}_{cycle} C_p (T_{dis,coil} - T_{suc,coil}) = \dot{m}_{comp} C_p (T_{dis,comp} - T_{suc,comp}) + \dot{Q}_{external} \quad (13)$$

where $\dot{m}_{cycle}$ is the refrigerant mass flow rate through the cycle, $\dot{m}_{comp}$ is the mass flow rate through the compressor,

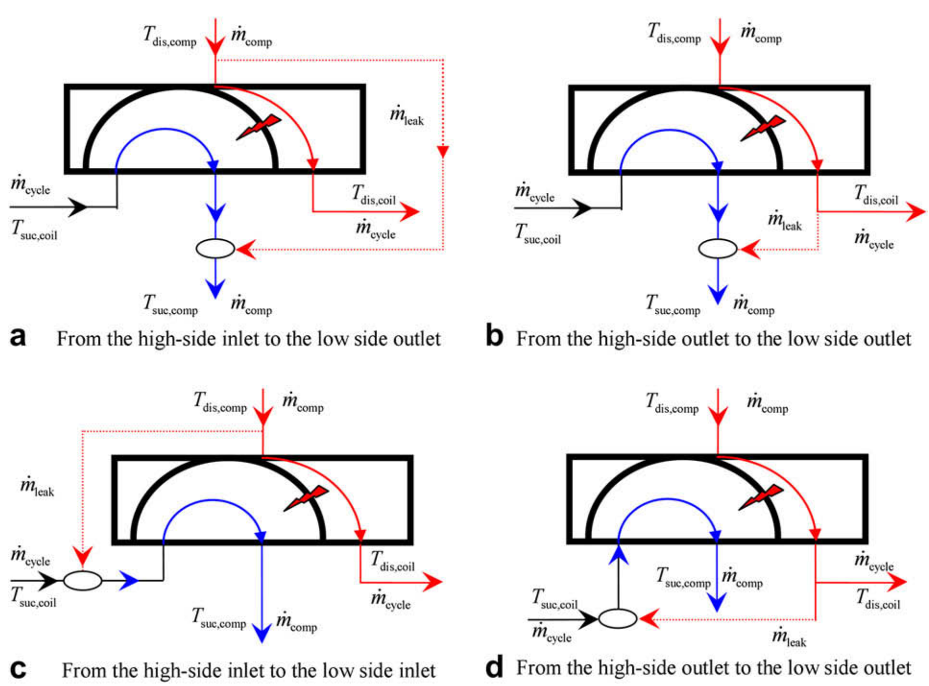

Fig. 4 – Four simplified cases of reversing valve leakage.

C_p is the refrigerant vapor specific heat, $T_{dis,coil}$ is the reversing valve high-side outlet temperature to the cycle (to the condenser), $T_{suc,coil}$ is the reversing valve low-side inlet temperature from the cycle (from the evaporator), $T_{dis,comp}$ is the reversing valve high-side inlet temperature from the compressor, $T_{suc,comp}$ is the temperature of the reversing valve low-side outlet to the compressor, and $\dot{Q}_{external}$ is the heat loss to the ambient. The compressor and cycle mass flow rates are related to leakage flow rate according to

$$\dot{m}_{comp} = \dot{m}_{leak} + \dot{m}_{cycle} \quad (14)$$

where $\dot{m}_{leak}$ is the leakage mass flow rate.

The heat loss from the high side of the reversing valve body is

$$\dot{Q}_{external} = (UA)\mathrm{LMTD} \quad (15)$$

where UA is the product of the overall heat transfer coefficient (U) and the heat transfer surface area (A) and LMTD is the logarithmic mean temperature difference calculated by

$$\mathrm{LMTD} = \frac{(T_{dis,comp} - \mathrm{AMB}) - (T_{dis,coil} - \mathrm{AMB})}{\ln\left((T_{dis,comp} - \mathrm{AMB})/(T_{dis,coil} - \mathrm{AMB})\right)} \quad (16)$$

where AMB is the ambient air temperature.

Eqs. (13)–(16) can be combined to determine the ratio of the leakage flow rate to the cycle flow according to

$$\frac{\dot{m}_{leak}}{\dot{m}_{cycle}} = \frac{(T_{suc,comp} - T_{suc,coil}) - \left[(T_{dis,comp} - T_{dis,coil}) - (UA/C_p)(\mathrm{LMTD}/\dot{m}_{cycle})\right]}{T_{dis,comp} - T_{suc,comp}} \quad (17)$$

Eq. (17) provides a simple decoupling feature that can be used to detect reversing valve leakage. However, it implicitly includes the refrigerant cycle flow rate, $\dot{m}_{cycle}$. A simple virtual measurement for compressor flow rate can be determined using a simple compressor model and low-cost measurements as outlined by Li and Braun (2007b). Since the heat loss term is relatively small compared to the other terms in Eq. (17), then the cycle flow rate can be replaced with compressor flow rate leading to

$$\mathrm{DF}_{LRV} \equiv \frac{\dot{m}_{leak}}{\dot{m}_{cycle}} = \frac{(T_{suc,comp} - T_{suc,coil}) - \left[(T_{dis,comp} - T_{dis,coil}) - (UA/C_p)(\mathrm{LMTD}/\dot{m}_{comp})\right]}{T_{dis,comp} - T_{suc,comp}} \quad (18)$$

where DF_{LRV} is the decoupling feature for valve leakage. This simple feature includes the effects of both internal and external heat transfers that can occur between the high and low pressure sides of the valve and between the high side of the valve and its ambient environment. It should be independent of other faults that are external to the reversing valve. It can be estimated from low cost measurements.

3. Issues for implementation and commissioning

The goal of the decoupling-based FDD methodology is to achieve multiple-simultaneous FDD with low costs in terms of implementation and commissioning. The decoupling features developed in previous sections have the following three characteristics: (1) they are based on steady-state operating conditions; (2) their inputs are either directly measured by low-cost sensors or virtually derived from models termed virtual sensors; (3) their unknown parameters can be determined using information readily available from equipment manufacturers and/or limited training data.

Since the decoupling features are based on steady-state operating conditions, a steady-state detector is used to filter out the transient data. A combined slope and variance steady-state detection algorithm (Li and Braun, 2003) is used. This algorithm computes standard deviation and the slope of the best-fit line through a fixed-length sliding window of recent measurements.

Table 1 shows the measurements and parameters required for implementing the decoupling features. The decoupling feature for check valve leakage in FXO systems uses two direct pressure measurements and one virtual measurement, $\dot{m}_{cycle}$.

Table 1 – Measurements and parameters used in decoupling features

Faults		Decoupling feature formula	Measurements		Unknown parameters
			Direct	Virtual	
Check valve leakage	FXO system	$\frac{\dot{m}_{cycle}}{[\mathrm{CA}_{FXO}]\sqrt{\rho(P_{up}-P_{down})}} - 1$	P_{up}, P_{down}, $P_{dis,com}$, $P_{suc,comp}$	$\dot{m}_{cycle}$	CA_{FXO}
	TXV system	$\frac{T_{sh,sp}-T_{sh}}{T_{sh,sp}}$	T_{suc}, T_{evap} (or P_{evap})	None	$T_{sh,sp}$
Reversing valve leakage		$(T_{suc,comp} - T_{suc,coil}) - \left[\left(T_{dis,comp} - T_{dis,coil}\right) - \frac{(UA/C_p)}{(\mathrm{LMTD}/\dot{m}_{comp})}\right]\frac{}{T_{dis,comp}-T_{suc,comp}}$	$T_{suc,coil}$, $T_{dis,coil}$, $T_{suc,comp}$, $T_{dis,comp}$, $P_{dis,comp}$, $P_{suc,comp}$, AMB	$\dot{m}_{comp}$	UA

In the absence of reversing valve leakage $\dot{m}_{cycle}$ is equal to $\dot{m}_{comp}$:

$$\dot{m}_{cycle} = \dot{m}_{comp} \tag{19}$$

while in the presence of reversing valve leakage, the combination of Eqs. (13) and (15) can serve as a virtual sensor to derive $\dot{m}_{cycle}$:

$$\dot{m}_{cycle} = \frac{[\dot{m}_{comp} C_p (T_{dis,comp} - T_{suc,comp}) + (UA)LMTD]}{C_p (T_{dis,coil} - T_{suc,coil})} \tag{20}$$

where $\dot{m}_{comp}$ can be derived from a virtual refrigerant mass flow rate sensor presented by Li and Braun (2007b). The unknown parameter, UA, can be estimated under conditions in the absence of reversing valve leakage faults by evaluating

$$UA = (C_p LMTD/\dot{m}_{comp}) [(T_{dis,comp} - T_{dis,coil}) - (T_{suc,comp} - T_{suc,coil})] \tag{21}$$

The unknown parameter, CA_{FXO}, can be estimated under an operating condition in the absence of a check valve leakage fault by evaluating

$$CA_{FXO} = \frac{\dot{m}_{cycle}}{\sqrt{\rho (P_{up} - P_{down})}} \tag{22}$$

For TXV systems, the decoupling feature for check valve leakage only requires superheat and its setpoint Superheat can be directly calculated from suction line temperature and evaporating temperature. The superheat setpoint could be readily available from manufacturers' operation manual or obtained when the system operates normally.

The decoupling feature for reversing valve leakage requires five direct temperature measurements: $T_{suc,coil}$, $T_{dis,coil}$, $T_{suc,comp}$, $T_{dis,comp}$ and AMB, and one virtual measurement, $\dot{m}_{comp}$, which can be derived from virtual refrigerant mass flow rate sensor (Li and Braun, 2007b). Again the unknown parameter, UA, can be estimated by Eq. (21).

4. Laboratory evaluation

4.1. System description and fault implementation

A 10.5 kW (3-ton) split heat pump was tested in psychrometric rooms to evaluate the proposed decoupling features. The heat pump used R-22 as the refrigerant with a nominal charge of 3.25 kg. The system had an HSPF of 7.2 and an SEER of 10.0. A schematic of the heat pump refrigeration circuit is illustrated in Fig. 5. Both indoor and outdoor units originally had a fixed-orifice expansion device installed. In addition, the system was retrofit with a TXV for heating mode to allow testing for both types of expansion devices. To protect the compressor from slugging, the system comes with a suction-line accumulator. Liquid slugging is of particular concern for heat pumps because the optimal charge inventory for heating mode is typically less than that for a cooling mode. A suction line accumulator accommodates the superfluous charge seen in a heating mode when the optimum charge is based on cooling mode operation. This is particularly important for systems that incorporate an FXO. When a TXV is employed, the flow rate is adjusted to maintain a superheat in the suction line and refrigerant accumulates in the condenser.

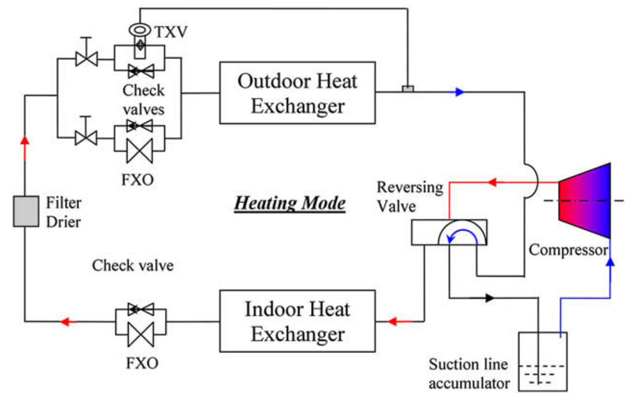

Fig. 5 – Schematics of the tested heat pump.

T-type thermocouples with an accuracy of ±0.5 °C are used to measure temperatures. Refrigerant pressures were measured using OMEGA pressure transducers with an accuracy of ±1% full scale (0–1379 kPa for low side pressures and 0–3447 kPa for high side pressures).

The method for implementing faults is described in Table 2. Valve leakage faults were simulated through partially opening a bypass valve installed in parallel with the corresponding valve. Each level of simulated faults corresponds to a fixed valve opening. In general, five fault levels were intended to be implemented for both reversing valve leakage and check valve leakage to evaluate FDD sensitivity under each set of driving conditions (see Table 3). However, at very low ambient conditions (e.g. −8.3 °C) the system could only operate under small fault levels without shutting down due to safety cutouts. Various combinations of five indoor flow rate levels, ranging from 65% to 135% of the nominal value, and five charge levels, ranging from 70% to 130% of the nominal value, were used to evaluate FDD robustness.

As shown in Table 3, both heating and cooling modes were tested in three wide-spanned ambient conditions: −8.3 °C, 1.7 °C and 8.3 °C for heating mode and 24 °C, 35 °C and 46 °C for cooling mode. The indoor dry bulb temperature was maintained at constant conditions during testing: 24 °C for cooling mode and 21 °C for heating mode. For cooling mode, the wet bulb temperature was controlled to accommodate both wet and dry coil conditions.

4.2. Evaluation results

4.2.1. Check valve leakage

4.2.1.1. FXO system. Fig. 6 shows how the decoupling feature for detecting and diagnosing check valve leakage faults in FXO systems reacts to incremental fault levels. As mentioned in a prior section, some testing points of higher fault levels at the ambient conditions of −8.3 °C are missing due to safety cutouts. The results are presented as a function of degradation in heating capacity in order to put the fault effects on the same scale. In general, the value of the decoupling feature and the heating capacity degradation increase with increasing fault

Table 2 – Method of implementing faults and corresponding fault levels simulated

Faults	Fault introduction method	Fault level expression	Fault level simulated					
			0	1	2	3	4	5
Reverse valve leakage	Partially open a bypass valve between discharge and suction lines	% Bypass valve opening	0%	5%	10%	15%	20%	None
Check valve leakage	Partially open a parallel bypass valve	% Bypass valve opening	0%	5%	10%	15%	20%	None
Improper indoor air flow rate	Partially block evaporator air flow with paper	% Nominal air volume flow rate	N/A	65%	85%	100%	115%	135%
Improper charge	Vary system charge	% Nominal charge	N/A	70%	85%	100%	115%	130%

level. The changes in fault feature become significant for heating degradations greater than about 5%. It is interesting to note that heating capacity is more sensitive to fault level for lower ambient temperatures. This is because leakage increases with decreasing evaporation temperature for a given valve opening. The implication of the ambient dependence is that a check valve leakage fault should be easier to detect at lower ambient conditions when its effect is more significant (even causing shutting down at higher fault levels).

Fig. 7 shows the decoupling feature in the absence of a check valve leakage fault, but over a wide range of refrigerant charge levels and indoor air flow rates. The decoupling feature is very insensitive to other faults with variations in the value of the decoupling feature ranging from −0.12 to +0.14. If 0.15 is set as the FDD threshold, the proposed feature can detect and diagnose a check valve leakage fault in an FXO system before its heating capacity degrades 5%.

4.2.1.2. *TXV systems*. Fig. 8 shows the sensitivity of the decoupling feature to fault level and ambient temperature for the system using a TXV. Similar to the results for the system with an FXO, the decoupling feature for the TXV system increases with increasing fault level and is more sensitive to faults at lower ambient temperatures. However, the feature saturates at '1' when the TXV fully closes and the superheat goes to zero. In addition, the feature for TXV systems is more sensitive to faults than that for FXO systems.

Similar to the FXO system, the robustness of the decoupling feature was tested for a wide range of refrigerant charge levels and indoor air flow rates with no check valve leakage. As shown in Fig. 9, the variation in the decoupling feature is a bit larger than that for the FXO system. However, the changes due to other faults are very small relative to the changes in the fault feature due to check valve leakage. If 0.27 is set as the FDD threshold, the proposed feature can detect and diagnose a check valve leakage fault in a TXV system before its heating capacity degrades 3%.

Table 3 – Driving conditions for laboratorial testing

Operating modes	Ambient conditions (°C)	Indoor conditions	
		Dry-bulb (°C)	Wet-bulb
Heating	−8.3, 1.7, 8.3	21	N/A (no control)
Cooling	24, 35, 46	24	Dry/wet coils

4.2.2. *Reversing valve leakage*

4.2.2.1. *Evaluating basic assumptions*. The decoupling feature for reversing valves was developed assuming that the refrigerant is a vapor within the reversing valve. This assumption is satisfied for a system with a TXV as an expansion device, except at extreme fault conditions where the TXV valve is fully closed. However, for a system with an FXO the assumption is not readily satisfied in heating mode. Fig. 10 shows superheat of the refrigerant entering the low side of the reversing valve for the FXO system operating in heating mode. When the refrigerant charge is higher than the nominal level, the inlet refrigerant of the reversing valve is rarely superheated. At the nominal charge level, the refrigerant is superheated only at low flow rates and high ambient temperatures. At low ambient temperatures such as −8.3 °C, the refrigerant is never superheated. As previously described, the system is excessively charged for heating when optimally charged for cooling. For a system with an FXO, the accumulator provides a storage vessel for the excess charge and the condition entering the compressor is typically a saturated vapor.

The reversing valve development included heat loss from the high side of the valve to the ambient but neglected heat loss from the low side to the ambient. Table 4 gives temperature change across the two refrigerant streams flowing through the reversing valve under a no-fault condition (i.e., no leakage) with single-phase refrigerant conditions. When the system operates in cooling mode, the temperature rise of one stream is approximately equal to the temperature drop of the other. This means that the valve is adiabatic to the ambient and the heat loss can be neglected. This is because the driving potential for heat transfer is relatively low in cooling mode. However, the refrigerant temperature

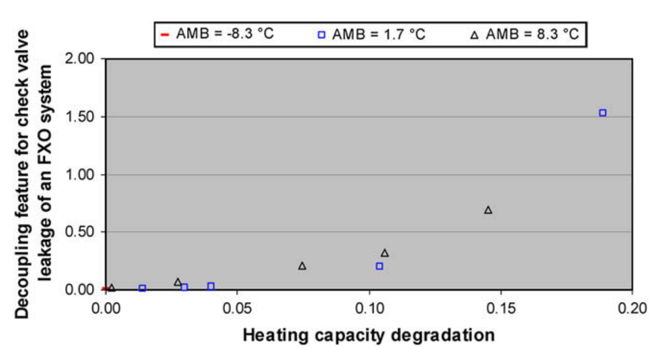

Fig. 6 – Check valve leakage FDD sensitivity evaluation for an FXO system operating at a heating mode.

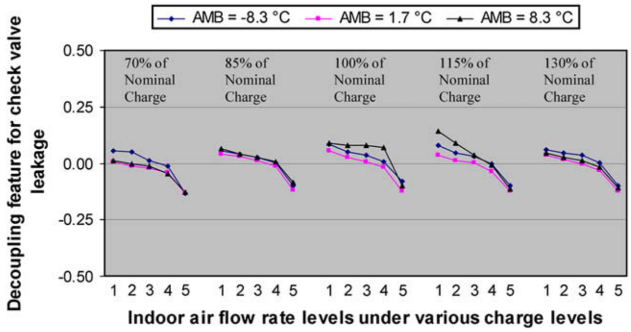

Fig. 7 – Check valve leakage FDD robustness evaluation for an FXO system operating in heating mode.

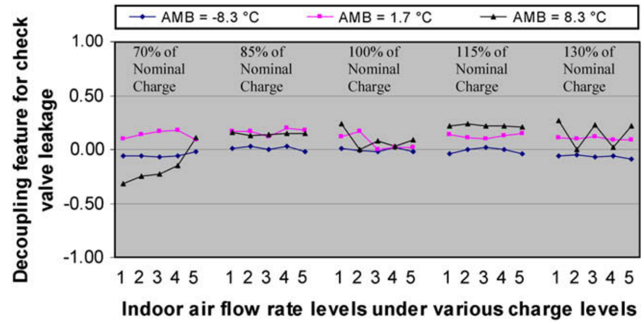

Fig. 9 – Check valve leakage FDD robustness evaluation for a TXV system operating in heating mode.

changes deviate substantially for heating mode, especially at very low ambient conditions. The following conclusions can be inferred from the heating results in Table 4.

(1) The refrigerant temperature changes for the high side are greater than those on the low side, which means that there are more significant heat losses to the ambient on the high side.

(2) The lower the ambient temperature, the greater the temperature change on the high side, while the temperature change on the low side is pretty constant over the entire range of ambient temperature. This means the low side is nearly adiabatic to the ambient environment and the temperature change for the low side is primarily caused by the internal heat transfer.

(3) The refrigerant temperature change for the high side is independent of expansion device while the temperature change on the low side is dependent on expansion device types. The temperature change is close to zero for FXO systems, while it is a non-zero constant for TXV system. This is because the inlet condition of the reversing valve for an FXO system is in two phases.

In summary, the assumption that the reversing valve low side is adiabatic to the ambient is valid, and the external heat loss from high side to the ambient can be neglected in cooling mode but not in heating mode.

4.2.2.2. *Results*. Fig. 11 shows how the decoupling feature for detecting and diagnosing reversing valve leakage faults in FXO systems reacts to incremental fault levels. As mentioned in a prior section, some testing points of higher fault levels at the ambient conditions of −8.3 °C are missing due to safety cutouts. The feature is not sensitive to fault level for all of these cases because the refrigerant entering the reversing valve on the low side is always a two-phase mixture. Reversing valve leakage faults could not be detected for this FXO system operating in heating mode.

However, in cooling mode, a vapor enters the reversing valve from the evaporator under many operating conditions. In addition, heat transfer between the valve and ambient air is minimal for conditions associated with cooling. Therefore, there is a better opportunity for diagnosing reversing valve faults for cooling mode than for heating mode. Fig. 12 shows the reversing valve diagnostic feature and superheat exiting the evaporator as a function of fault level for a range of different ambient conditions for both wet and dry evaporator coils in cooling mode. The decoupling feature increases with fault level whenever the evaporator superheat is positive, such as at low ambient temperature conditions (24 °C) and higher ambient temperature conditions (35 °C) with low fault levels. However, at very high ambient temperature conditions (46 °C) the refrigerant exiting the evaporator is a two-phase condition and the feature does not work well.

Fig. 13 shows the sensitivity of the decoupling feature to variations in charge levels and indoor and outdoor air flow rates in the absence of reversing valve leakage when the system operates in cooling mode. The range of variation in the

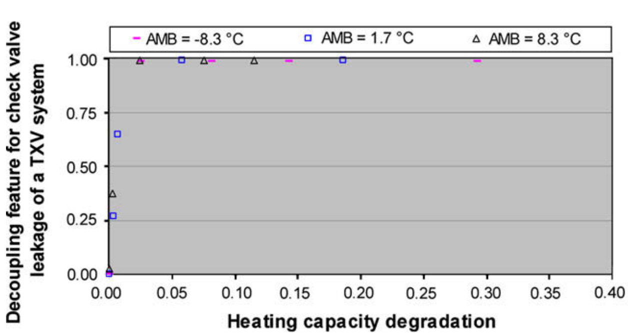

Fig. 8 – Check valve leakage FDD sensitivity evaluation for a TXV system operating in heating mode.

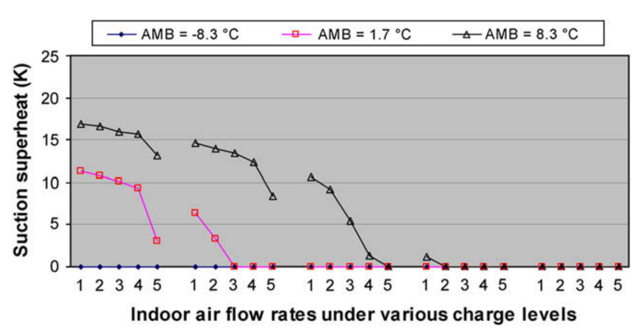

Fig. 10 – Low side refrigerant superheat of an FXO system operating in heating mode with no faults.

Table 4 – Temperature differences (K) between the inlet and outlet of the reversing valve in the absence of leakage

	−8.3 °C (Heating), 24 °C (cooling)		1.7 °C (Heating), 35 °C (cooling)		8.3 °C (Heating), 46 °C (cooling)	
	High side	Low side	High side	Low side	High side	Low side
Cooling/FXO	3.8	4.2	4.1	4.7	4.7	4.9
Heating/TXV	12.8	3.8	8.3	3.2	6.5	2.9
Heating/FXO	13.4	−0.2	8.7	0.4	7.2	1.6

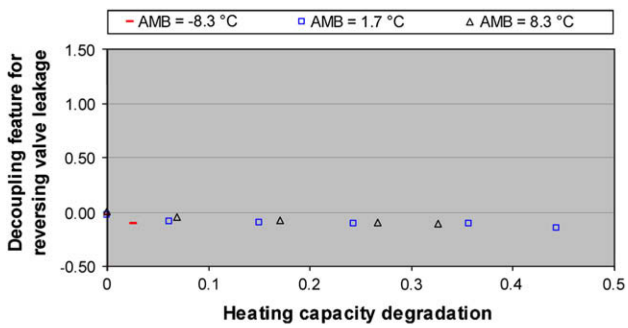

Fig. 11 – Reversing valve leakage FDD sensitivity evaluation for an FXO system operating in heating mode.

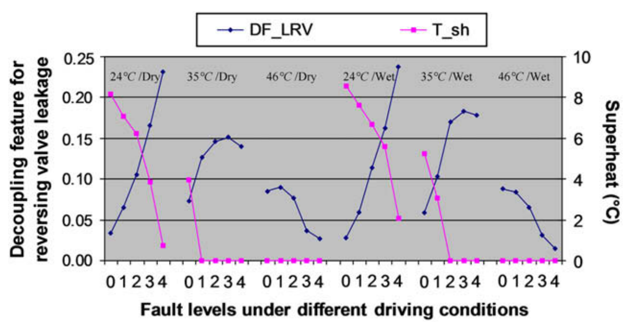

Fig. 12 – Reversing valve leakage FDD sensitivity evaluation for an FXO system operating in cooling mode.

decoupling feature (−0.075 to 0.043) in Fig. 13 is small relative to the changes in response to reversing valve leakage shown in Fig. 12.

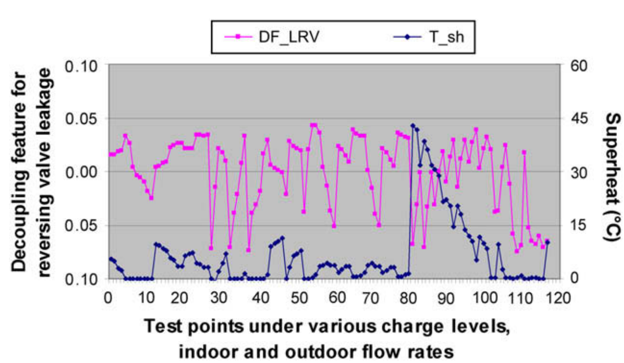

Fig. 13 – Reversing valve leakage FDD robustness evaluation for an FXO system operating in cooling mode.

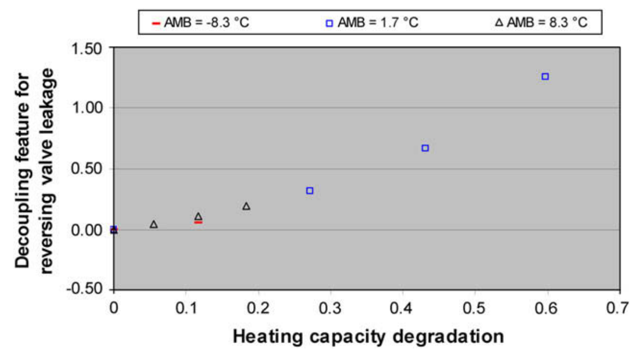

Fig. 14 – Reversing valve leakage FDD sensitivity evaluation for a TXV system operating in heating mode.

For systems with a TXV, refrigerant entering the reversing valve from the evaporator is generally superheated and it is possible to diagnose reversing valve leakage in heating mode. Figs 14 and 15 show the sensitivity and robustness of the decoupling feature for detecting and diagnosing reversing valve leakage faults in the TXV system for heating mode. As mentioned in a prior section, some testing points of higher fault levels at the ambient conditions of −8.3 °C are missing due to safety cutouts. In general, the value of the decoupling feature increases with increasing fault levels. Fig. 15 shows how the decoupling feature varies with refrigerant charge levels and indoor air flow rates in the absence of the reversing valve fault. The decoupling feature is very insensitive to other faults with variations in the value of the decoupling feature ranging from −0.01 to +0.01. Compared to the feature for an FXO system, the feature for a TXV system has much smaller variations when the system operates under the impact of refrigerant charge faults. The assumptions made to derive

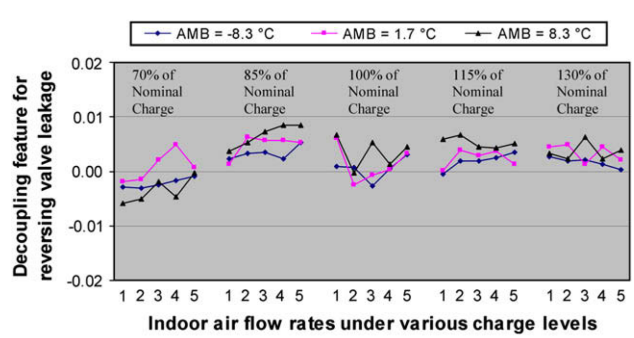

Fig. 15 – Reversing valve leakage FDD robustness evaluation for a TXV system operating in heating mode.

the feature can be referred to explain this phenomenon. One of the assumptions is that the reversing valve inlet and outlet refrigerant states are vapor. A system with a TXV can maintain its evaporator outlet superheat pretty close to its setpoint (much higher than zero) even if the system is under the impact of refrigerant charge faults. That is, the assumption can be satisfied readily and good performance can be anticipated. However, as shown in Fig. 13, the superheat of the system with an FXO cannot be maintained at a non-zero value so that the assumption cannot be met readily. Consequently, variations in the feature will be greater. If 0.01 is set as the FDD threshold for a TXV system, the proposed feature can detect and diagnose a reversing valve leakage fault in a TXV system before its heating capacity degrades 6%.

5. Summary

This paper developed diagnostic features for leakage within check valves and reversing valves that are used in heat pumps. For check valve leakage, it was necessary to develop different features for systems that employ different types of expansion devices. The diagnostic feature for reversing valve leakage employs the assumption that the refrigerant is always a vapor. However, this is not typically the case for heating mode in systems that employ a fixed-area expansion device. As a result, it is necessary to diagnosis reversing valve leakage during operation in cooling fault for this type of system.

The decoupling features were extensively evaluated in terms of sensitivity and robustness on a 3-ton split heat pump system. The decoupling feature for check valve leakage can detect and diagnose leakage faults before its impact on heating capacity reaches 5% for FXO systems and 3% for TXV systems. Robustness testing demonstrated that the decoupling feature is very insensitive to indoor air flow rate and refrigerant charge faults.

The decoupling feature for reversing valve leakage was shown to be a good diagnostic indicator under conditions where refrigerant leaving the evaporator is superheated. For the test system with an FXO in heating mode, this condition only occurred under no-fault conditions with a relatively warm ambient temperature of 8.3 °C. However, for cooling mode there were a larger number of operating conditions where the reversing valve fault could be identified for the system with an FXO. For the system with a TXV, the decoupling feature worked well in heating mode for all conditions considered. However, it is necessary to correct for the effects of ambient temperature on heat loss. This correction is not necessary for diagnosing reversing valve leakage in cooling mode. For the TXV system, the diagnostic feature successfully diagnosed the reversing valve leakage fault in heating mode before heating capacity degraded by 6%.

Acknowledgement

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