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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.

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

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 $f_{ij}(\cdot)$ denotes the function relationship between ‘fault j’ and ‘variable i’.