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Normalized performance parameters for a residential heat pump in the cooling mode with single faults imposed

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HIGHLIGHTS

- The effects of nine common faults on heat pump cooling performance were correlated.
- The correlation may be applied to determine the annual cost of an individual fault.
- The normalized correlation is applicable to residential style split heat pump systems.

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ABSTRACT

The cooling mode performance of a residential split heat pump operating under nine different faults was described using normalized performance parameters determined from a ratio of the fault value to the no-fault value obtained from heat pump tests in environmental chambers. The normalized parameters were the coefficient of performance (COP), total capacity, refrigerant-side capacity, sensible heat ratio, outdoor unit power, and total power. A correlation for the normalized performance parameters was developed to produce a continuous representation of the performance characteristics given the fault level and indoor and outdoor temperature conditions.

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1. Introduction

Fault detection and diagnostic (FDD) technology found its first applications in safety critical systems, e.g., nuclear power plants, airplanes. For safety non-critical systems, such as space-conditioning and refrigeration equipment, the interest in applying FDD has lagged until these technologies approach the threshold of economic viability. Reports of major studies on FDD for heating, ventilation and air-conditioning (HVAC) systems started to appear in the literature in the nineties, and the number of publications noticeably increased within the last ten years.

Table 1 lists a few examples of studies published since 2001. The majority of studies focused on analytical developments and provided limited performance data of systems operating under faults. The objective of this paper is to present global performance parameters of a residential heat pump operating in the cooling mode under single fault. These parameters are presented in a non-dimensional format; their values were calculated by dividing a value obtained under faulty operation to a fault-free value under the same operating condition. The paper also presents correlations, which express these non-dimensional parameters as a function of operating conditions and the fault level. The non-dimensional presentation of faulty performance facilitates a better understanding of performance degradation of a heat pump due to common faults. The non-dimensional correlations can also be used to estimate the increase in seasonal energy consumption and energy cost due to faults by performing seasonal simulations of a building equipped with a heat pump operating with a fault.

2. Laboratory measurements

2.1. Experimental apparatus

The experimental apparatus used in this study was described in detail by Kim et al. [6]. The studied system was a single-speed, split heat pump with an 8.8 kW rated cooling capacity. The heat pump was equipped with a thermostatic expansion valve (TXV). Fig. 1 shows a schematic diagram of the experimental setup with the locations of the main measurements. The air-side measurements included indoor dry-bulb and dew-point temperatures, outdoor

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Nomenclature

a	coefficient of multivariate polynomial
CF	improper outdoor air flow rate (condenser fouling) fault
CMF	compressor or four-way reversing valve leakage fault
COP	coefficient of performance
EF	improper indoor air flow rate (evaporator fouling) fault
F	fault level [% or dimensionless (fraction)]
FDD	fault detection and diagnosis
HVAC	heating, ventilating, air-conditioning equipment
LL	liquid line restriction fault
NC	presence of non-condensable gases fault
OC	refrigerant overcharge fault
P	pressure [Pa]
Q	capacity [W]
SC	refrigerant subcooling at the liquid line service valve [°C]
SHR	sensible heat ratio (sensible capacity divided by total capacity)
T	temperature [°C]
TXV	thermostatic expansion valve
UC	refrigerant undercharge fault
VOL	electric line voltage fault
W	power [W]
X or x	measured data or performance parameter
Y	normalized performance parameter

Greek symbols

α	function shown in Eq. 2
Δ	difference
φ	calculated data of performance parameter

Subscripts

i	feature index
ID	indoor dry-bulb
IDP	indoor dew-point
OD	outdoor dry-bulb
ODU	outdoor unit
sat	saturation
tot	total

dry-bulb temperature, barometric pressure, and pressure drop across the air tunnel (not shown on the schematic). T-type thermocouple grids and thermopiles with twenty-five nodes measured air temperatures and temperature change, respectively. On the refrigerant side, pressure transducers and T-type thermocouple probes measured the inlet and exit parameters at every component of the system.

Table 2 lists uncertainties of the major quantities measured. For a complete uncertainty analysis the reader can refer to Kim et al. [6].

2.2. Studied faults and their implementation

Table 3 lists nine studied faults, including their definition and range. The majority of heat pump measurements for these faults were taken and reported by Kim et al. [6]. For the purpose of this study, we conducted additional tests on the same equipment and test apparatus, specifically for the improper electric line voltage fault and improper liquid line refrigerant subcooling fault, which were not studied by Kim et al. [6]. Also, additional tests were performed for a few other faults to expand their range to those listed in Table 3.

The compressor valve leakage fault and the four-way valve leakage fault are considered together because they have a similar effect on the heat pump performance by reducing the refrigerant mass flow rate through the system. In a compressor, a leak can occur at the suction or discharge valves for the reciprocating type, or between the high-pressure and low-pressure portions of the scroll design. The four-way valve can leak from the hot gas, high-pressure side to the low-pressure, suction gas passages. In this study, the compressor/four-way valve leakage fault was implemented using a hot gas bypass from the discharge to the suction of the compressor, and the fault level was defined as the ratio of change in refrigerant mass flow rate to the no-fault refrigerant mass flow rate. With this definition, a complete loss of refrigerant mass flow rate would correspond to the 100% fault level.

The outdoor and indoor air flow faults can be caused by coil fouling. The outdoor air flow fault was implemented by blocking portions of the outdoor heat exchanger face area with paper sheets; the ratio of blocked area to total area determined the fault level, with the −100% fault level indicating total blockage. The indoor air flow fault was implemented by lowering the speed of the nozzle chamber booster fan to increase the external static pressure across the indoor air handler. The fault level was calculated as a ratio of the fault-imposed air mass flow rate to the no-fault air mass flow rate, with the −100% fault level indicating a complete loss of air flow.

A liquid line restriction fault can be caused by a dirty refrigerant filter/dryer or by a kinked liquid line. This fault was implemented by closing a throttling valve installed in the liquid refrigerant line. The fault level was calculated as a ratio of the pressure difference between the liquid line service valve located at the condenser exit and the indoor TXV to the no-fault pressure differential. With this

Table 1
Selected studies on FDD.

Investigator(s)	System type	Study focus
Comstock and Braun [1]	Centrifugal chiller	Experiment. eight single faults
Kim et al. [2,3]	Residential heat pump	Experiment for cooling mode, single-faults diagnosed with rule-based chart
Chen and Braun [4]	Rooftop air-conditioner	Simplified rule-based chart method
Navarro-Esbri et al. [5]	General vapor compression system	Dynamic model based FDD for real-time application
Kim et al. [6,7]	Single-speed, residential heat pump	Single-faults and steady-state detector study
Wang et al. [8]	HVAC system for new commercial buildings	System-level FDD involving sensor faults
Cho et al. [9]	Air-handling unit for buildings	Multiple faults
Li and Braun [10]	Direct expansion vapor compression system	Multiple faults
Du and Jin [11]	Air handling unit	Multiple faults