FDD Applied to a Residential Split System Heat Pump

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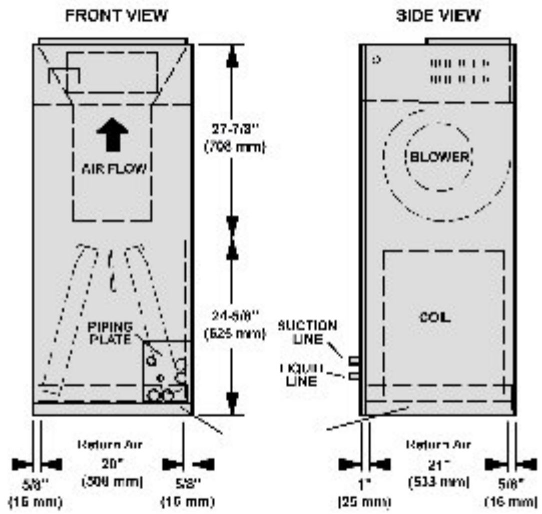
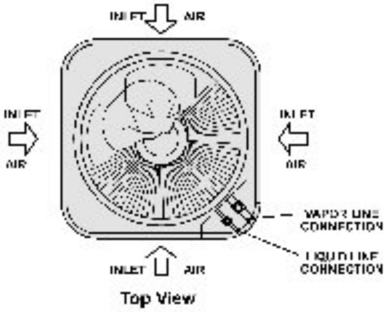
Residential split-system heat pump

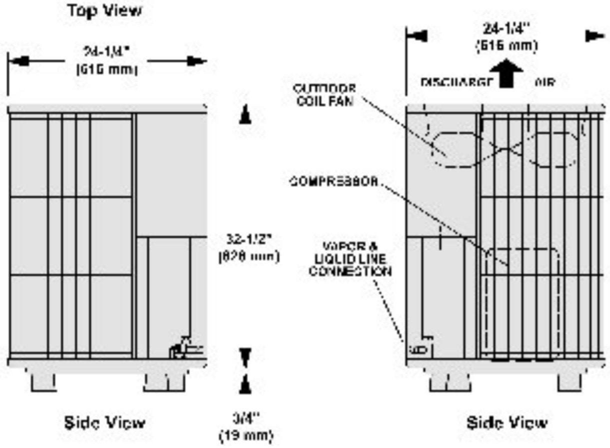
- **System Characteristics**

- Refrigerant: R410A
- 2.5-ton split heat pump system
- 13 SEER, 8.5 HSPF
- TXV in cooling and heating modes
- Scroll compressor



ID unit (Indoor A-coil in upflow)





OD unit

FDD in the heating mode

- Steady-State Detector (SSD)
- Polynomial Reference Model for important system features
- Fault Detector/Classifier

Cooling	Heating
Under/Over Charge	Under/Over Charge
Improper Airflow through HXs	Improper Airflow through HXs
Liquid Line Restriction	Liquid Line Restriction
Compressor/Reversing Valve Leakage	Compressor/Reversing Valve Leakage
Non-condensables	

Fault-free reference model

- FDD scheme requires a reference fault-free value for features
- Real-time sampling of feature values requires a steady-state detector

Independent variables

T_{OD} : outdoor or condenser air dry-bulb temperature

T_{ID} : indoor or evaporator air dry-bulb temperature

T_{IDP} : indoor or evaporator air dew-point temperature

- **Example: Second order multivariate reference polynomial**

$$\phi_i = a_0 + a_1 T_{OD} + a_2 T_{ID} + a_3 T_{IDP} + a_4 T_{OD} T_{ID} + a_5 T_{ID} T_{IDP} + a_6 T_{IDP} T_{OI}$$
$$+ a_7 T_{OD}^2 + a_8 T_{ID}^2 + a_9 T_{IDP}^2$$

<u>All measurements, including test conditions, have uncertainties.</u>

Features and residuals

- **Features:** Characteristic measurements to detect and diagnose faults

T_{OD}
T_{ID}
T_{IDP}

⇨

T_{ER} : evaporator exit saturation temperature
ΔT_{sh} : evaporator exit superheat
T_{DW} : compressor discharge wall temperature
T_{CR} : condenser inlet saturation temperature
ΔT_{sc} : liquid line subcooling
T_{CA} : condenser air temperature rise
ΔT_{EA} : evaporator air temperature drop
ΔT_{LL} : liquid line temperature drop. ♪

- **Residuals:** difference in measurements and expectations T_{ID}
  - Expectations are estimated by no-fault reference model.

Residual, $\Delta\phi = \phi_{\mathrm{Measurement}} - \phi_{\mathrm{Reference}}$

Fault implementation example

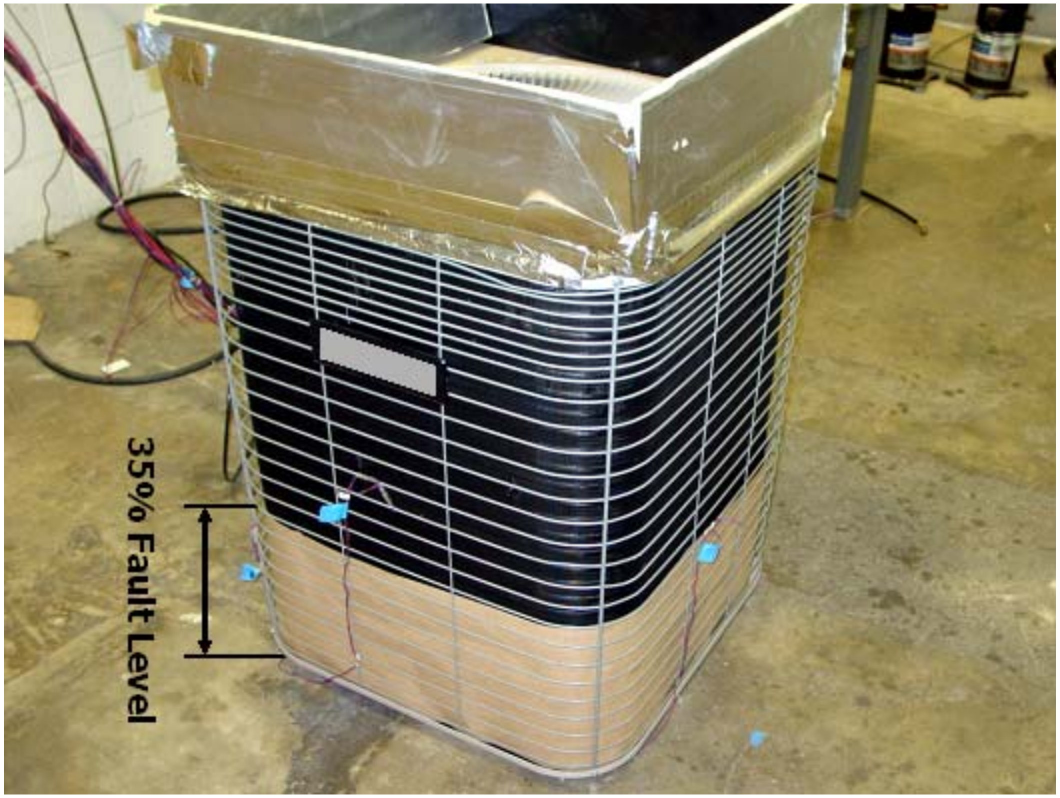
Improper outdoor air flow rate (Condenser fouling)

Reduction of air flow

i.e., obstructions stuck to HX, bent fins, fan fault . . . . .

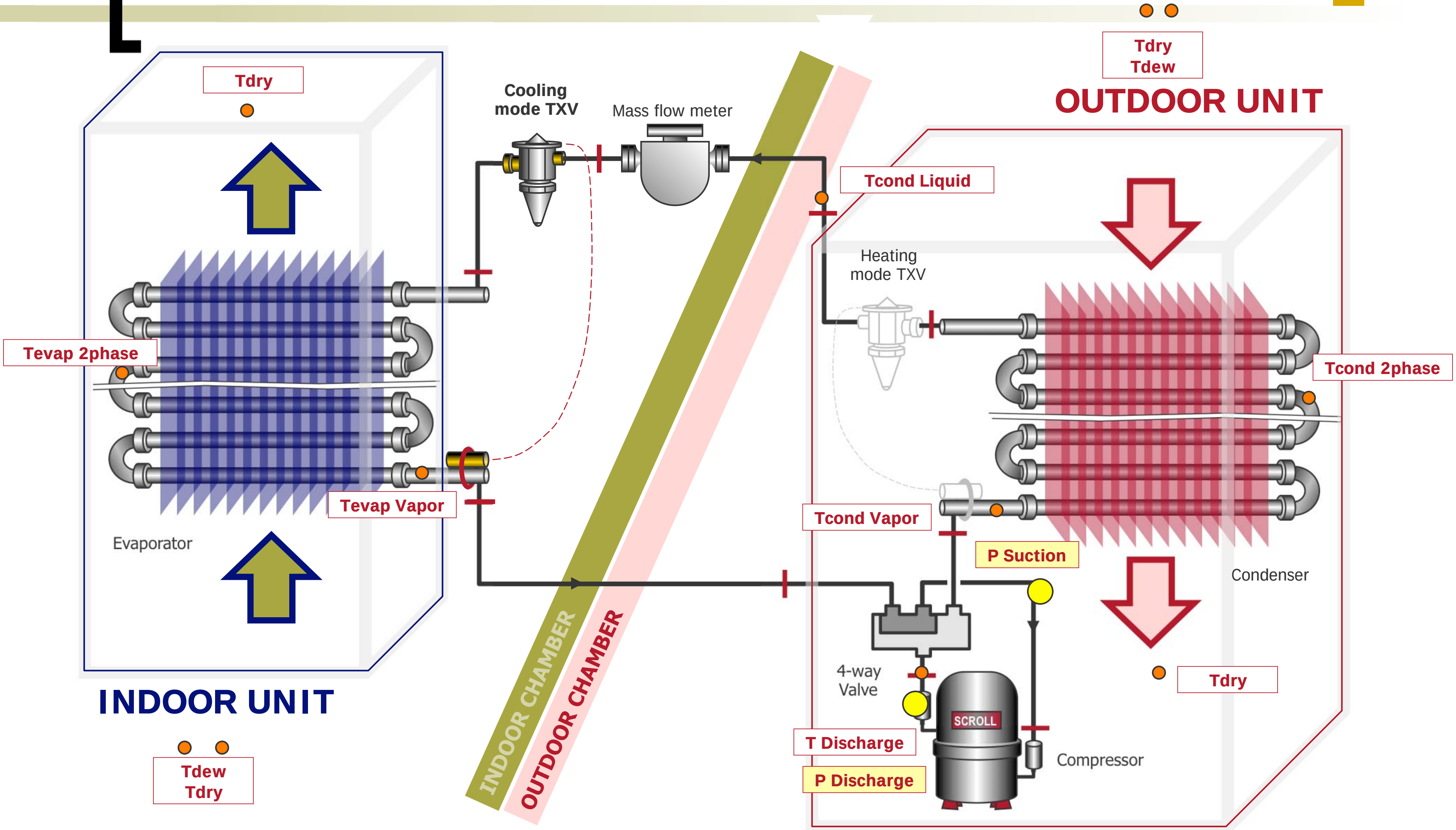
Fault Implementation:

Blocking the lower part of the outdoor HX.

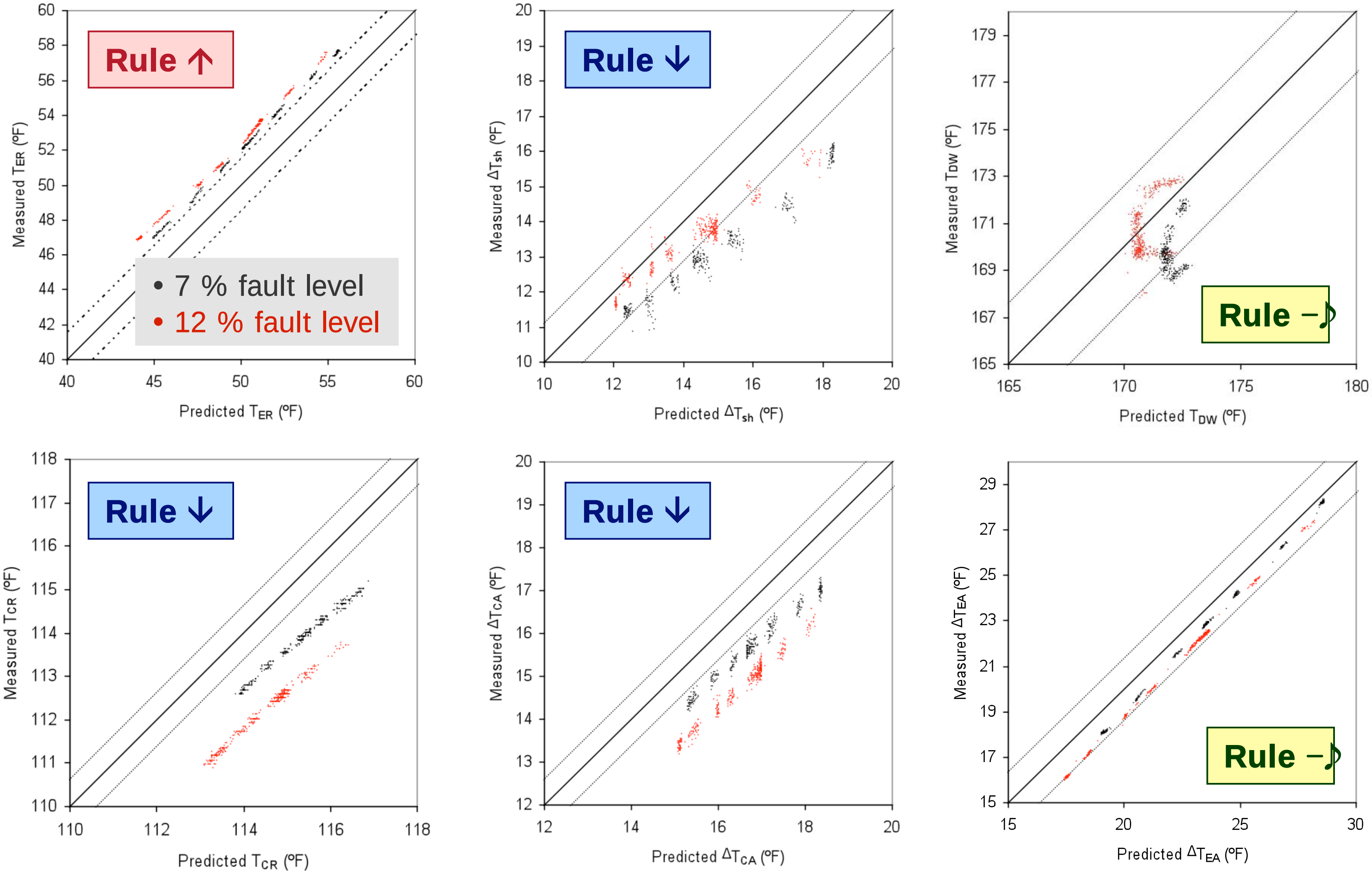


Partially blocked condensing unit.

Measurements for FDD



Residual pattern for a compressor/reversing valve fault



Probability of a fault

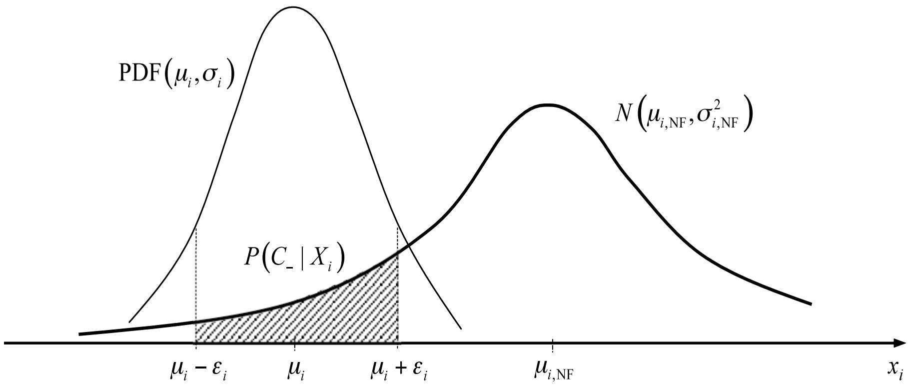
$$z_i = \frac{x_i - \mu_{i,\mathrm{NF}}}{\sigma_i}$$

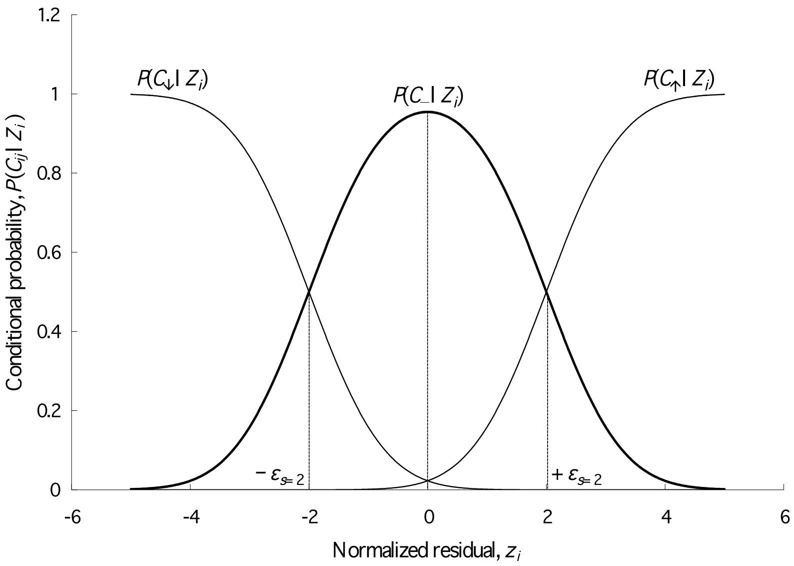
$$\varepsilon_i \approx s\sigma_i$$

$$P(C_{\downarrow}, z_i) = P(z_i \geq s) = \frac{1}{2}\left[1 - \operatorname{erf}\left\{\frac{1}{\sqrt{2}}(z_i + s)\right\}\right]$$

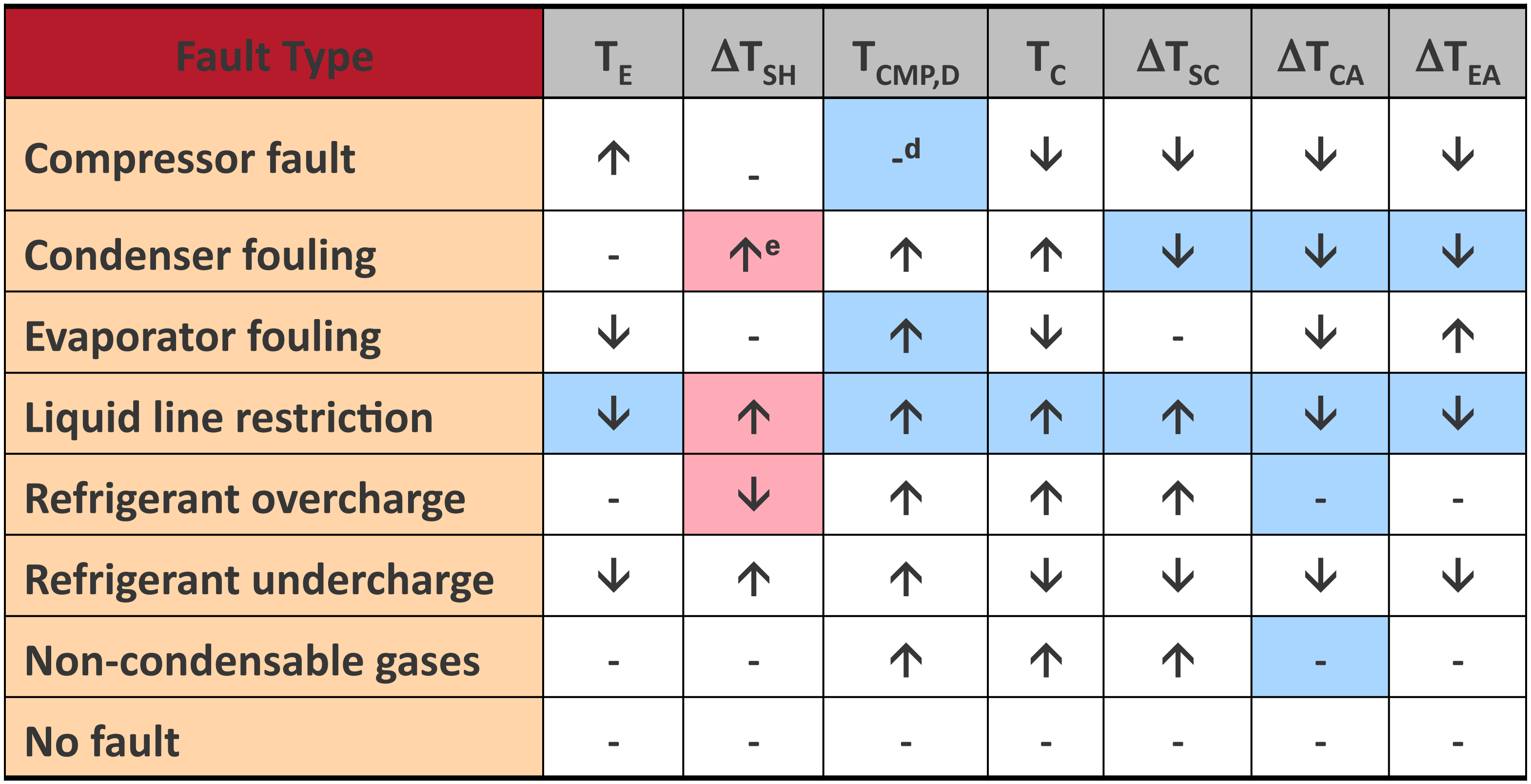
$$P(C_{\uparrow}, z_i) = P(z_i \leq s) = \frac{1}{2}\left[1 + \operatorname{erf}\left\{\frac{1}{\sqrt{2}}(z_i - s)\right\}\right]$$

$$P(C_{-}, z_i) = P(-s < z_i < s) = \frac{1}{2}\left[\operatorname{erf}\left\{\frac{1}{\sqrt{2}}(z_i + s)\right\} - \operatorname{erf}\left\{\frac{1}{\sqrt{2}}(z_i - s)\right\}\right]$$





Cooling rule-based chart [a, b, c]



Fault Type	T_E	ΔT_{SH}	$T_{CMP,D}$	T_C	ΔT_{SC}	ΔT_{CA}	ΔT_{EA}
Compressor fault	↑	-	-[d]	↓	↓	↓	↓
Condenser fouling	-	↑[e]	↑	↑	↓	↓	↓
Evaporator fouling	↓	-	↑	↓	-	↓	↑
Liquid line restriction	↓	↑	↑	↑	↑	↓	↓
Refrigerant overcharge	-	↓	↑	↑	↑	-	-
Refrigerant undercharge	↓	↑	↑	↓	↓	↓	↓
Non-condensable gases	-	-	↑	↑	↑	-	-
No fault	-	-	-	-	-	-	-

[a] Residential split air conditioner with a constant speed scroll compressor and a TXV.

[b] ↑, ↓, - represent the direction of positive, negative, and neutral residual respectively.

[c] No change implies the variations within the uncertainty of measurement.

[d,e] Cells colored by light blue and pink show inconsistent rules compared to the result of Chen and Braun (2001)

Heating rule-based chart

Fault Type	T_E	ΔT_{SH}	$T_{CMP,D}$	T_C	ΔT_{SC}	ΔT_{CA}	ΔT_{EA}
Compressor fault	- ↑	-	-	↓	-	- ↓	-
Condenser fouling	-	-	↑	- ↑	-	↑	-
Evaporator fouling	↓	↑	↑ - ↓	- ↓	-	- ↓	-
Liquid line restriction	-	-	-	-	-	-	-
Refrigerant overcharge	-	-	↑	↑	↑	-	-
Refrigerant undercharge	- ↓	-	-	- ↓	↓	- ↓	-
No fault	-	-	-	-	-	-	-

Cooling/Heating rule-based chart comparison

Fault Type	T_E	ΔT_{SH}	$T_{CMP,D}$	T_C	ΔT_{SC}	ΔT_{CA}	ΔT_{EA}
Compressor fault	↑ - ↑	-	-	↓	↓ -	↓ - ↓	↓ -
Condenser fouling	-	↑ -	↑	↑ - ↑	↑ -	↓ ↑	↓ -
Evaporator fouling	↓	- ↑	↑ ↑-↓	↓ - ↓	-	↓ - ↓	↑ -
Liquid line restriction	↓ -	↑ -	↑ -	↑ -	↑ -	↓ -	↓ -
Refrigerant overcharge	-	↓ -	↑	↑	↑	-	-
Refrigerant undercharge	↓ - ↓	↑ -	↑ -	↓ - ↓	↓	↓ -↓	↓ -
No fault	-	-	-	-	-	-	-

Fault classifier module

Fault Detection and Diagnostic System for Split Heat Pump
-Minsung Kim, HVAC&R Equipment Performance Group

	Moving Window					Moving Avg
Tcai	100.056	100.067	100.103	99.9717	100.018	100.043
Teai	69.9515	69.9901	69.8903	69.9787	70.0535	69.9728
Teai_dp	50.4155	50.4155	50.4647	50.4647	50.4647	50.445
						Moving Avg Out
TE	42.4071	42.5109	42.5109	42.4849	42.5109	42.4849
dsh	12.7436	12.547	12.5324	12.5841	12.8253	12.6465
TD	183.128	183.208	183.447	183.205	183.341	183.266
TC	117.519	117.609	117.631	117.564	117.564	117.577
dsc	6.59834	6.47791	6.39059	6.50457	6.5358	6.50144
DTca	14.5838	14.5209	14.6438	14.6408	14.5799	14.5938
DTea	20.1359	20.133	20.021	20.1239	20.1193	20.1066
						EER Moving Avg
EER	10.2042	10.1869	10.1854	10.1788	10.2105	10.1932

EER Degradation (%) -2.59318

Alarm Control (%) -2

EER Warning 🟩

Model Out	Residual	Standard Deviation	Probability
44.3176	-1.83267	0.370591	0
12.3703	0.276176	0.819581	0
181.404	1.8619	1.08599	0.156413
118.065	-0.487064	0.232733	0
6.91052	-0.409082	0.474247	3.81497E-31
14.8991	-0.305276	0.197122	0
17.881	2.22564	0.383406	2.33688E-29
			5.92341E-28

Model Out	EER Residual	EER Stdev
10.4645	-0.271364	0.391699

Example of a FDD System with 15% loss in evaporator airflow

What more do we need?

- Commissioning tool using FDD module
- Learning module
    - System adjusts to every installation
    - System adjusts as it ages
- Heating mode unique problems
    - Refrigerant charging in heating mode
    - Frosting of the outdoor heat exchanger

What more do we need? (cont.)

- Standardized fault codes for residential systems
  - Everyone needs to define a fault in the same way
  - Standard fault codes simplify communicating faults to a central system
- FDD for variable speed systems and multi-function/hybrid systems
- FDD for mixed systems
- Standard method for comparing FDD devices/algorithms

List of FDD publications from BFRL

- 2009, “Heating Mode Performance Measurements for a Residential Heat Pump with Single Faults Imposed,” NIST Technical Note 1648, National Institute of Standards and Technology, Gaithersburg, MD.
- 2009, “Performance of a Residential Heat Pump Operating in the Cooling Mode with Single Faults Imposed,” Applied Thermal Engineering 29(4), 770-778.
- 2008, “Cooling Mode Fault Detection and Diagnosis Method for a Residential Heat Pump,” NIST Special Publication 1087, National Institute of Standards and Technology, Gaithersburg, MD.
- 2008, “Design of a steady-state detector for fault detection and diagnosis of a residential air conditioner,” International Journal of Refrigeration 31(5), 790-99.
- 2006, “Performance of a Residential Air Conditioner at Single-Fault and Multiple-Fault Conditions,” NISTIR 7350, National Institute of Standards and Technology, Gaithersburg, MD.