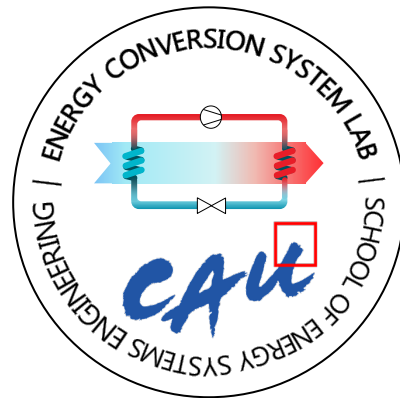


Single Fault Impact Analysis of a Residential Heat Pump in the Cooling Mode According to the Temperature Conditions



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Previous FDD studies on Heat Pumps

Progressive increase in Heat pumps, importance of FDD was highlighted

- Mainly focused on performance variation by fault levels
Performance parameters : COP, Cooling capacity, Target temperature
- Limited test cases (Comp., Expn. device, Operating temp)

Table Summary of previous experimental testing

Author	Compressor	Expn. device	T _{ID} [°C]	T _{OD} [°C]
Palmiter et al. (2011)	Scroll	TXV	26.7	27.8, 35.0, 48.9, 51.7
Kim et al. (2012)	Tandem, Rotary, Reciprocating	FXO / EEV	27.0	35.0
Mowris et al. (2012)	-	FXO / TXV	26.7	47.8
Qureshi et al. (2014)	Reciprocating	TXV	21.0	31.6
SCE (2015)	-	TXV	26.7	35
Du et al. (2016)	Scroll / Reciprocating	TXV / FXO	26.7	27.8, 37.8 / 35.6, 36.1 / 27.8, 35.0
Hu et al. (2021)	Rotary	TXV	26.7	27.8, 35.0, 40.5

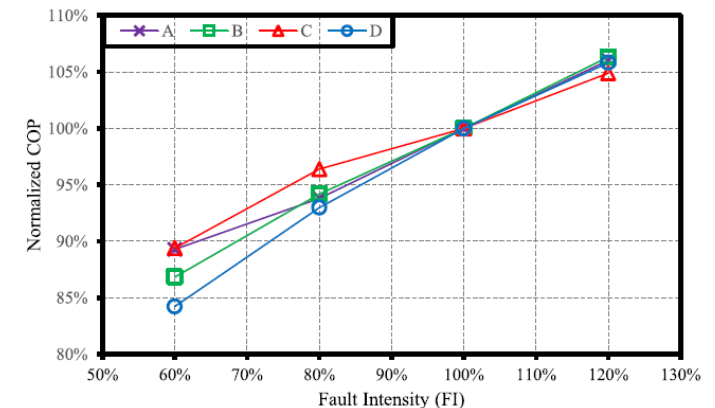
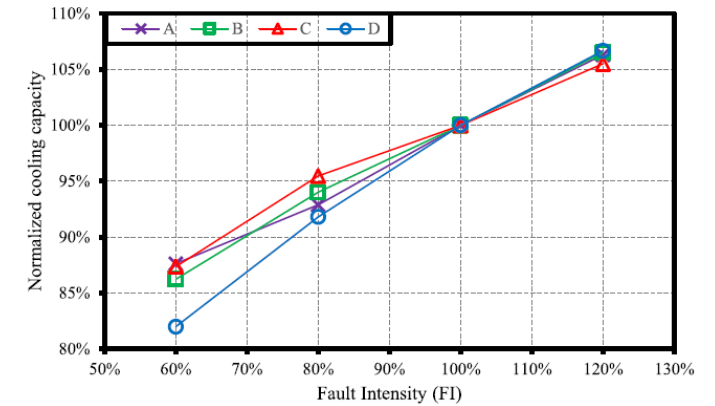


Figure Impacts of EF faults on the system performance^[1]

[1] Hu et al., Applied Thermal Engineering, 2021

Effect of operating temperature

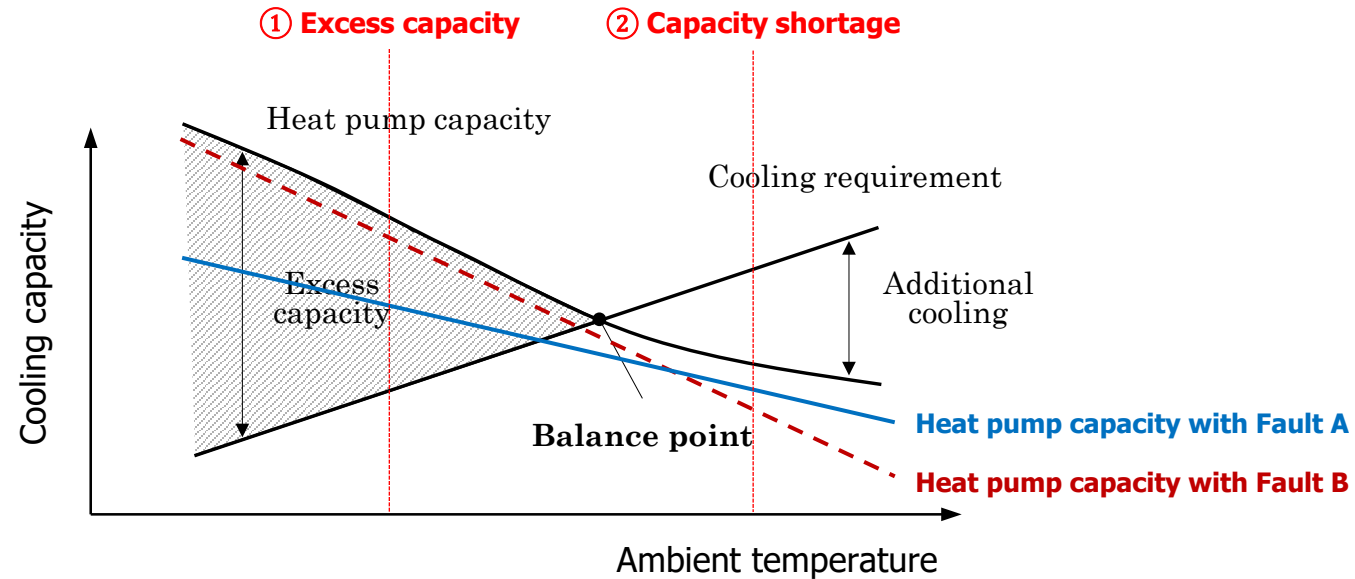
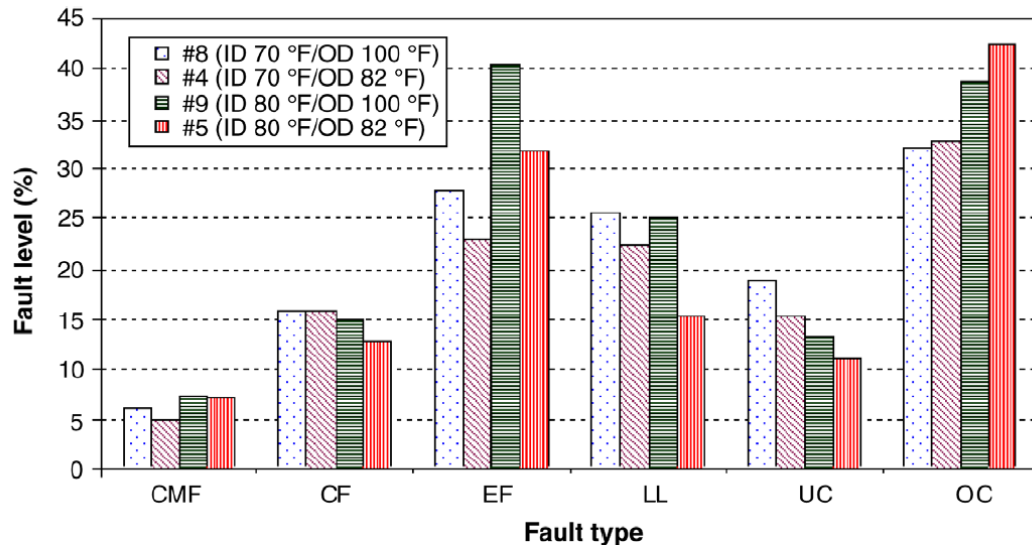


Figure Seasonal performance characteristics of heat pump system with a constant speed compressor^[2]

- **System performance** depending on operating conditions **changes when fault is imposed**

[2] Kim, Ph. D Thesis, Seoul National University, 2002

Study about faults on various operating conditions



- Estimated fault level to cause 5 % EER reduction
 - ✓ EF & OC → Low fault impact
 - ✓ LL & OC → Large difference with operating conditions
- **Fault impact varies with different**
 - **Fault type**
 - **Operating condition**



How might operating conditions influence the fault impact?

Figure Estimated fault levels for each fault at a 5 % degradation in EER at 4 different operating conditions^[3]

CMF compressor/reversing valve leakage fault	LL refrigerant liquid line restriction fault
CF condenser airflow fouling fault	UC refrigerant undercharge fault
EF evaporator airflow fouling fault	OC refrigerant overcharge fault

[3] Kim et al., Applied Thermal Engineering, 2009

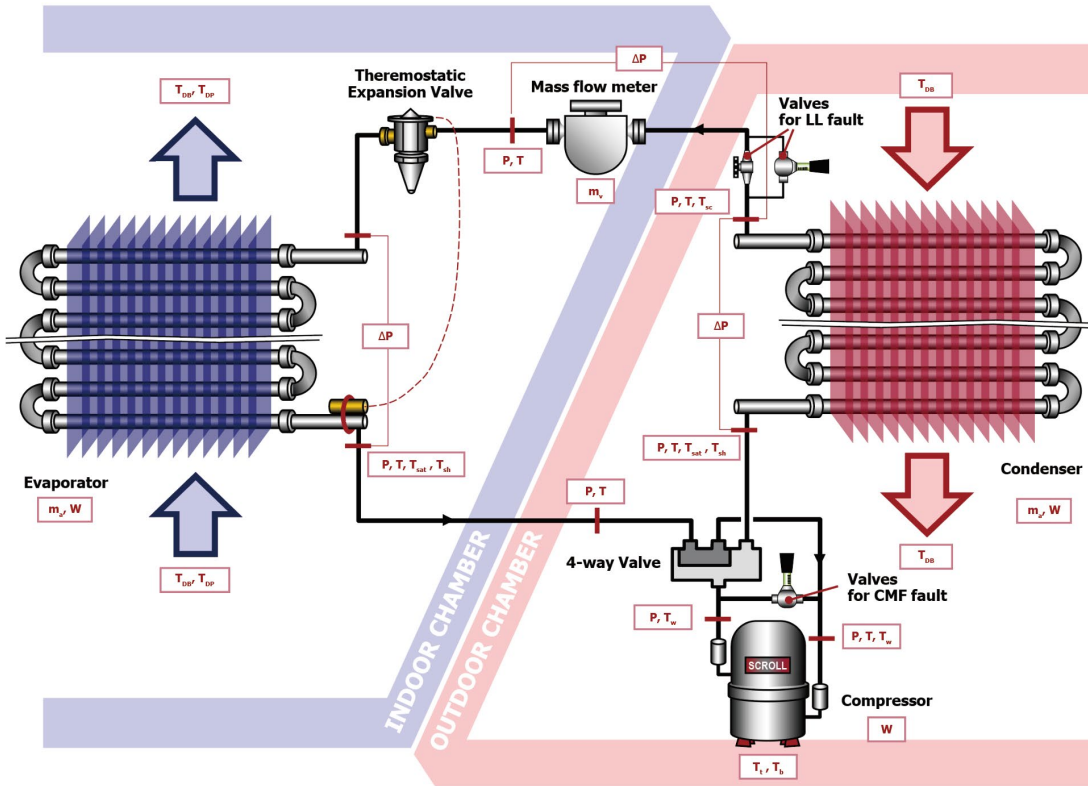


Figure Experimental setup with the heat pump in cooling mode^[3]

Table Operating conditions of fault-free steady state (FFSS) tests

Test Index	Indoor		Outdoor	
	Dry-bulb T (°C)	RH (%)	Dry-bulb T (°C)	RH (%)
1*	26.7	50	35.0	40 to 60
2	21.1	50	21.1	40 to 60
3	26.7	50	21.1	40 to 60
4**	21.1	50	27.8	40 to 60
5**	26.7	50	27.8	40 to 60
6	21.1	50	32.2	40 to 60
7	26.7	50	32.2	40 to 60
8**	21.1	50	37.8	40 to 60
9**	26.7	50	37.8	40 to 60
10	21.1	Dry coil	21.1	40 to 60
11	26.7	Dry coil	21.1	40 to 60
12	21.1	Dry coil	27.8	40 to 60
13	26.7	Dry coil	27.8	40 to 60
14	21.1	Dry coil	32.2	40 to 60
15	26.7	Dry coil	32.2	40 to 60
16	21.1	Dry coil	37.8	40 to 60
17	26.7	Dry coil	37.8	40 to 60

- **System : R410A 8.8 kW residential heat pump with constant-speed scroll compressor and TXV**
- **Fault-free tests : #2~17**
- **Fault tests : #4, 5, 8, 9**

Fault implementation

- 6 common faults in air-conditioner were selected
- Fault level was defined as the ratio of parameters compared to fault-free operation

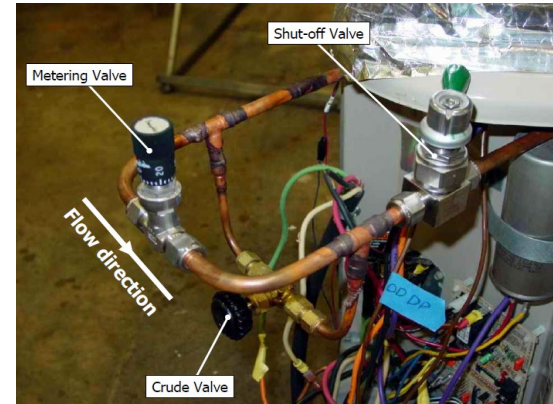


Figure CMF fault

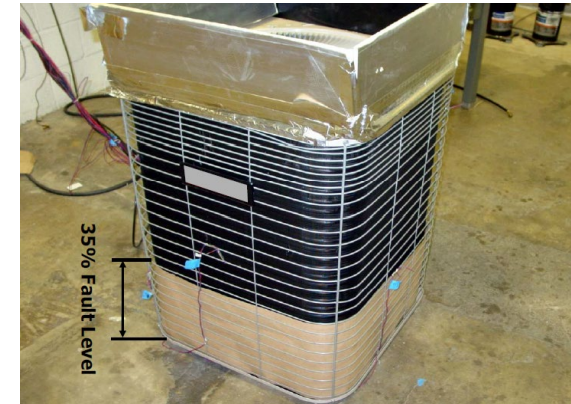


Figure CF fault

Table Description of studied faults

Fault	Abbr.	Determination of level of fault
Compressor leakage (4-way valve leakage)	CMF	% of refrigerant flow rate
Improper outdoor air flow rate (Condenser fouling)	CF	% of coil area blocked
Improper indoor air flow rate (Evaporator fouling)	EF	% of correct air flow rate
Liquid-line restriction	LL	% of normal pressure drop through TXV
Refrigerant overcharge	OC	% overcharge from the correct charge
Refrigerant undercharge	UC	% undercharge from the correct charge

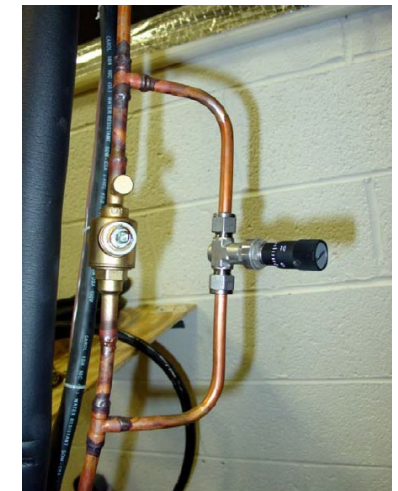


Figure LL fault

Fault-free steady-state (FFSS) model

- **Model for system parameters (COP, Cooling capacity) using NF data**

- 2nd order multivariate polynomial model (T_{ID} , T_{OD} , T_{IDP})

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

$$COP = \frac{\dot{Q}_{EA}}{\dot{W}_{comp}} \quad \dot{Q}_{EA} = \dot{Q}_{EA,sens} + \dot{Q}_{EA,lat}$$

- **Estimate No-fault reference value at Fault test condition**

- Estimate COP_{NF} , $\dot{Q}_{EA,NF}$ and performance degradation r

$$r(COP)[\%] = \frac{COP_F - COP_{NF}}{COP_{NF}} \times 100$$

$$r(\dot{Q}_{EA})[\%] = \frac{\dot{Q}_{EA,F} - \dot{Q}_{EA,NF}}{\dot{Q}_{EA,NF}} \times 100$$

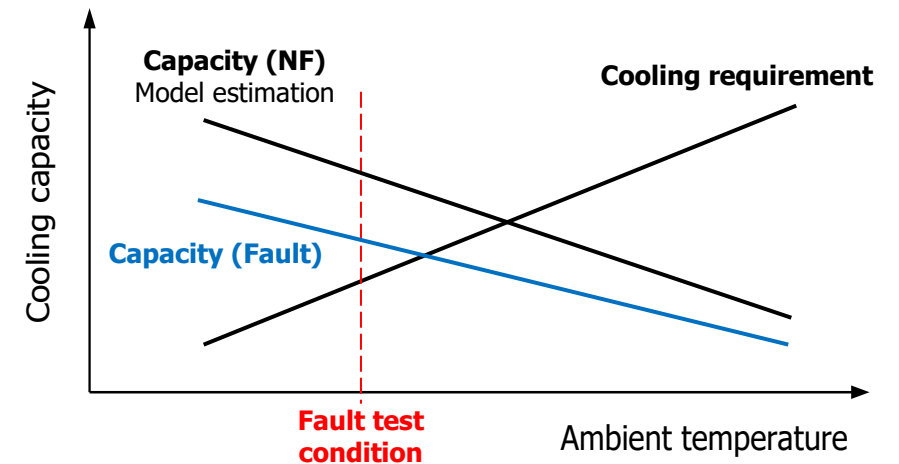


Figure FFSS model and the fault test data

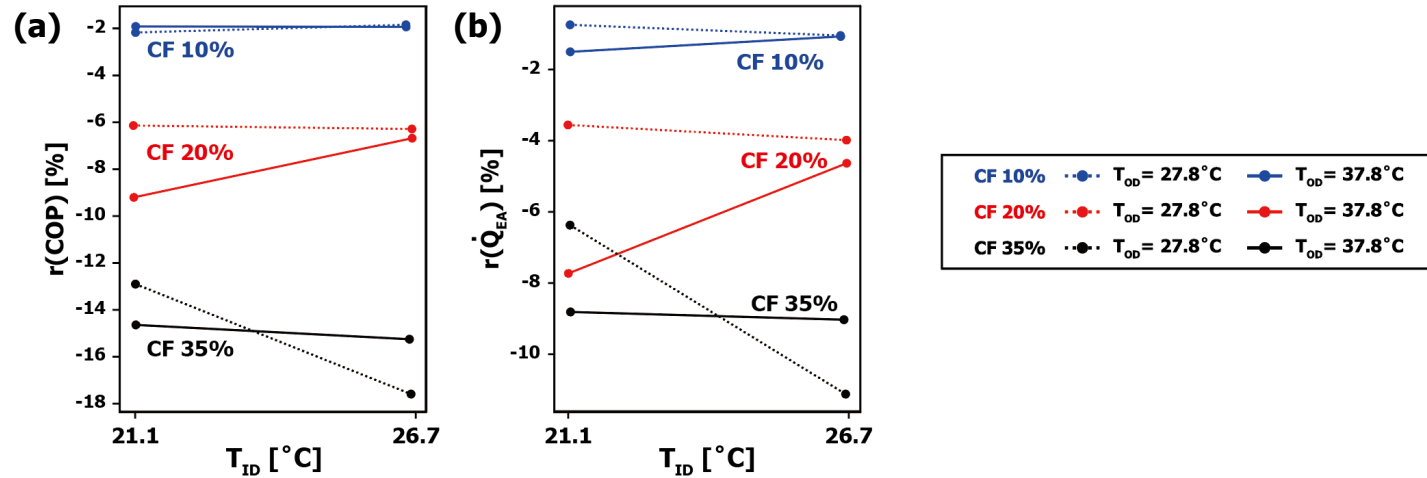


Figure Performance parameters with temperature conditions of CF faults

❖ CF fault characteristics

- CF fault → Heat exchange through the condenser decreased, P_{Cond} ↑ & DSC ↓

❖ CF fault level (10%) : Little performance change (Enough condenser capacity)

❖ CF fault level (20%, 35%)

- At low T_{OD} , COP drops less : low load, higher \dot{m}_{ref} , better compensation of decreased \dot{m}_{air}
- At CF 35%, T_{ID} 26.7, T_{OD} 27.8 – System performance drops significantly : \dot{m}_{air} reduced too much → low DSC → two-phase mixture enters TXV

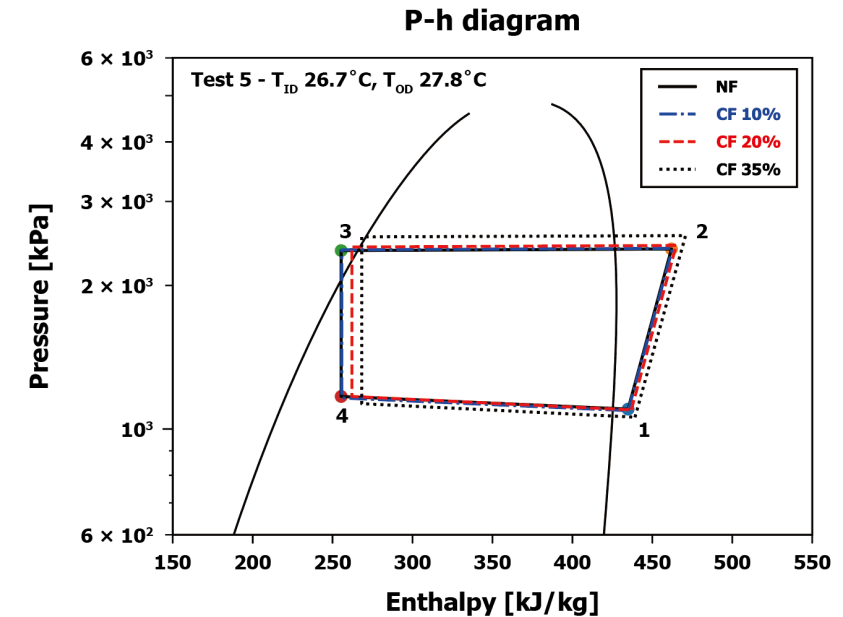


Figure P-h diagrams of every CF levels for test 5

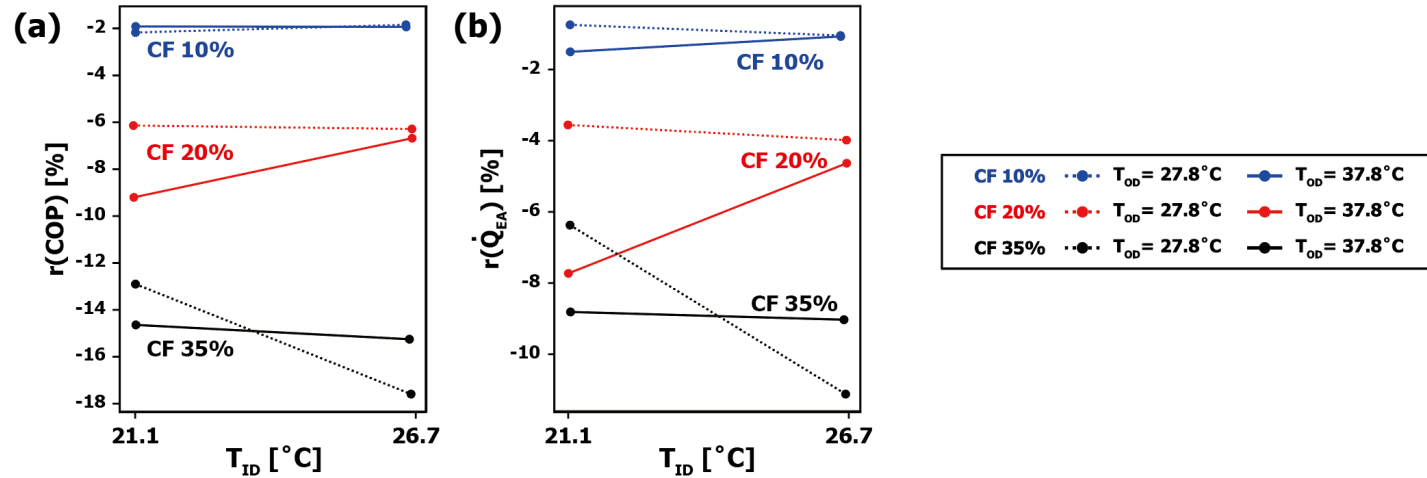


Figure Performance parameters with temperature conditions of CF faults

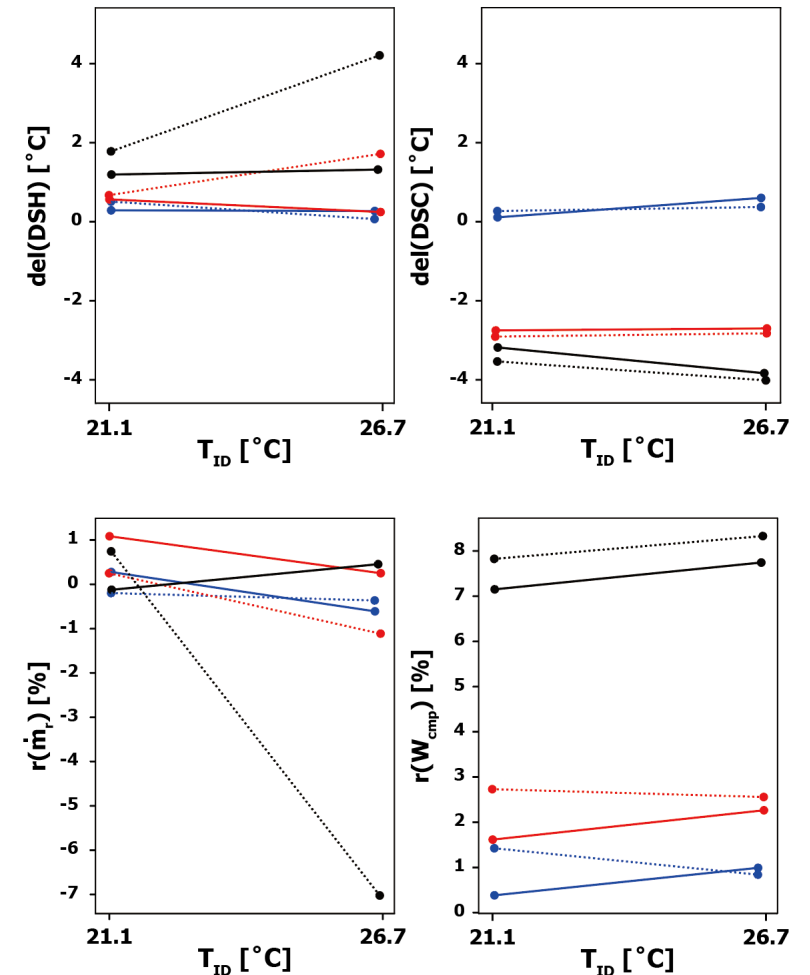
❖ CF fault characteristics

- CF fault \rightarrow Heat exchange through the condenser decreased, $P_{Cond} \uparrow$ & DSC \downarrow

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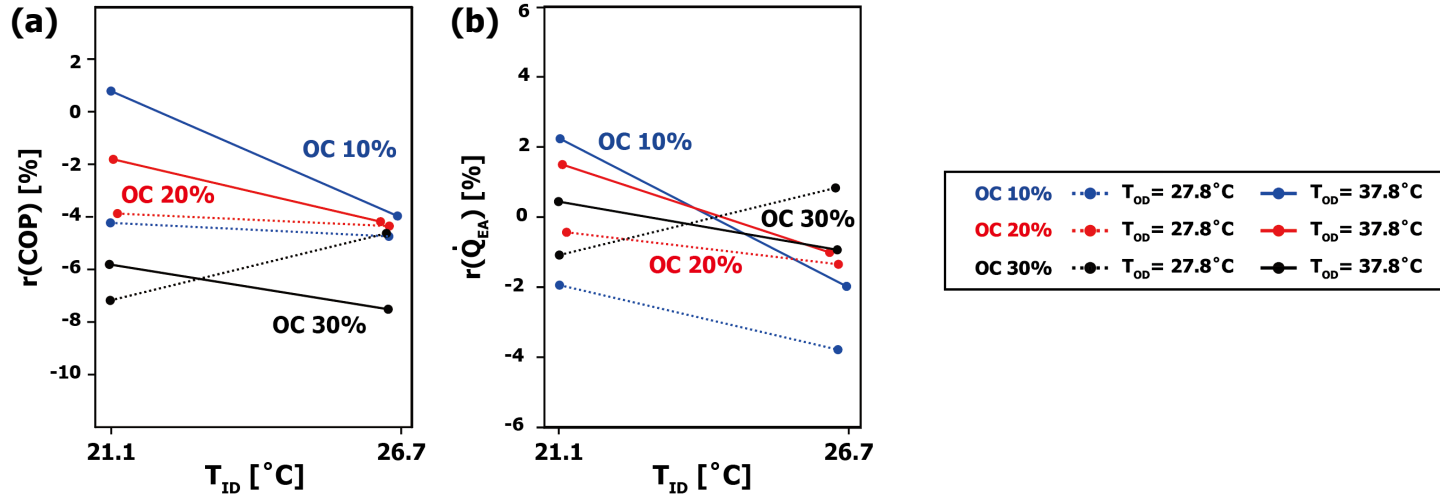


Figure Performance parameters with temperature conditions of OC faults

❖ OC fault characteristics

- OC fault level increases → $P_H \uparrow$, $\Delta T_c \uparrow$ → DSC ↑
 $P_{Evap} \uparrow$, DSH ↓ → TXV closed

❖ OC fault level (10%, 20%, 30%)

- Performance variation is minimal
 - Cooling capacity changes < 4%, COP drop is due to $W_{Comp} \uparrow$
 - Charge amount even with OC 30% is in the acceptable range

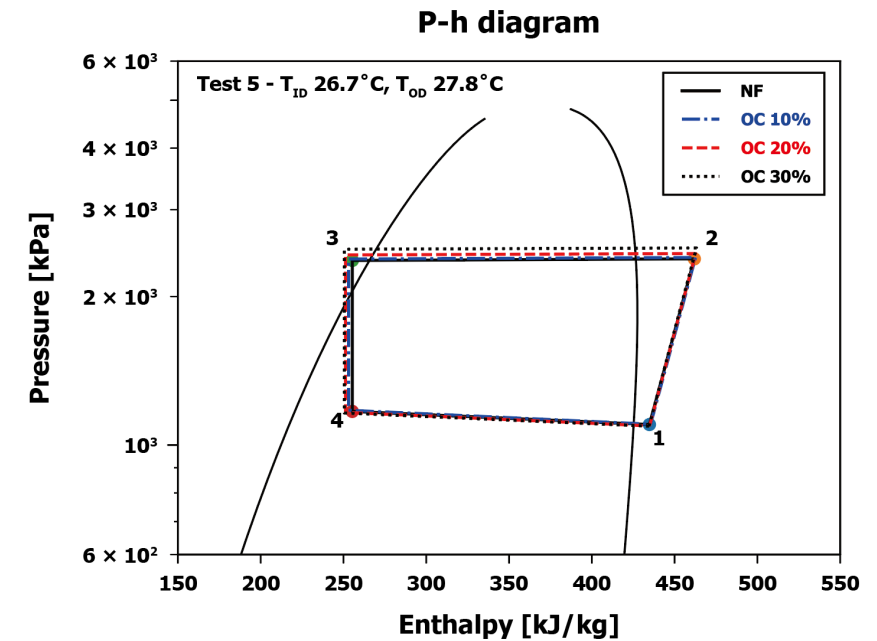
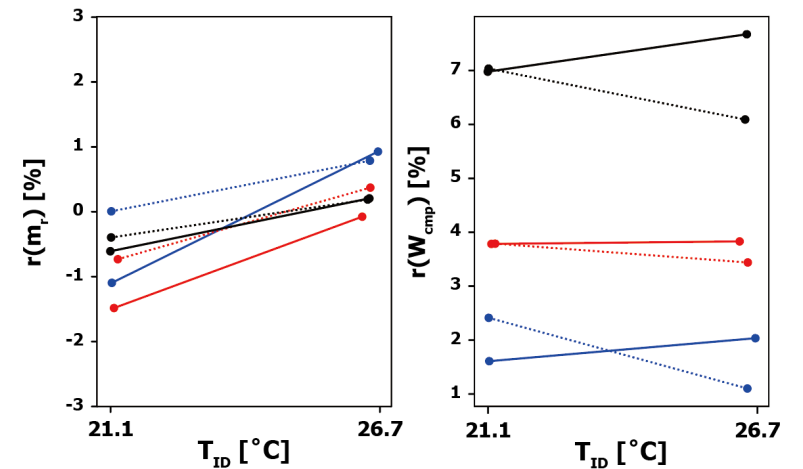
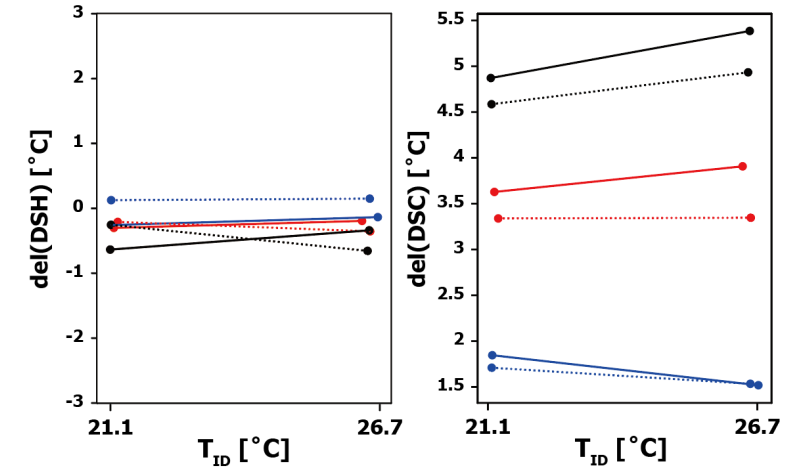
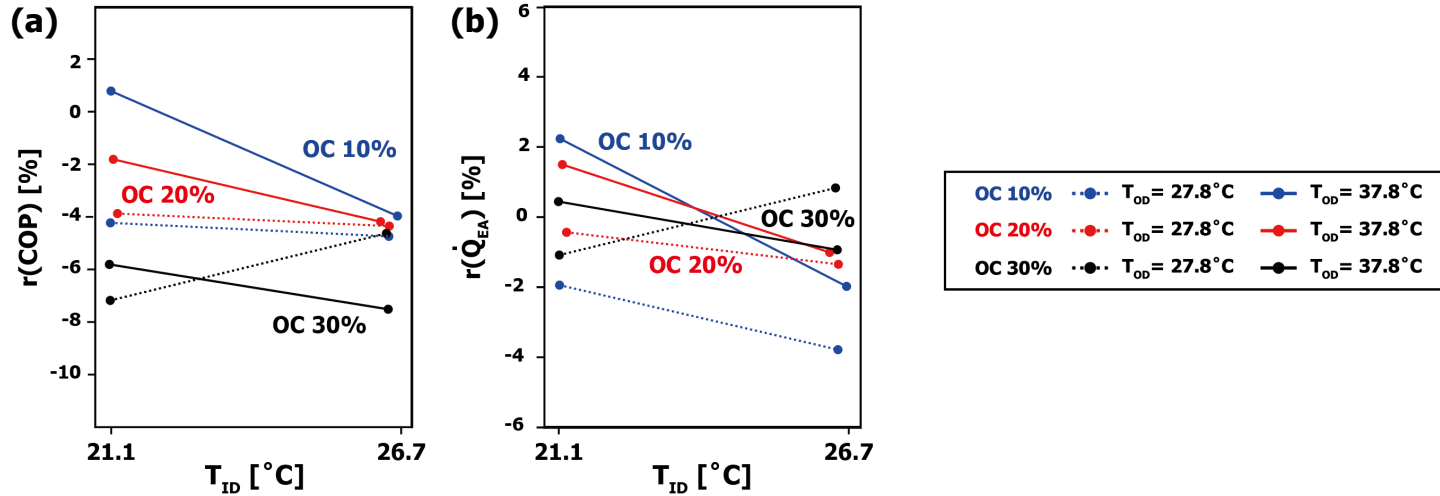


Figure P-h diagrams of every OC levels for test 5



❖ OC fault characteristics

- OC fault level increases $\rightarrow P_H \uparrow, \Delta T_c \uparrow \rightarrow DSC \uparrow$
 $P_{Evap} \uparrow, DSH \downarrow \rightarrow TXV$ closed

❖ OC fault level (10%, 20%, 30%)

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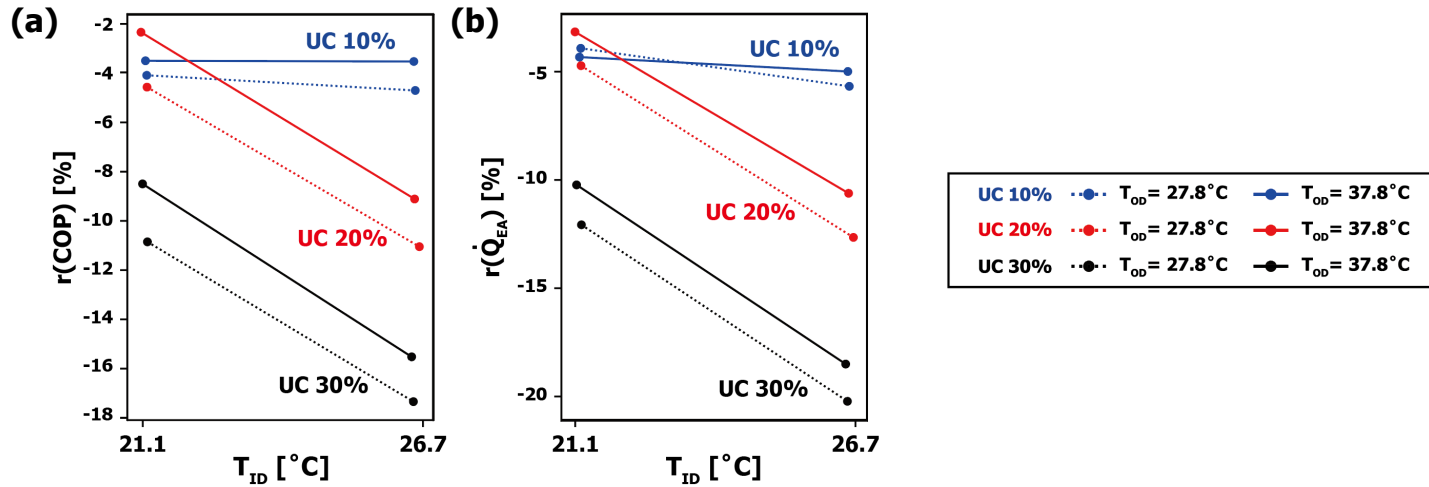


Figure Performance parameters with temperature conditions of UC faults

❖ UC fault characteristics

- UC fault $\rightarrow P_H \downarrow, DSC \downarrow \rightarrow P_{Evap} \downarrow, DSH \uparrow \rightarrow TXV$ opening \uparrow
- Less performance drop at lower T_{ID} (21.1)
: System nominal charge targets T_{ID} (26.7) \rightarrow initially overcharged condition

❖ UC fault

- TXV in control (10%) : Charge amount is still acceptable, Small variation in performance
- TXV saturated : \dot{m}_{ref} , \dot{Q}_{EA} and COP drops significantly

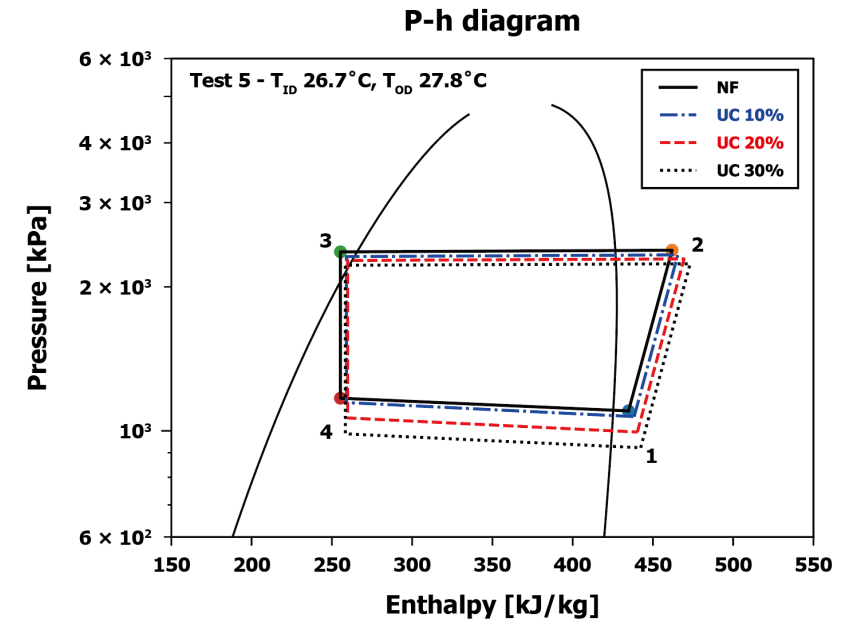


Figure P-h diagrams of every UC levels for test 5

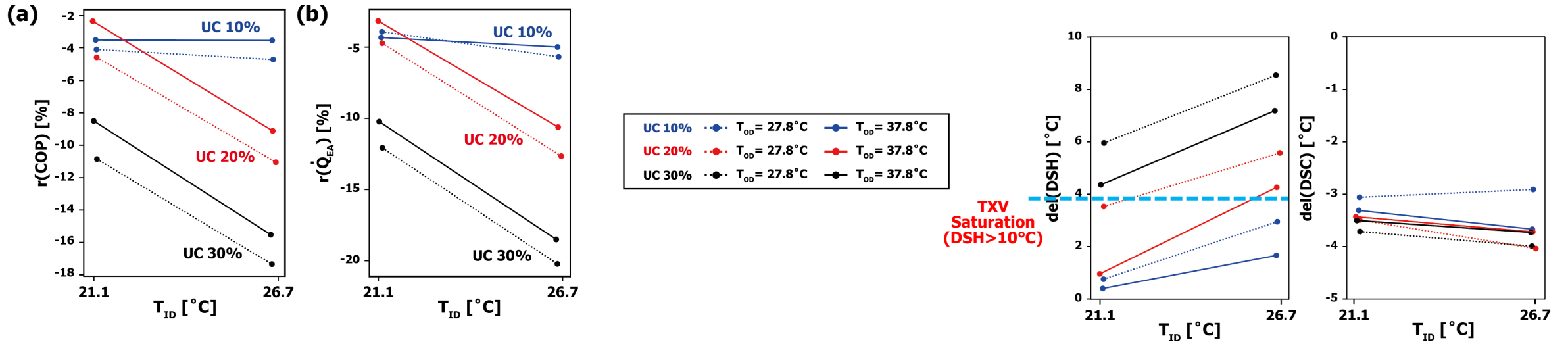


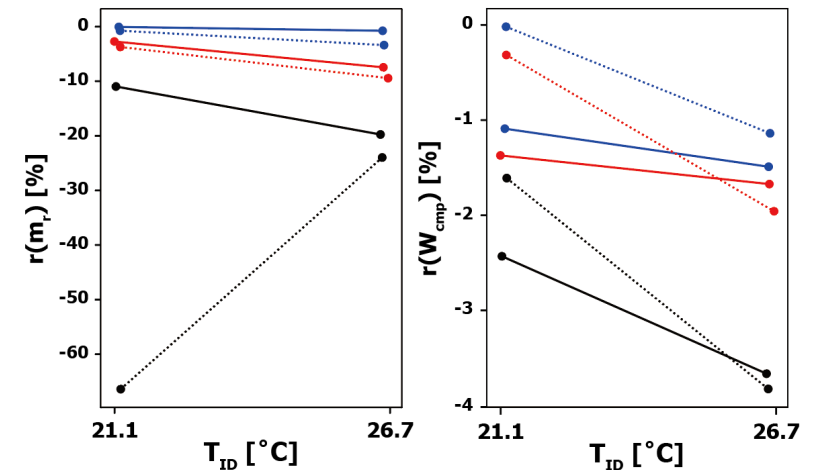
Figure Performance parameters with temperature conditions of UC faults

❖ UC fault characteristics

- UC fault $\rightarrow P_H \downarrow, DSC \downarrow \rightarrow P_{Evap} \downarrow, DSH \uparrow \rightarrow TXV \text{ opening } \uparrow$
- Less performance drop at lower T_{ID} (21.1)
: System nominal charge targets T_{ID} (26.7) \rightarrow initially overcharged condition

❖ UC fault

- TXV in control (10%) : Charge amount is still acceptable, Small variation in performance
- TXV saturated : \dot{m}_{ref} , \dot{Q}_{EA} and COP drops significantly



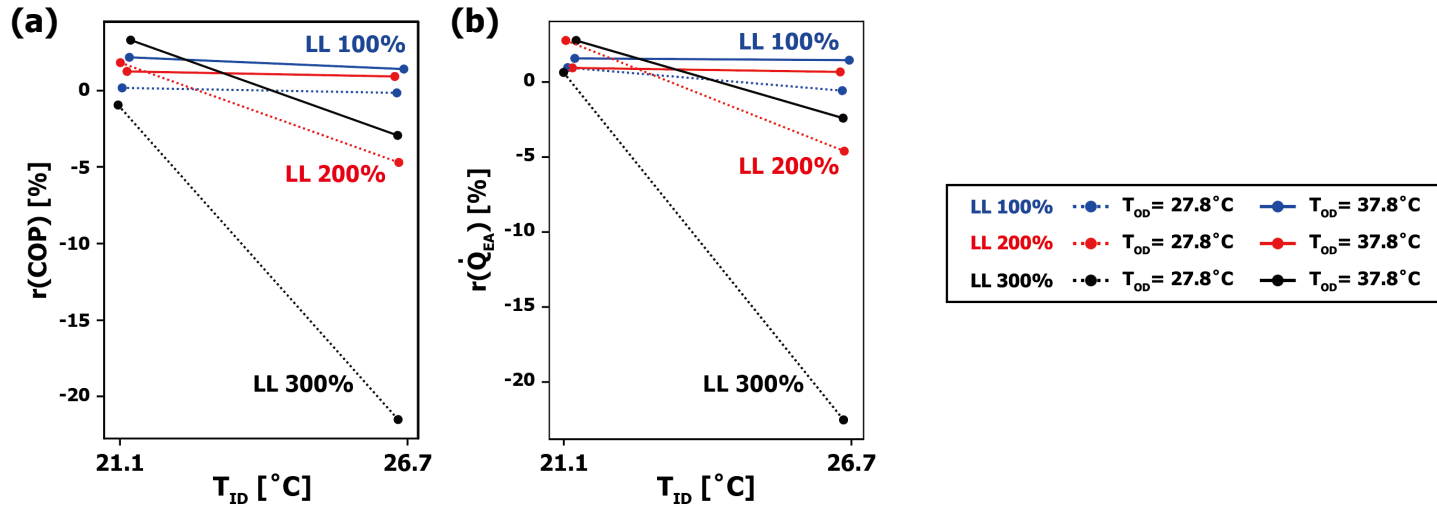


Figure Performance parameters with temperature conditions of LL faults

❖ LL fault characteristics

- LL fault : Clogged filter/dryer \rightarrow Increased pressure drop before and after TXV
 $\dot{m}_{ref} \downarrow \rightarrow$ DSH $\uparrow \rightarrow$ TXV opening \uparrow

❖ LL fault – Low T_{ID} & High T_{ID} (100%)

- TXV is in control : Performance variation is small

❖ LL fault – High T_{ID} (200%, 300%)

- TXV is saturated (Fully opened) : $\dot{m}_{ref} \downarrow$, $P_{Evap} \downarrow$, $\dot{Q}_{EA} \downarrow$
- (ID 26.7/ OD 27.8) : Too much pressure drop before TXV, **two-phase mixture enters TXV**

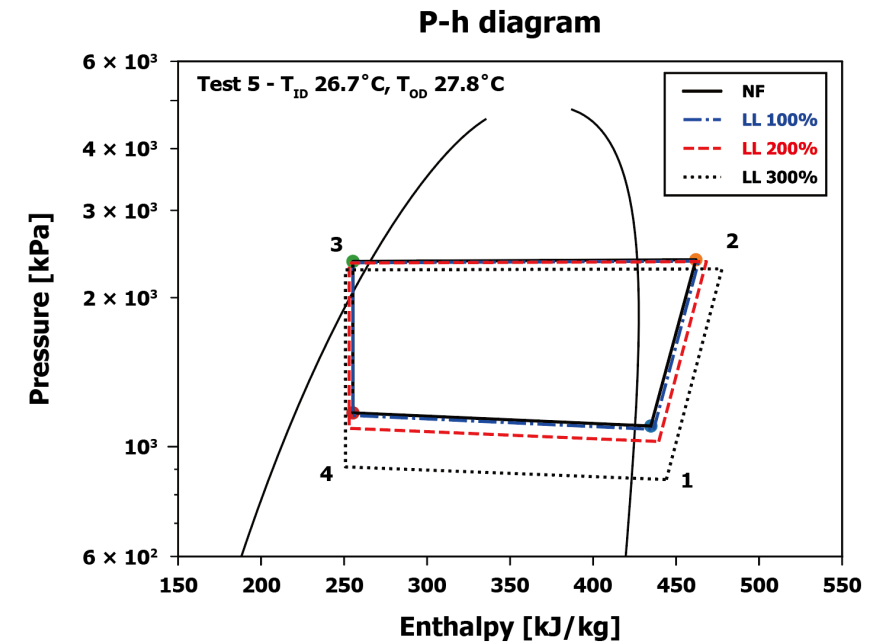


Figure P-h diagrams of every LL levels for test 5

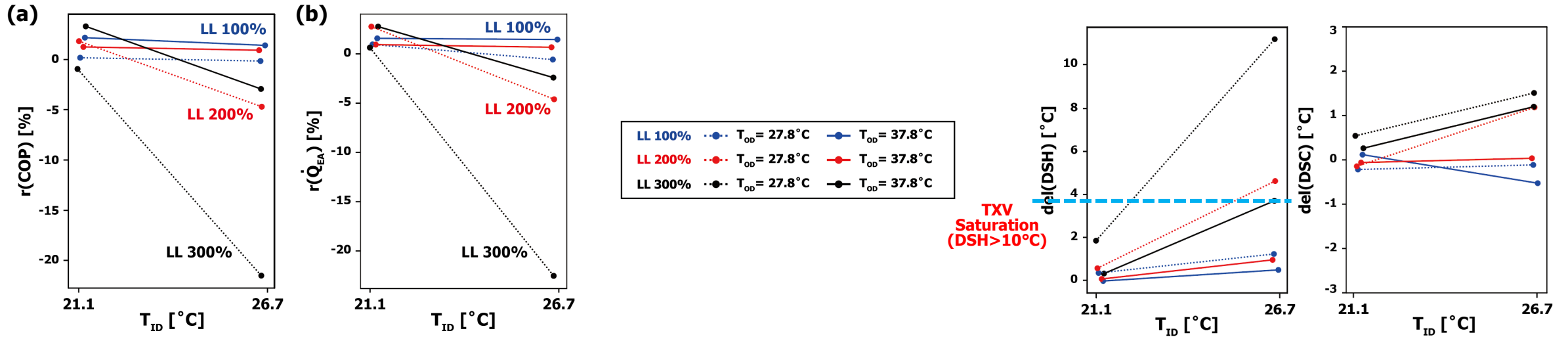


Figure Performance parameters with temperature conditions of LL faults

❖ LL fault characteristics

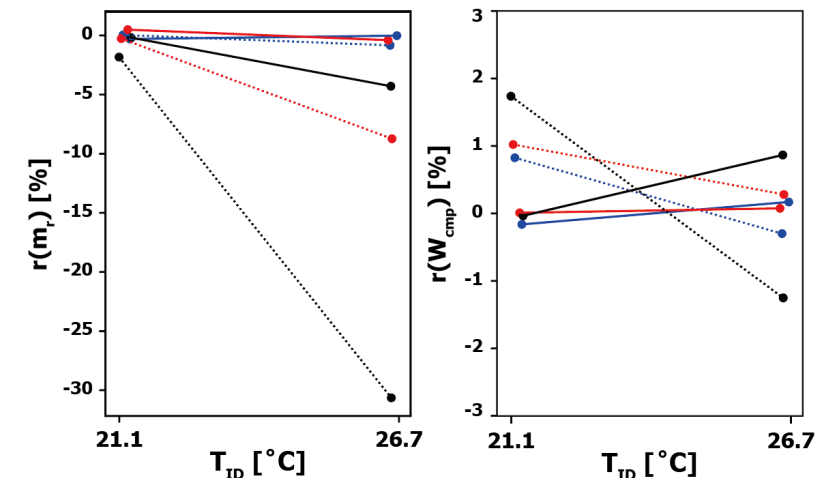
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- (ID 26.7/ OD 27.8) : Too much pressure drop before TXV, **two-phase mixture enters TXV**



Effects of operating conditions – Comparative evaluation

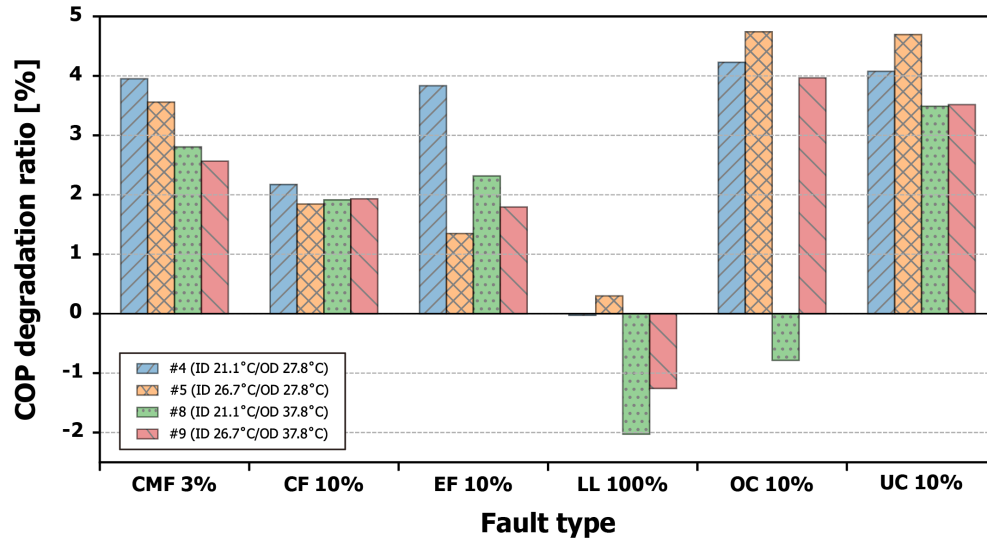


Figure COP degradation ratio under mild fault levels

❖ Mild fault level

- In all faults, COP reduction is within 5%
- **CMF, OC, UC** → Large performance degradation
- **EF, LL, OC** → Significant change depending on operating conditions

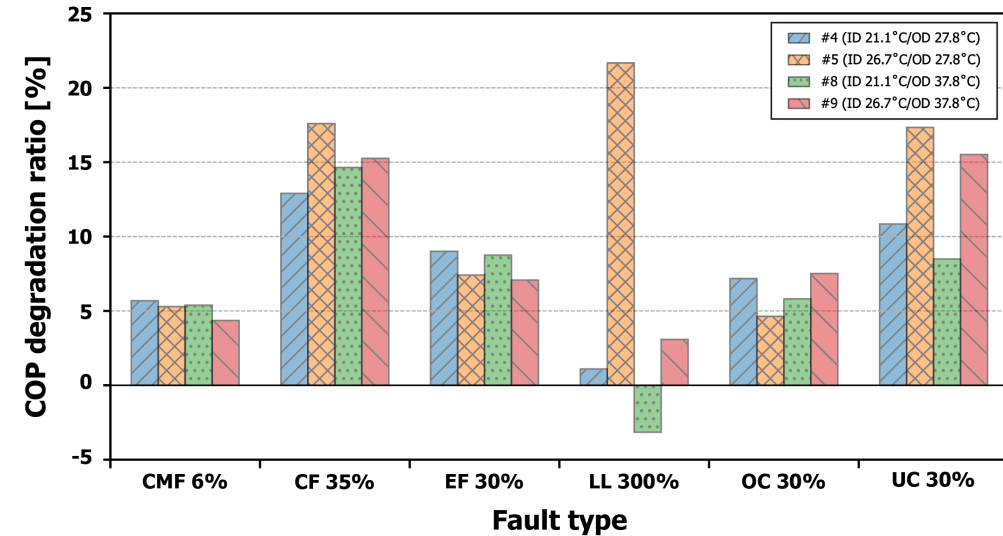


Figure COP degradation ratio under hard fault levels

❖ Hard fault level

- In all faults, COP reduction is within 23%
- **LL, UC** → Large performance degradation
- **LL, UC** → Significant change depending on operating conditions

- **System behavior with single fault under different operating conditions were analyzed.**
- **The performance changes varied depending on the faults and operating conditions.**
- **When examining the long-term performance of a system with single fault, the influence of operating conditions is expected to be significant.**

Thank you

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