



Research Paper

Effects of multiple simultaneous soft faults in variable-speed rooftop units: Experimental analysis and criticisms in detection and diagnosis[☆]

P. Catrini^{*}, A. Piacentino

Department of Engineering, University of Palermo, Viale delle Scienze, Palermo, Italy

ARTICLE INFO

Keywords:

Rooftop unit
Variable-speed drive
Fault detection and diagnosis
Performance degradation
Multiple faults
Fouling
Refrigerant charge

ABSTRACT

Soft faults in cooling systems, such as heat exchanger fouling or improper refrigerant charge, commonly arise from inadequate maintenance practices. To mitigate energy performance degradation, effective fault detection and diagnosis techniques must be implemented. However, diagnosing multiple simultaneous faults remains particularly challenging, especially in variable-speed systems, where control-induced interactions can significantly distort conventional fault signatures originally established for constant-speed operation. Based on the outcomes of previous experimental investigations on single faults, this study experimentally investigates the combined effects of evaporator fouling, condenser fouling, and refrigerant undercharge in a 17.5 kW_c variable-speed rooftop unit. The analysis examines how individual fault signatures interact, dominate, compensate for one another, or deviate from linear superposition. The results indicate that sensible cooling capacity degradation is primarily driven by evaporator fouling, with reductions of 10.6% and 19.1% observed under evaporator fouling alone and under combined evaporator and condenser fouling conditions, respectively. In terms of thermodynamic variables capable of detecting the anomalies, the discharge pressure and the subcooling remain condenser fouling-dominated in the fouled unit with correct refrigerant charge; conversely, the undercharge induces nonlinear and competing effects, such as a mitigation of the discharge pressure increase (with residuals up to 2.4 bar). A symptom matrix is proposed to classify linear dominance, nonlinear contributions, and competing interactions under multiple-fault conditions, revealing that diagnostic rules derived under single-fault or fixed-speed assumptions cannot be directly extended to variable-speed systems operating under concurrent disturbances, where control-induced compensation reshapes fault observability.

1. Introduction

In the last decades, significant efforts in the air-conditioning sector have focused on the development and deployment of systems with increasingly high nominal efficiencies, driven by stricter energy regulations [1] and the need to mitigate the environmental impact associated with the growing demand for space cooling [2]. Although these advancements have substantially improved the rated performance of cooling equipment [3], comparatively less attention has been devoted to ensuring that such performance is maintained throughout the operational lifetime of the systems [4]. In practice, cooling systems frequently undergo progressive performance degradation due to the occurrence of so-called soft faults [5], including fouling of heat exchangers [6], refrigerant undercharge/overcharge [7], leakages [8], and the presence of non-condensable gases [9]. These faults negatively affect energy

efficiency, environmental performance [10], and operational reliability [11].

To mitigate these effects, the deployment of Fault Detection and Diagnosis (FDD) techniques is essential. Research on FDD methods dates to the 1990s [12], and since then, numerous approaches have been proposed and investigated [13]. Existing methods range from qualitative rule-based approaches [14] to quantitative physics-based models [15] and data-driven techniques [16]. Regardless of the adopted methodology, the effectiveness of any FDD strategy ultimately relies on a sound understanding of the impact of faults on the system [17]. For this reason, a substantial body of experimental and numerical studies has studied the effects of individual faults in air-conditioning systems [18], with particular attention paid to refrigerant charge faults [19]. Other works have investigated the influence of measurement accuracy on fault detectability [20], while additional contributions have proposed alternative and time-efficient procedures to reproduce faults in

[☆] This article is part of a Special issue entitled: 'SDEWES 2025' published in Applied Thermal Engineering.

^{*} Corresponding author.

E-mail address: pietro.catrini@unipa.it (P. Catrini).

Nomenclature			
CC	Cooling Capacity [kW]	CND	Condenser
EER	Energy Efficiency Ratio [–]	EES	Engineering Equation Solver
IDT	Indoor Air Dry-Bulb Temperature [°C]	EF	Evaporator Fouling
ODT	Outdoor Air Dry-Bulb Temperature [°C]	EVP	Evaporator
R _x	Residual of the “x-th” variable [same units as “X”]	FDD	Fault Detection and Diagnosis
RH	Indoor Air Relative humidity [%]	IDF	Indoor Fan
SAT	Supply Air Dry-Bulb Temperature [°C]	ODF	Outdoor Fan
SHR	Sensible to Heat Ratio [–]	RTU	Rooftop Unit
U _x	Uncertainty in the “x-th” variable [same unit as “X”]	TXV	Thermostatic Expansion Valve
U _{X_R}	Uncertainty in the residual of the “x-th” variable [same unit as “X”]	UndCH	Undercharge
Acronyms		Subscripts and superscripts	
CF	Condenser	F	Referred to a faulty condition
CMP	Compressor	ID	Referred to the indoor environment
		NF	Referred to a fault-free condition
		sp	Referred to setpoint
		x	Referred to “x-th” variable

laboratory settings, such as for heat exchanger fouling [21] or charge faults [22].

Although the analysis of single-fault scenarios is essential for disentangling the effects of individual anomalies, it considerably simplifies the diagnostic task [12]. Indeed, in real applications, air-conditioning systems often operate for long periods under poor maintenance conditions, making the simultaneous presence of multiple faults highly likely [23]. Under such circumstances, the diagnostic task becomes significantly more complex, since fault signatures may interact nonlinearly, reinforce each other, or partially compensate, thereby reducing the reliability of traditional FDD indicators [24]. The challenge is further amplified in modern variable-speed systems. Indeed, unlike fixed-speed units, where faults typically manifest as direct deviations in pressures, temperatures, and delivered capacity, variable-speed systems actively respond to performance degradation through automated control actions [25], which may reshape or mask classical fault signatures.

Some studies have addressed the occurrence of multiple faults in vapor-compression systems. In this respect, a brief survey is presented in the following subsection to identify existing knowledge gaps and clarify the motivation and scope of the present work.

1.1. Research advances in multiple-fault analyses for vapor-compression systems

Different approaches have been adopted so far for the analysis of multiple faults in vapor-compression systems, with experimental investigations prevailing over simulation-based studies. In general, researchers have aimed not only to assess the system response under multiple simultaneous faults—by comparison with single-fault conditions—but also to identify diagnostic indicators predominantly influenced by one fault relative to others. Specifically, Li and Braun [26] propose a methodology based on decoupling features and virtual sensors that enables the detection and diagnosis of simultaneous faults in vapor-compression systems by isolating them through low-cost measured or estimated variables. In another paper [27], the same authors proposed decoupling features for detecting the presence of leakages in reversing valves. The developed decoupling features demonstrated strong robustness under multiple simultaneous fault conditions, maintaining insensitivity to charge and airflow variations. In another paper [28], they evaluated the influence of “virtual refrigerant pressure” sensors on diagnosing multiple faults. Their results showed that multi-fault diagnostic performance was largely preserved for air-conditioning systems, while only limited sensitivity losses and occasional misclassifications were observed for heat pumps operating in heating mode. Hu et al. [29] proposed the liquid line temperature drop for detecting liquid line

restriction. The effectiveness was experimentally validated under double, triple, and quadruple fault combinations—including refrigerant charge deviations, improper evaporator airflow, and non-condensable gas—showing strong robustness to interacting faults. Llopis-Mengual et al. [30] analyzed the effects of typical soft faults on air-to-air heat pumps using a previously validated numerical model. Their study considered the occurrence of multiple faults in two small-capacity units, rated at 8.8 kW_C and 10.14 kW_C, respectively. The study provided a comprehensive assessment of the variations in the main thermodynamic variables induced by each fault condition. The identified trends enabled the selection of suitable performance indicators for the detection and diagnosis of both single and simultaneous faults.

Other studies focused on the effects of multiple faults on the overall operation of vapor-compression systems. For instance, Llopis-Mengual et al. [31] experimentally examined the impact of simultaneous faults in a variable-speed air-to-water heat pump, considering different combinations of refrigerant undercharge, overcharge, condenser fouling, and evaporator fouling. Their results showed that fault interactions can significantly improve performance degradation and that the impact depends on control strategy and system configuration. However, the study focused on performance deterioration rather than on the development of a multi-fault diagnostic framework and did not address fault isolation or decoupling under simultaneous fault conditions. In another study, Llopis-Mengual et al. [32] developed and validated an FDD algorithm that explicitly addresses multiple simultaneous faults by leveraging realistic datasets and machine learning classification; their study demonstrated the feasibility of detecting both single and combined fault scenarios in low-instrumentation systems. Zhou et al. [33] experimentally investigated single, double, and triple simultaneous faults in a variable refrigerant flow system, demonstrating that fault interactions can exhibit both superimposing and canceling effects on cooling capacity and performance; however, the study focused on performance degradation and variable trend analysis rather than on the development of a multi-fault diagnostic or fault isolation framework. Wu et al. [34] investigated the combined effects of fouling and erroneous refrigerant charge in a variable refrigerant flow system, demonstrating that simultaneous faults could amplify performance degradation and non-additive interactions. Hu and Yuill [35] experimentally investigated the impact of multiple simultaneous faults (refrigerant charge, non-condensable gases, airflow reduction, and liquid line restrictions) on an air-conditioning system equipped with an orifice as the metering device. Combined faults led to capacity and efficiency reductions of up to 42% and 39%, respectively. Despite performance degradation, the evaluated refrigerant charge diagnostic method remained robust under multiple-fault conditions. In another

work [36], the same authors analyzed combinations of refrigerant charge faults, airflow faults, liquid-line restrictions, and non-condensable gases in a residential heat pump operating in cooling mode and equipped with a thermostatic valve. Their results showed that multiple simultaneous faults can generate nonlinear interactions, masking effects, and competing behaviors among conventional diagnostic features such as superheating, subcooling, pressures, and power consumption. In particular, the authors observed that refrigerant superheating may remain comparatively stable under several fault combinations because of thermostatic valve compensation effects, while stronger nonlinear interactions emerge when the valve approaches fully open operation conditions. Pelella et al. [8] numerically investigated the impact of simultaneous refrigerant leakage and fouling on the cooling performance of an air-source heat pump. Their results showed that the simultaneous occurrence of these soft faults leads to non-additive performance degradation, highlighting the importance of accounting for fault interactions when assessing system behavior under multi-fault conditions.

1.2. Addressed knowledge gaps and contributions of this study

The previous review highlighted that both experimental and modelling studies consistently demonstrate that simultaneous faults interact nonlinearly and exacerbate performance degradation in vapor-compression systems [30,34,35]. These interactions affect not only global performance indicators (e.g., capacity and coefficient of performance) but also challenge diagnostic methods typically developed under single-fault assumptions [30,31,33]. Although advanced diagnostic tools, such as virtual charge and pressure sensors, have shown a certain degree of robustness under multiple-fault scenarios [26–28,35], the literature remains predominantly focused on systems equipped with constant-speed compressors [9,27,28,35]. Only more recent investigations have extended the analysis to variable-speed units [25,31]. For instance, in [31], Llopis and Navarro investigated multiple faults in a variable-speed air-to-water heat pump and highlighted the influence of compressor speed on fault sensitivity. However, the tests were performed at predefined compressor-speed conditions, whereas the response under active capacity control was not explored. Conversely, Bellanco et al. [25] analyzed common faults in a variable-speed heat pump operating under active compressor-speed control and highlighted that the unit could continue satisfying the thermal demand despite the presence of faults. Nevertheless, the analysis focused exclusively on single-fault conditions. Consequently, the interaction of multiple soft faults under automated capacity control (where compressor and fan speeds are continuously modulated to maintain setpoints) is unexplored. In this context, previous experimental investigations conducted by the same authors of the present study on a variable-speed rooftop unit (RTU) highlighted the importance of explicitly analyzing fault behavior in systems equipped with variable-speed-based capacity control. Specifically, in [37], the authors analyzed the effects of evaporator fouling on a variable-speed RTU and showed that the reduction in cooling capacity is automatically compensated by an increase in fan speed to meet the desired indoor temperature setpoint. In a subsequent study [22], the same authors examined condenser fouling and refrigerant charge faults on the same unit. Their results indicated that suction pressure exhibits low sensitivity to refrigerant undercharge, while condenser fouling does not significantly affect suction pressure or compressor inlet superheating, because of the control action. However, some knowledge gaps remain. First, previous studies have predominantly focused either on

fixed-speed systems or on variable-speed units operated at predefined compressor-speed conditions. Consequently, the interaction between multiple simultaneous soft faults and the automatic capacity-control strategies remains largely unexplored. Experimental evidence on how controller-induced compensation mechanisms modify, amplify, or mask conventional fault signatures when multiple faults occur simultaneously while the unit continues satisfying the thermal demand still lacks. Second, although several experimental investigations have quantified the performance degradation associated with multiple faults, most of them have focused on capacity and efficiency deterioration rather than on the physical mechanisms governing fault interaction and fault observability. Therefore, the relative dominance of individual faults, the occurrence of competing effects, and the emergence of nonlinear interactions among fault signatures under realistic variable-speed operation are still insufficiently understood. Last but not least, conventional symptom matrices used in FDD research are typically derived from experiments in which faults are imposed and the resulting variations of diagnostic variables are directly recorded. Such an approach implicitly assumes that the observed deviations are primarily governed by the fault itself. While this assumption is generally valid for constant-speed systems, where the operating point is only marginally affected by automatic control actions, it may not hold for modern variable-speed units. In variable-speed RTUs, the controller continuously modulates compressor and fan speeds to restore the required cooling capacity and maintain the imposed temperature setpoints. Consequently, the measured fault signatures are not solely determined by the physical fault but also by the compensating actions of the control system. Under these conditions, traditional symptom matrices may become unreliable because diagnostic variables can be partially masked, amplified, or reshaped by controller-induced compensation. Therefore, a framework capable of explicitly accounting for fault dominance, compensation effects, and nonlinear interactions is required to correctly interpret fault signatures under realistic variable-speed operation.

To address these gaps, the present work investigates the combined effects of multiple soft faults on the operation and energy performance of a 17.5-kW_c variable-speed rooftop unit available at the Herrick Laboratories (Purdue University, USA), previously employed for single-fault investigations in [22,37]. Two component-level faults — evaporator fouling and condenser fouling — are analyzed in combination with a system-level fault represented by refrigerant undercharge. The experimental campaign was conducted under controlled indoor and outdoor boundary conditions at both full- and part-load operation, following a time-saving testing procedure proposed in [8]. The analysis explicitly focuses on fault interaction mechanisms and their implications for diagnosability. In particular, the study examines how individual fault signatures interact, dominate, compensate, or mask one another when occurring simultaneously. The contributions can be summarized as follows:

1. The response of a variable-speed RTU to multiple simultaneous soft faults is experimentally characterized under both full- and part-load conditions. The effects of combined faults on key operating variables — including refrigerant pressures, temperatures, mass flow rate subcooling, superheating, and cooling capacity — are analyzed while explicitly accounting for controller-induced speed modulation. Unlike other studies on variable-speed systems conducted at fixed compressor speed [31], this study specifically investigates multiple-fault interactions for conditions in which the RTU remains capable of maintaining the imposed supply-air-temperature setpoint. This

enables the analysis of realistic “hidden degradation” scenarios in which the system appears to operate correctly from the building-control perspective, while substantial thermodynamic and energetic degradations are internally compensated through adaptive compressor and fan modulation. Therefore, conventional fault-sensitive variables may become partially masked (e.g., suction pressure), reshaped, or less responsive compared to fixed-speed systems [25].

2. A residual-based diagnostic framework is proposed to systematically evaluate the interaction among fault signatures under single- and multiple-fault operating conditions. The methodology, already proven to be effective for analyzing simultaneous-fault interactions in vapor-compression systems [36], combines residual analysis with uncertainty propagation to distinguish statistically significant fault effects from measurement noise. The developed framework enables the identification of dominant fault mechanisms, the quantification of nonlinear fault interactions, and the assessment of fault masking or amplification phenomena occurring under simultaneous degradation conditions. Furthermore, its application to a variable-speed RTU operating provides new insights into how control actions influence fault observability and reshape diagnostic signatures under realistic operating conditions where the cooling demand remains satisfied.
3. An extended symptom matrix tailored to variable-speed operation is developed to synthesize the main outcomes of the residual-based analysis and support the identification of decoupling features for multi-fault diagnosis. Unlike conventional symptom matrices, which are typically derived from single-fault experiments and implicitly assume that the observed deviations are directly attributable to the fault itself, the proposed framework explicitly accounts for the influence of controller-induced compensation on fault signatures. By systematically comparing deviations in a selected set of operating variables under single- and multiple-fault conditions, the study evaluates whether diagnostic rules established for isolated faults remain valid once the control system reacts to restore the required cooling capacity. The framework enables the classification of the observed responses according to dominant fault mechanisms, nonlinear contributions, competing interaction effects, and control-induced masking phenomena, thereby providing a concise yet

physically meaningful representation of fault-interaction patterns in variable-speed RTUs.

The remainder of the paper is organized as follows. Section 2 describes the examined RTU, the experimental test rig, and the testing matrix. Section 3 details the testing procedures adopted to reproduce faulty conditions. Section 4 presents and discusses the main results, and Section 5 provides the conclusions.

2. Details on the experimental setup and testing procedures

Part of the information concerning the reference RTU, the experimental facility, and the adopted testing methodology has already been reported in two previous publications by the authors [22,37]. The most relevant aspects are briefly summarized herein, while appropriate references are provided to guide interested readers toward a more detailed description.

Fig. 1 illustrates the configuration of the reference RTU [38], rated by the manufacturer for a nominal cooling capacity of 17.5 kW_c. The unit features a unique scroll compressor (CMP) driven by a variable frequency drive. Coils, with copper tubes and aluminum fins, are employed for both the condenser (CND) and the evaporator (EVP), each equipped with a dedicated variable-speed fan. The refrigeration circuit operates with R410A. Refrigerant flow is regulated by a thermostatic expansion valve (TXV), which monitors refrigerant superheating at the EVP outlet.

To modulate the delivered cooling capacity, two control loops are implemented. The primary control action consists of inverter-driven modulation of the CMP speed, which is adjusted to meet the supply air temperature setpoint (SAT_{sp}). In parallel, the speed of the indoor fan (IDF) is regulated to meet the indoor air temperature around its reference value (IDT_{sp}). Although a variable-speed fan is also installed on the condenser side (hereafter referred to as ODF), its rotational speed is not independently controlled but instead varies proportionally with the CMP speed.

Fig. 2 presents a schematic overview of the experimental facility together with the testing procedure adopted to map the performance of the RTU in the presence of faults [22,37]. The setup (see Layer no. 1) consists of two large psychrometric chambers, equipped with dedicated air-conditioning systems designed to reproduce controlled indoor and

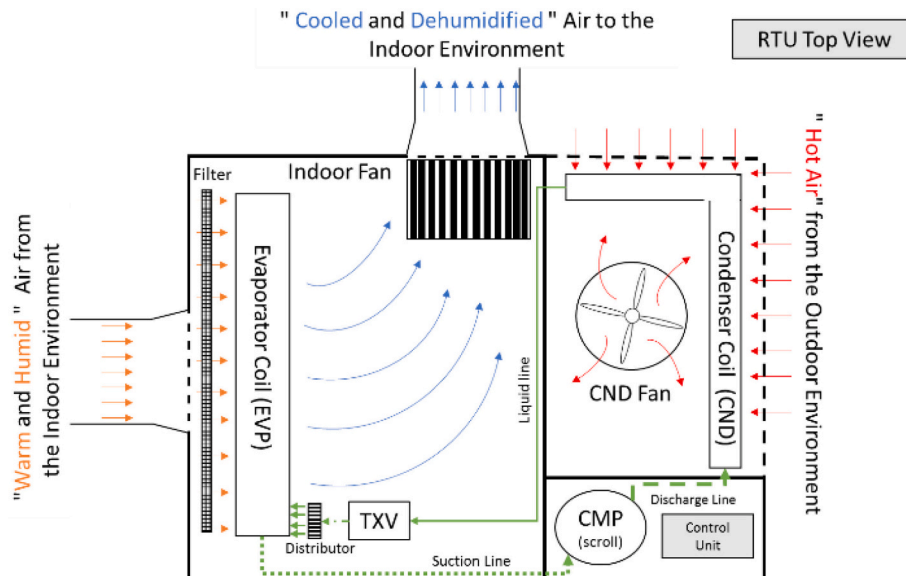


Fig. 1. Simplified scheme of the examined RTU with main components and the acronyms used [37].

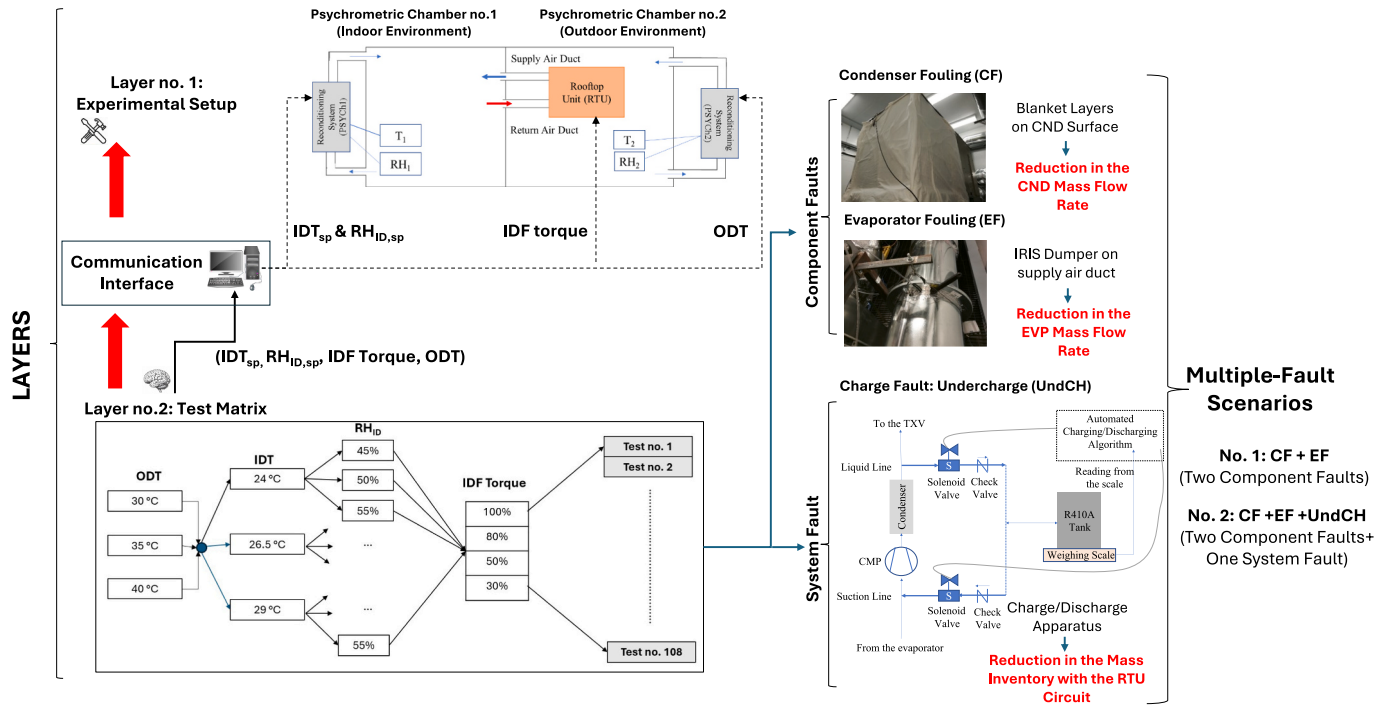


Fig. 2. Experimental facility and RTU testing framework (based on [22,37]).

outdoor boundary conditions [22]. The RTU is located within the chamber used to simulate the outdoor environment. Supply and return air ducts connect the RTU to the chamber used to simulate the indoor space.

The testing methodology implemented in Layer no. 2 was used to map the RTU performance and has been described in [22,37]. Each experimental condition (see Fig. 2) was defined by selecting one value from each of the following parameters: (i) three outdoor air temperatures (ODT: 30, 35, and 40 °C); (ii) three indoor air dry-bulb temperatures (IDT: 24, 26, and 29 °C); (iii) three indoor relative humidity levels (RH_{ID}: 45%, 50%, and 55%); and (iv) four IDF torque settings (100%, 80%, 50%, and 30%). The IDF torque levels were imposed to modulate the air flow crossing the EVP coil, thereby reproducing full-load and progressively decreasing part-load conditions.

As shown in Fig. 2, the full-factorial combination of these parameters resulted in a total of 108 steady-state experimental tests. The test conditions, defined in Layer no. 2, were implemented at the facility level (Layer no. 1) through a dedicated desktop interface that communicates with the control systems of both psychrometric chambers and the RTU, ensuring coordinated operation. The experimental campaign was first performed under fault-free conditions to establish the reference performance of the RTU at both full-load and part-load operation. In this baseline scenario, the unit is operated with clean coils and the refrigerant charge set to its nominal value.

Finally, the RTU operation is monitored through a National Instruments data acquisition system. All input and output variables were acquired at 1 s intervals. Steady-state conditions were identified using a 10-min moving average criterion, by verifying the temporal stability of the monitored parameters within the selected time window [38].

2.1. Uncertainty in measurements and impacts

Measurement uncertainties were evaluated based on the accuracy specifications of the adopted instrumentation, which are reported in Table 1 together with the corresponding locations within the tested RTU. The uncertainty analysis methodology is briefly summarized here for completeness.

The cooling capacity provided by the RTU was calculated based on measurements of refrigerant pressures, temperatures, and mass flow rate. In this respect, an uncertainty analysis was performed using the Engineering Equation Solver (EES) [39]. The uncertainty propagation procedure implemented in EES follows the methodology recommended by the National Institute of Standards and Technology (NIST) [40]. For brevity, selected results are reported in the Supplementary Material. In all operating conditions investigated, the uncertainty associated with cooling capacity remained below 1% of the corresponding mean value.

As indicated in Table 1, the power consumption of both the CMP and the IDF was directly measured using watt transducers. These devices offer an accuracy of $\pm 0.5\%$ of their full-scale value. Accordingly, the resulting accuracy was 40 W for the CMP (yielding a relative uncertainty below 3%) and ± 15 W for the IDF (corresponding to a relative uncertainty under 5%).

2.1.1. Residual-based significance analysis

To assess whether the variations induced by the investigated faults were experimentally meaningful, a residual-based significance analysis was performed for the main operating variables (e.g., sensible cooling capacity, refrigerant pressures, subcooling, superheating, and others). For a generic monitored variable “X”, the residual was defined as:

$$R_X = X_F - X_{NF} \quad (1)$$

where X_F and X_{NF} represent the values measured under faulty (F) and no-fault conditions (NF), respectively, at the same operating point (e.g., same IDF torque or same cooling capacity). The statistical significance of each residual was evaluated by comparing its absolute value with the combined uncertainty of the two measurements, calculated through standard uncertainty propagation [12], as:

$$U_{X_R} = \sqrt{U_{X,F}^2 + U_{X,NF}^2} \quad (2)$$

where $U_{X,F}$ and $U_{X,NF}$ denote the uncertainties associated with the variable under faulty and fault-free conditions, respectively. A residual was considered statistically significant when its magnitude exceeded the corresponding combined uncertainty bound ($|R_X| > U_{X_R}$). This

Table 1

Instrumentation used to monitor air, refrigerant, and absorbed power [22,37].

	Sensors Type	Sensors Location	
Refrigerant Temperature	<i>T-type Thermocouples</i> (Accuracy ± 0.5 °C)	CMP Suction CMP Discharge CND Outlet	TXV inlet EVP Inlet EVP Outlet
Refrigerant Pressure	Pressure Transducers with voltage output (Accuracy $\pm 0.25\%$ of the full-scale reading; ± 8.6 kPa for discharge and liquid line pressure; ± 5.2 kPa for suction pressure).	CMP Suction CMP Discharge Liquid line outlet	
Refrigerant Mass flow rate	<i>Coriolis Mass flowmeter</i> (Accuracy $\pm 0.5\%$ of the full-scale reading, ± 0.43 g/s)	On the liquid line	
Dry Bulb Air Temperature	<i>T-type Thermocouples</i> (Accuracy ± 0.5 °C)	<u>Return Air:</u> two-by-two grid spaced equally in a rectangular geometry and placed before the EVP <u>Supply Air:</u> two-by-two grid spaced equally in a rectangular geometry and placed after the supply fan <u>CND Inlet:</u> 8 thermocouples mounted in a four-by-two grid at the condenser-inlet face <u>CND Outlet:</u> 4 thermocouples mounted radially at the CND outlet Air samples taken before the EVP inlet and at the beginning of the supply air duct	
Dew Point Air Temperature	<i>Dew point hygrometer with chilled mirror probe</i> (Accuracy ± 0.15 °C)	IDF	
Power Consumption	<i>Watt Transducers</i> (Accuracy of $\pm 0.5\%$ of the full-scale reading)	CMP Power ODF	

procedure allowed distinguishing fault-induced variations from changes attributable to experimental uncertainty.

Finally, additional interaction residuals were evaluated by comparing the combined-fault condition against the corresponding single-fault scenarios. This procedure allowed assessing whether the addition of a second fault produced experimentally meaningful variations beyond the uncertainty bounds of the individual fault conditions.

3. Description of multiple-fault experimental simulation

As shown in Fig. 2, three faulty conditions were experimentally reproduced: two component-level faults—Condenser Fouling (CF) and Evaporator Fouling (EF)—and one system-level fault, namely refrigerant Undercharge (UndCH).

CF and EF were not replicated by injecting dust directly on the heat exchanger surfaces. Instead, the faults were emulated by increasing the air-side pressure drop, leading to a lower airflow rate across the coils. More specifically, as shown in Fig. 2, CF was implemented by placing one or two layers of fabric over the CND coil surface to increase the air-side pressure drop [22]. The “heavy” CF condition (two layers of fabric) resulted in an approximately 35% reduction in CND airflow rate. On the other side, EF was simulated by partially closing an iris damper installed on the supply air duct, thereby restricting airflow through the EVP [37]. Under clean conditions, the pressure drop across the RTU was 150 Pa,

while a severe EF scenario corresponded to an increased pressure drop of 380 Pa.

The approach followed here was based on key findings from previous studies, which demonstrated that performance degradation due to fouling is primarily associated with airflow reduction caused by higher pressure losses, rather than with the additional thermal resistance introduced by dust accumulation [6,41,42]. In particular, Yang et al. [6,42] show that the dominant effect of air-side fouling is the increase in pressure drop and the consequent reduction in airflow, while the impact on heat transfer performance is comparatively small. In particular, the authors observed an increase in pressure drop up to 200%, whereas the variation in the air-side heat transfer coefficient ranged between approximately -14% and $+4\%$ [6]. Bell and Groll [41] observed that particulate fouling primarily accumulates on the frontal surface of the coil, forming a blockage that significantly increases air-side pressure drop, while the reduction in heat transfer is comparatively limited (typically within 3–10%). These findings indicate that fouling predominantly acts as a flow restriction mechanism, reducing the effective airflow through the heat exchanger rather than substantially increasing thermal resistance. Therefore, this approach ensures repeatability and controlled fault severity levels while ensuring a quick restoration of fault-free conditions without requiring an ad hoc procedure for cleaning coils. The following approach was also followed by other authors, such as Llopis and Navarro in [31] or Wu et al. [34].

It is acknowledged that this approach does not explicitly account for the additional thermal resistance due to fouling deposits (e.g., conduction through the fouling layer and local variations in convective heat transfer). Therefore, the methodology may slightly underestimate performance degradation under severe fouling conditions, particularly in cases where thin insulating layers dominate. Nevertheless, for system-level analysis of RTU units—where airflow strongly governs capacity and efficiency, this approximation is considered appropriate and consistent with experimental literature.

UndCH was imposed using an automated refrigerant charging/discharging system consisting of two solenoid valves installed on the CMP suction and liquid lines, respectively, together with a refrigerant storage tank and a precision weighing scale for charge quantification [22]. The system allowed controlled refrigerant transfer between the unit and an external storage tank. A severe UndCH condition corresponded to a -39.5% reduction in refrigerant mass relative to the nominal 8.6 kg charge was tested.

Multiple-fault scenarios were reproduced by simultaneously imposing combinations of the previously described faults. In particular, the following scenarios were considered:

- *Scenario no. 1:* simultaneous occurrence of two component-level faults, i.e., CF + EF.
- *Scenario no. 2:* simultaneous occurrence of two component-level faults and one system-level fault, i.e., CF + EF + UndCH.

A limitation of the present study is that multiple-fault scenarios were investigated only under relatively severe fault conditions for each involved anomaly. This choice was intentionally adopted to enhance the observability of fault-interaction mechanisms under variable-speed operation, amplifying nonlinear and compensating effects while minimizing the influence of measurement uncertainty and control-induced masking. Consequently, the interaction patterns identified in this study should be interpreted as representative of relatively severe soft-fault conditions rather than universally applicable to all fault intensities. Under milder fault levels, adaptive control compensation may partially attenuate the observable impact of simultaneous faults, potentially reducing both fault detectability and the apparent nonlinearity of the diagnostic variables [36,43]. Therefore, the extrapolation of

the present findings to low-severity faults should be undertaken with caution.

4. Results and Discussion

Before presenting the results of the experimental campaign, some aspects should be clarified:

- To facilitate the interpretation of the impacts of multiple faults on the examined RTU, the results obtained under single-fault scenarios (EF [37], CF [22], and UndCH [22]) are also included.
- For the sake of brevity, only two sets of test conditions are considered throughout the analysis: (i) $IDT = 26\text{ }^{\circ}\text{C}$, $RH_{ID} = 50\%$, and $ODT = 30\text{ }^{\circ}\text{C}$; and (ii) $IDT = 24\text{ }^{\circ}\text{C}$, $RH_{ID} = 50\%$, and $ODT = 40\text{ }^{\circ}\text{C}$. The first condition corresponds to a more humid operating regime, characterized by a lower sensible-to-total heat ratio (≈ 0.79) due to a greater latent load contribution, whereas the second condition approaches near-dry operation, with a higher sensible heat ratio (≈ 0.93) [22].
- The analysis focuses on the impact of faults on the delivered sensible cooling capacity. As discussed in Section 2, the examined RTU is controlled based on the IDT rather than relative humidity. Therefore, steady-state operation is achieved when the sensible cooling capacity delivered by the RTU balances the sensible cooling load. Consequently, the comparison between fault-free and faulty conditions is primarily performed at comparable sensible cooling capacities delivered by the RTU. This approach was intentionally adopted to reproduce realistic operating scenarios in which the RTU appears to operate correctly from the building-control perspective (i.e., the imposed SAT_{sp} and IDT_{sp} are satisfied), while one or more soft faults simultaneously affect the thermodynamic behavior of the system. Under these conditions, the variable-speed controller continuously modulates the CMP and fans' operation to compensate for fault-induced performance degradation and maintain the required cooling delivery. As a result, several conventional fault-sensitive variables may become partially masked or exhibit a reduced sensitivity compared to fixed-speed systems. Therefore, the investigated multiple-fault scenarios represent particularly challenging and realistic conditions for fault detection and diagnosis, since the RTU can continue satisfying the thermal demand despite the presence of significant underlying degradations.

Figs. 3(a-b) present preliminary results that support the interpretation of the following subsections: the EVP air mass flow rate and the

corresponding SAT under the investigated fault conditions, at 100% and 30% IDF torque. As shown in Fig. 3(a), under EF, CF + EF, and CF + EF + UndCH scenarios, the EVP-side air mass flow rate decreases significantly due to the additional airflow resistance introduced by the fouled EVP coil. Nevertheless, as shown in Fig. 3(b), the SAT remains close to the imposed setpoint. This behavior can be explained by considering that the reduction in airflow rate decreases the amount of air that must be conditioned. Consequently, despite the degradation introduced by EF, the RTU remains capable of maintaining the SAT close to the imposed setpoint because a smaller air mass flow rate is processed through the unit. Conversely, an increase in SAT is observed for the UndCH scenario at 100% IDF torque, where the measured SAT is approximately $0.7\text{ }^{\circ}\text{C}$ higher than the imposed setpoint. This result indicates that UndCH directly affects the ability of the RTU to provide the cooling capacity required to maintain the desired SAT. Therefore, under UndCH conditions, variations in cooling capacity are primarily associated with the inability of the unit to satisfy the SAT_{sp} , whereas under EF conditions, the reduction in cooling capacity at a given IDF torque is mainly attributable to the lower airflow rate processed by the RTU.

4.1. Results for scenario No. 1: condenser and evaporator fouling

First, the results for the testing condition: $IDT = 26\text{ }^{\circ}\text{C}$, $RH_{ID} = 50\%$, and $ODT = 30\text{ }^{\circ}\text{C}$ in the CF + EF scenario. In Fig. 4(a), the sensible cooling capacity is reported as a function of the IDF fan speed. As indicated by the black line, in the fault-free case, the RTU delivers a maximum sensible capacity of around 14.1 kW (point A), obtained by setting the IDF torque to its maximum value, whereas the minimum capacity (point D), corresponding to 30% IDF torque, is 7.5 kW. Under faulty operation, differences emerge comparing single- and multiple-fault scenarios. In the case of EF, the maximum sensible capacity lowers to 12.6 kW (point A', -10.6% compared to the fault-free case), due to the reduction in the mass flow rate across the EVP coil (see Fig. 3 (a)) [37]. Therefore, the RTU cannot meet cooling demands in the range of 11.5–14.1 kW. Conversely, in the CF scenario (point A''), it remains practically unchanged. In this respect, data in the Supplementary Material (see Table S.3) show that residuals of sensible cooling capacity moving from no-fault to CF condition are not statistically significant. When CF and EF are simultaneously imposed (CF + EF, point A'''), the maximum sensible capacity drops to 11.4 kW (-19.1% compared to the fault-free case). Therefore, in the case of CF+EF, the RTU cannot meet cooling demands in the range of 11.4–14.1 kW and can satisfy only loads between 6.7 and 11.5 kW, as indicated by the vertical black arrow on the y-axis of the figure.

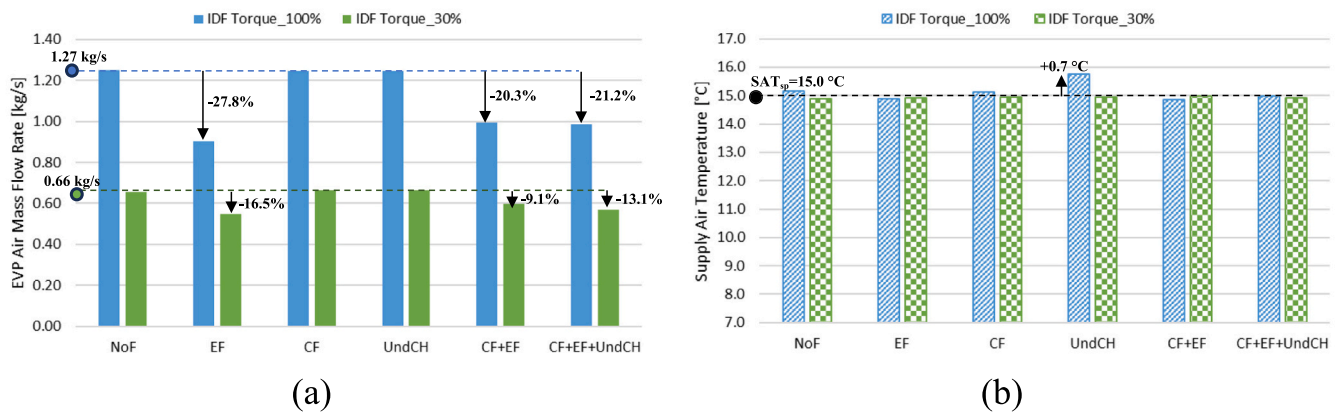


Fig. 3. (a) Evaporator-side air mass flow rate and (b) SAT values under no-fault and faulty conditions at maximum and minimum IDF torque values, for the case $IDT = 26\text{ }^{\circ}\text{C}$, $RH_{ID} = 50\%$, and $ODT = 30\text{ }^{\circ}\text{C}$.

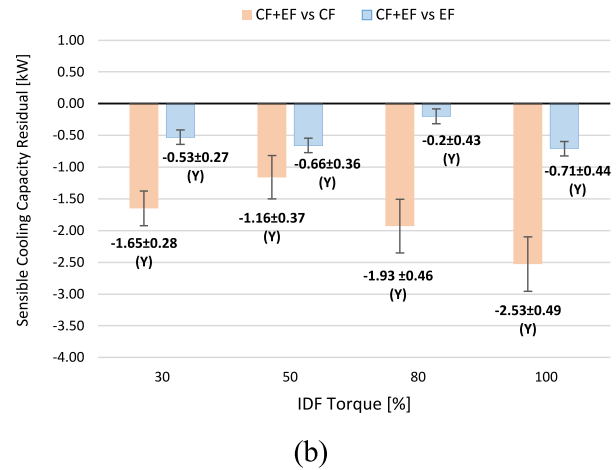
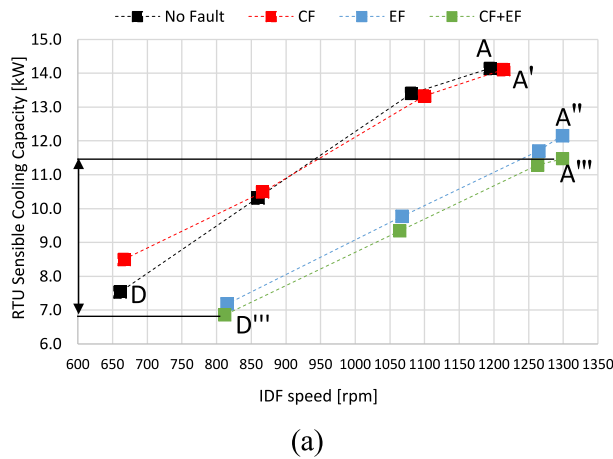


Fig. 4. Experimental results for scenario $IDT = 26^\circ\text{C}$ - $RH_{ID} = 50\%$ - $ODT = 30^\circ\text{C}$ in the case of CF + EF: (a) sensible cooling capacity; (b) sensible cooling capacities residuals and statistical significance.

To assess whether the observed variations in sensible cooling capacity under CF + EF conditions are genuinely caused by the faults or could instead result from the propagation of measurement uncertainties, Fig. 4(b) reports the residuals of sensible cooling capacity for the combined CF + EF scenario relative to the corresponding single-fault conditions (it is worth noting that residual values for the single-fault scenarios relative to fault-free operation are reported in the Supplementary Material within Table S.3). Worth noting that, in the figure, “Y” denotes statistically significant residuals ($|R| > \text{uncertainty}$), whereas “N” indicates residuals within the uncertainty bounds ($|R| \leq \text{uncertainty}$).

As shown in Fig. 4(b), the residuals in the CF + EF scenarios calculated relative to the CF condition (i.e., CF + EF vs CF) are consistently large and statistically significant across the entire operating range, indicating that the addition of EF leads to a substantial degradation in sensible cooling capacity. Conversely, when the residuals are calculated relative to the EF condition, their magnitude is considerably smaller. Although most of these residuals slightly exceed the associated uncertainty bounds and can therefore still be considered statistically distinguishable, their absolute values remain limited compared to the corresponding residuals relative to CF. This behavior confirms that the cooling-capacity degradation observed under combined CF + EF operation is primarily governed by EF, while CF provides only a secondary contribution.

Figs. 5(a-g) display the main operating variables of the RTU in fault-free and faulty conditions. Worth noting that the comparison among fault conditions is performed along the J-line and K-line, corresponding to operating points with comparable sensible cooling capacities. Specifically, points K (fault-free), K' (CF), K'' (EF), and K''' (CF + EF) on the K-line, corresponding to test conditions with maximum IDF torque condition for the CF + EF scenario. The same procedure was applied to the operating points J, J', J'', and J''' on the J-line corresponding to the minimum sensible cooling capacity in the CF scenario. Table 2 collects the residual analysis results for the operating conditions on J-line and K-line in Figs. 5.a-g.

Fig. 5(a) shows the refrigerant discharge pressure. As in the case of CF (see the red line), a 20.5% increase ($+4.2$ bar, see also the $R_{CF, NoFault}$ in Table 2) in the discharge pressure is found in CF + EF (points K'), compared to the fault-free case (points K). Interestingly, the discharge pressure curve in CF + EF almost overlaps with the one observed in CF only (points K' overlapped with K'''), being conversely not largely influenced by EF. In this regard, looking at residuals (see Table 2), CF generated large positive values with respect to the fault-free condition on both the J-line and K-line, reaching approximately $+3.46$ bar (points J' vs J) and $+4.18$ bar (points K' vs K), respectively. Conversely, EF

produced negative residuals ($R_{EF, NoFault}$), indicating a reduction in condensing pressure. The residual discharge pressure between CF + EF and CF became negligible on the K-line (-0.01 differences in the average values), suggesting that CF dominates the discharge pressure response at high loads. At low loads, the CF + EF scenario remained strongly influenced by CF, although residual deviated from zero, indicating the emergence of interaction effects between the two faults.

The suction pressure shown in Fig. 5(b) remained comparatively flat, with limited slope variations among operating conditions. According to Table 2, residuals associated with CF + EF remained, following the EF trend, and suggesting that EF has a prevailing influence on suction pressure degradation (-0.377 ± 0.074 bar). However, the limited variation observed under the investigated fault conditions makes this variable poorly suited for diagnostic purposes. This low sensitivity is mainly a consequence of the variable-speed control strategy. Indeed, as previously observed, under EF conditions, the reduced airflow rate allows the SAT_{sp} to be reached more easily, thereby limiting the variation in suction pressure and reducing its effectiveness as a fault-sensitive diagnostic parameter.

A markedly different behavior was observed for refrigerant subcooling in Fig. 5(c). Both CF and CF + EF produced strong positive and nearly linear increases with sensible cooling capacity. Table 2 reports residuals exceeding $+5.5^\circ\text{C}$ relative to the No Fault condition (Points K'' and K''' vs point K), well beyond the propagated uncertainty threshold. In contrast, EF alone remained within the uncertainty bounds, indicating no impact on this quantity. Moreover, CF and CF + EF exhibited nearly overlapping trends, particularly along the K-line, confirming that refrigerant subcooling is predominantly governed by CND-side degradation effects. Conversely, refrigerant superheating in Fig. 5(d) showed minimal variations among scenarios and weak dependence on operating load. In this regard, as reported in Table 2, all residuals remained below the combined uncertainty threshold of $\pm 1.0^\circ\text{C}$, indicating that superheating cannot reliably discriminate against the investigated fault conditions.

Figs. 5(e) and 5(f) show the CMP power consumption and refrigerant mass flow rate, respectively. The CMP power in Fig. 5(e) exhibited a strong quasi-linear increase with sensible cooling capacity. Residuals reported in Table 2 indicate that both CF and EF significantly increased CMP power consumption relative to the No Fault condition. In particular, the CF + EF condition generated the highest residuals on the K-line (, highlighting the amplification of fault interaction under high-load operation. The refrigerant flow rate in Fig. 5(f) also followed a linear increasing trend, with an increase in refrigerant mass flow rate under CF + EF conditions slightly lower than the one observed in the EF scenario. In Fig. 5(g), the IDF power is presented. In the case of CF, the increase

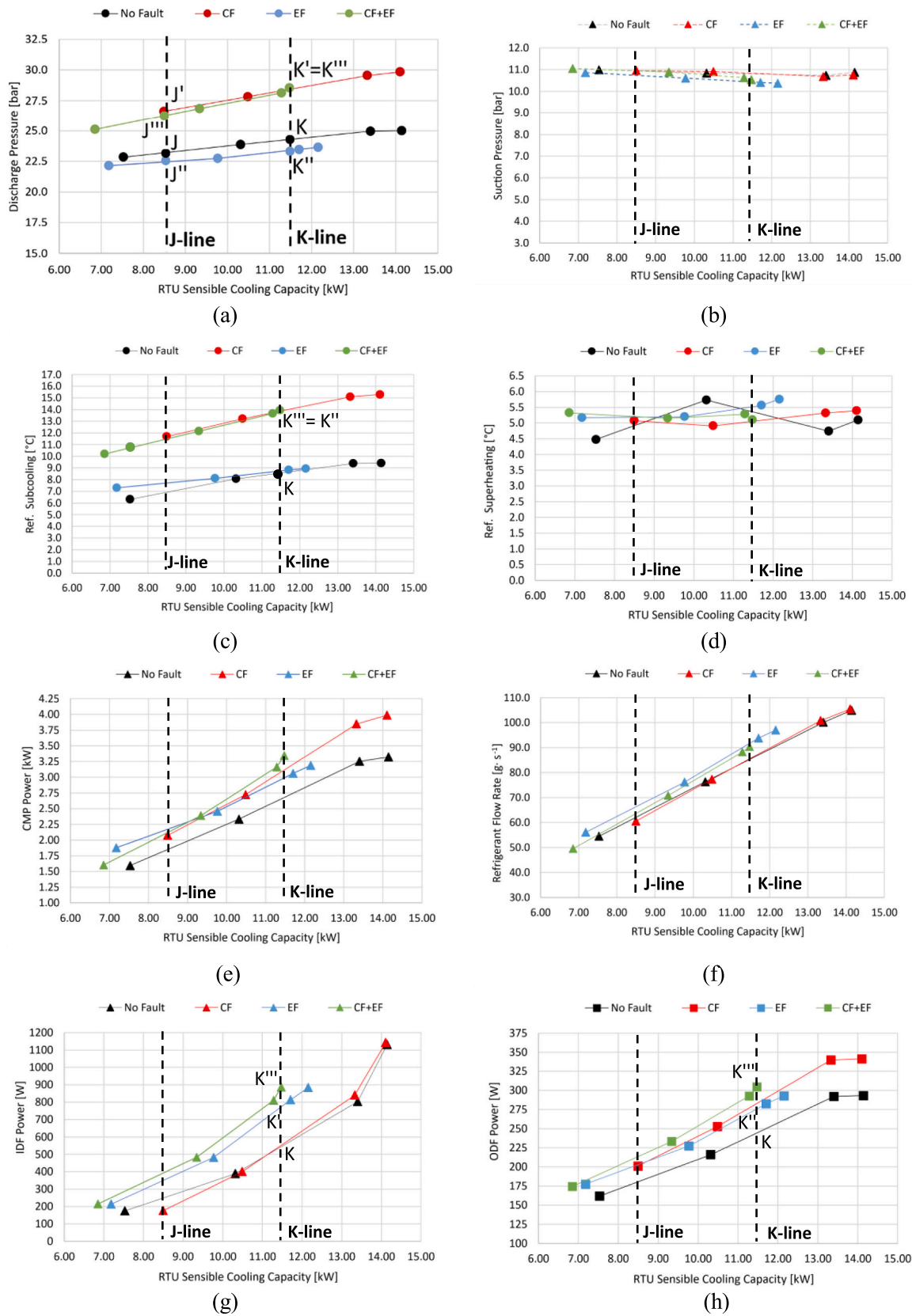
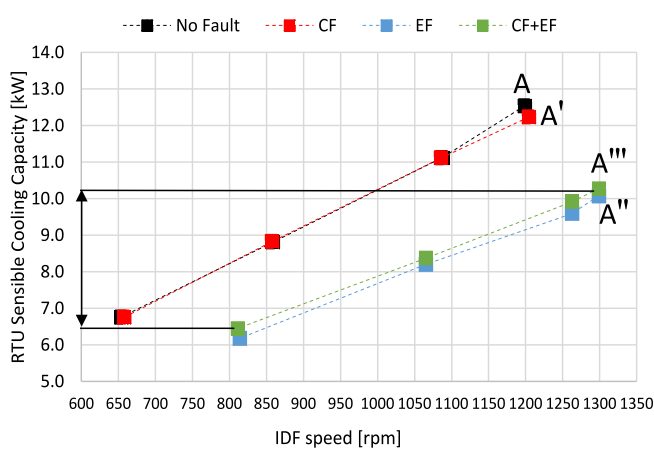


Fig. 5. Experimental results for the CF + EF scenario, assuming $IDT = 26^\circ\text{C}$, $RH_{ID} = 50\%$, $ODT = 30^\circ\text{C}$: (a) discharge pressures; (b) suction pressures; (c) refrigerant subcooling; (d) refrigerant superheating; (e) CMP power; (f) refrigerant mass flow rate; (g) IDF power; and (h) ODF power.

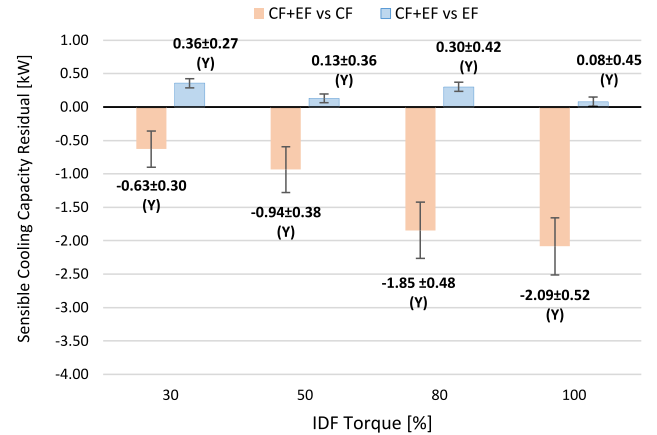
Table 2

Results of residual analysis for single-fault (CF and EF vs No Fault) and combined-fault(CF + EF vs No Fault) conditions at the J-line and K-line operating points for $IDT = 26\text{ }^{\circ}\text{C}$ - $RH_{ID} = 50\%$ - $ODT = 30\text{ }^{\circ}\text{C}$.

		RCF NoFault	REF NoFault	RCF+EF NoFault	Comments
Discharge Pressure [bar]	J-line	+3.461 $\pm$ 0.122	-0.761 $\pm$ 0.122	+3.061 $\pm$ 0.122	CF-dominated response
	K-line	+4.183 $\pm$ 0.122	-0.912 $\pm$ 0.122	+4.175 $\pm$ 0.122	
Suction Pressure [bar]	J-line	+0.051 $\pm$ 0.074	-0.205 $\pm$ 0.074	+0.001 $\pm$ 0.074	Low diagnostic sensitivity
	K-line	+0.032 $\pm$ 0.074	-0.377 $\pm$ 0.074	-0.222 $\pm$ 0.074	
Ref. Subcooling [$^{\circ}\text{C}$]	J-line	+4.9 $\pm$ 1.0	+0.8 $\pm$ 1.0	+4.6 $\pm$ 1.0	CF-dominated response
	K-line	+5.5 $\pm$ 1.0	+0.3 $\pm$ 1.0	+5.5 $\pm$ 1.0	
Ref. Superheating [$^{\circ}\text{C}$]	J-line	+0.1 $\pm$ 1.0	+0.3 $\pm$ 1.0	+0.3 $\pm$ 1.0	Low diagnostic sensitivity
	K-line	-0.3 $\pm$ 1.0	+0.2 $\pm$ 1.0	-0.2 $\pm$ 1.0	
CMP Power [kW]	J-line	+0.241 $\pm$ 0.057	+0.312 $\pm$ 0.057	+0.254 $\pm$ 0.057	Nonlinear interaction effects
	K-line	+0.432 $\pm$ 0.057	+0.375 $\pm$ 0.057	+0.725 $\pm$ 0.057	
Ref. Flow Rate [$\text{g}\cdot\text{s}^{-1}$]	J-line	-2.01 $\pm$ 0.61	+7.01 $\pm$ 0.61	+2.01 $\pm$ 0.61	Nonlinear interaction effects
	K-line	0.12 $\pm$ 0.61	+7.04 $\pm$ 0.61	+4.04 $\pm$ 0.61	
IDF Power [W]	J-line	-75.1 $\pm$ 21.2	+100.1 $\pm$ 21.2	+140.1 $\pm$ 21.2	EF-dominated response
	K-line	+10.2 $\pm$ 21.2	+235.12 $\pm$ 21.2	+340.3 $\pm$ 21.2	
ODF Power [W]	J-line	+20.5 $\pm$ 21.2	+22.6 $\pm$ 21.2	+33.5 $\pm$ 21.2	Affected by NL in CMP Power
	K-line	+38.6 $\pm$ 21.2	+32.1 $\pm$ 21.2	+60.2 $\pm$ 21.2	



(a)



(b)

Fig. 6. Experimental results for the scenario $IDT = 24\text{ }^{\circ}\text{C}$ - $RH_{ID} = 50\%$ - $ODT = 40\text{ }^{\circ}\text{C}$ in the case of CF + EF: (a) sensible cooling capacity; (b) sensible cooling capacities residuals and statistical significance.

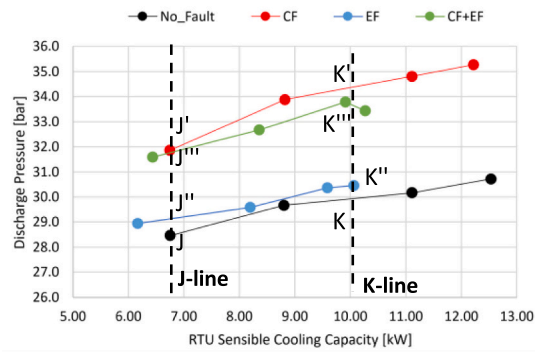
in IDF consumption was almost negligible (as also testified by the negligible residual $+10.2 \pm 21.2$ in Table 2). Conversely, the percentage increase in IDF consumption in EF ranges between 32 and 47% due to the higher resistance to the air flow rate through the coil. In the case of CF + EF, an +61.9% increase in IDF consumption was observed (point K''') compared to the corresponding fault-free case (point K), and 14.1% higher compared to the one measured in the EF scenario (point K''). The additional increase in IDF consumption compared to the EF case is due to the reduction in the delivered sensible cooling capacity shown in Fig. 4(a). Looking at Table 2, IDF showed strong positive residuals under EF and CF + EF conditions, indicating that EF substantially affects indoor airflow fan energy demand.

The ODF power is shown in Fig. 5(f). In the case of CF + EF (point K'''), the power consumed by the ODF increases, being +7.5% higher than the one in the EF scenario (point K'') and +7.1% compared to CF. ODF power residuals (see Table 2) were generally smaller, although still statistically significant in several cases, particularly under combined fault conditions.

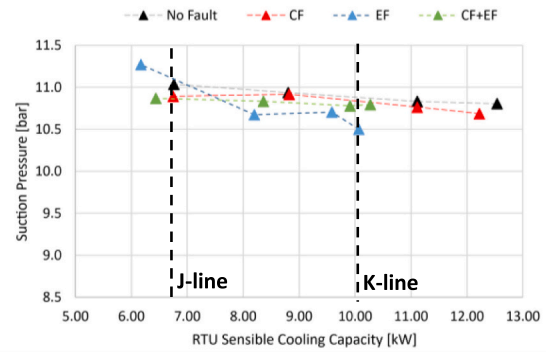
A similar analysis was conducted for the test condition $IDT = 24\text{ }^{\circ}\text{C}$, $RH_{ID} = 50\%$, $ODT = 40\text{ }^{\circ}\text{C}$. Fig. 6(a) shows that the sensible cooling capacity decreases moving from the fault-free condition (point A, 12.5 kW) to the CF + EF scenario (point A''', 10.3 kW) of about 2.2 kW. This

reduction is comparable to that observed under the EF case, for which a cooling capacity of 10.27 kW was found (point A''). Fig. 6(b) shows the residual of sensible cooling capacity under combined fault conditions (CF + EF) compared with the individual CF and EF scenarios at different IDF torque values. The residuals between CF + EF and CF are again consistently negative across all operating conditions, indicating that the simultaneous presence of EF and CF produces a further degradation in sensible cooling capacity compared to the CF condition alone. The largest deviation was observed at 100% IDF torque, where the residual reached approximately -2.09 kW, while the magnitude progressively decreased as the IDF torque was reduced, reaching -0.63 kW at 30% torque. This trend suggests that the combined fault impact becomes less pronounced at minimum load. Conversely, the residuals between CF + EF and EF remained close to zero for all operating points, ranging from 0.08 kW to 0.36 kW. In most cases, the residuals fall within the uncertainty bounds, indicating that the combined fault behavior is strongly dominated by the EF contribution. Only at 30% IDF torque does the residual slightly exceed the uncertainty interval, suggesting a weak interaction effect between the two faults. Overall, the results demonstrate again that EF has a predominant influence on the sensible cooling capacity degradation under the CF + EF scenario.

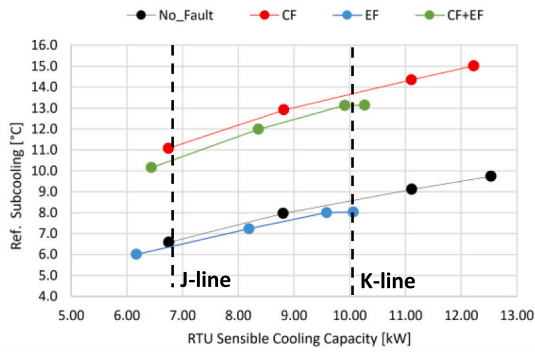
Figs. 7(a-g) display the main operating variables of the RTU in fault-



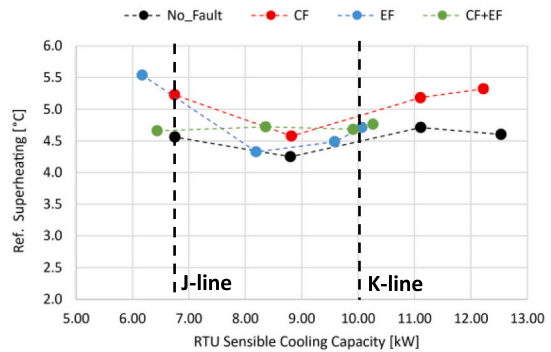
(a)



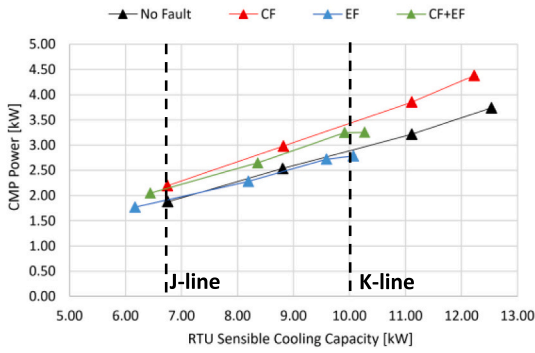
(b)



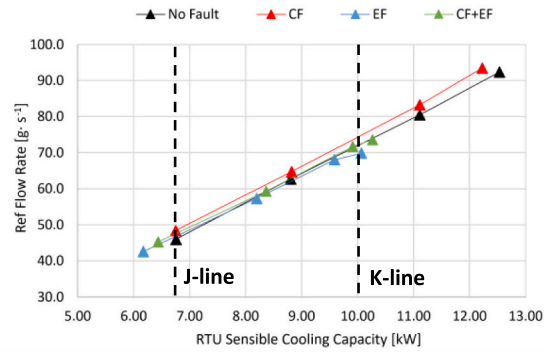
(c)



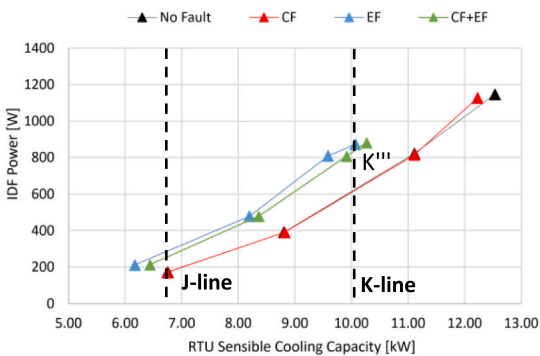
(d)



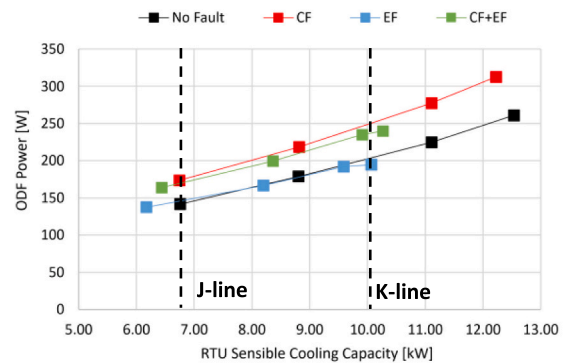
(e)



(f)



(g)



(h)

Fig. 7. Experimental results for the CF + EF scenario, assuming $IDT = 24\text{ }^{\circ}\text{C}$ - $RH_{ID} = 50\%$ - $ODT = 40\text{ }^{\circ}\text{C}$: (a) discharge pressures; (b) suction pressures; (c) refrigerant subcooling; (d) refrigerant superheating; (e) CMP power; (f) refrigerant mass flow rate; (g) IDF power; and (h) ODF power.

Table 3

Results of residual analysis for single-fault (CF and EF vs No Fault) and combined-fault (CF + EF vs No Fault) conditions at the J-line and K-line operating points for $IDT = 24\text{ }^{\circ}\text{C}$ - $RH_{ID} = 50\%$ - $ODT = 40\text{ }^{\circ}\text{C}$.

		R_{CF} NoFault	R_{EF} NoFault	R_{CF+EF} NoFault	Comments
Discharge Pressure [bar]	J-line	+3.591 ±0.122	+0.711 ±0.122	+3.381 ±0.122	CF-dominated response
	K-line	+4.562 ±0.122	+0.590 ±0.122	+3.731 ±0.122	
Suction Pressure [bar]	J-line	-0.134 ±0.074	+0.041 ±0.074	-0.154 ±0.074	Low diagnostic sensitivity
	K-line	-0.061 ±0.074	-0.407 ±0.074	-0.111 ±0.074	
Ref. Subcooling [°C]	J-line	+4.6 ±1.0	-0.2 ±1.0	+4.0 ±1.0	CF-dominated response
	K-line	+5.4 ±1.0	-0.3 ±1.0	+4.7 ±1.0	
Ref. Superheating [°C]	J-line	+0.6 ±1.0	+0.6 ±1.0	+0.1 ±1.0	Low diagnostic sensitivity
	K-line	+0.5 ±1.0	+0.3 ±1.0	+0.3 ±1.0	
CMP Power [kW]	J-line	+0.391 ±0.057	+0.094 ±0.057	+0.321 ±0.057	Nonlinear interaction effects
	K-line	+0.682 ±0.057	-0.036 ±0.057	+0.497 ±0.057	
Ref. Flow Rate [g·s ⁻¹]	J-line	+3.01 ±0.61	+1.52 ±0.61	+2.01 ±0.61	Nonlinear interaction effects
	K-line	+5.51 ±0.61	-0.21 ±0.61	+3.54 ±0.61	
IDF Power [W]	J-line	+0.1 ±21.2	+120.1 ±21.2	+100.4 ±21.2	EF-dominated response
	K-line	+65.1 ±21.2	+305.3 ±21.2	+290.1 ±21.2	
ODF Power [W]	J-line	+35.4 ±21.2	+7.1 ±21.2	+31.2 ±21.2	Affected by NL in CMP Power, with sensitivity to CF
	K-line	+57.2 ±21.2	+1.5 ±21.2	+42.7 ±21.2	

free and faulty conditions, for the case: $IDT = 24\text{ }^{\circ}\text{C}$ - $RH_{ID} = 50\%$ - $ODT = 40\text{ }^{\circ}\text{C}$. Table 3 collects the residual analysis performed for both single-fault and multiple-fault scenarios. Again, the analysis is performed at equivalent sensible cooling capacities indicated by the J-line and K-line in Figs. 7(a-g). Specifically, the K-line corresponds to test conditions with the maximum IDF torque condition for the EF scenario. The same procedure was applied to the operating points on the J-line corresponding to the minimum sensible cooling capacity in the fault-free scenario. Figs. 7(a-b) shows the pressure values at the CMP suction and discharge, respectively. Again, in the CF + EF, a higher discharge pressure is measured (see Fig. 7(a)) with values slightly lower than the CF scenario. As shown in Table 3, the residual observed under the CF + EF condition was lower than the sum of the residuals associated with the individual faults. Although sublinear interactions between the two faults are therefore evident, the CF + EF residual remained closer to the CF-only values, confirming the predominant influence of CF. By contrast, the impact on suction pressure (see Fig. 7(b)) is again limited. Looking at residuals in Table 3, suction pressure showed a slight deviation from no-fault values.

Subcooling (see Fig. 7(c)) is strongly influenced in the CF + EF scenario (+4.7 °C at full load, point K'''), with the corresponding curve nearly overlapping that of the CF-only condition. Residuals in Table 3 indicate that refrigerant subcooling exhibited relatively good linearity. On the J-line, the deviation between the combined residual and the sum of the individual residuals was -0.49 °C, while on the K-line it was -0.29 °C. These deviations are relatively small compared to the residual magnitudes. Refrigerant superheating (see Fig. 7(d)) is not affected by either fault. In this respect, residuals in Table 3 are not significant, being lower than the relative uncertainties.

As shown in Figs. 7(e-f), an increase in CMP power consumption and refrigerant mass flow rate is again found in the CF + EF scenario. However, residuals in Table 3 suggest nonlinear behavior. As shown in Fig. 7(f), IDF power consumption increases in the CF + EF, with a residual as the one observed in the EF scenario (see Table 3). More specifically, a 53.3% increase at 100% IDF torque (point K'') was observed compared to the fault-free case. Finally, ODF power increases (see Fig. 7(g)), with the CF + EF curve nearly overlapping with that of CF. In this respect, residuals in the CF + EF scenario are almost equal to those found in the CF scenario.

4.1.1. Discussion on key findings from scenario No. 1

Overall, the cross-analysis of the previous results indicates that the CF + EF condition generally produced residuals lower than the sum of the corresponding individual residuals, revealing predominantly

sublinear behavior. Among the investigated variables, refrigerant superheating was not significantly affected, with residuals consistently remaining within the propagated uncertainty bounds. This behavior highlights the capability of the TXV to effectively regulate EVP feeding and maintain stable superheating even under severe faulty operating conditions. This behavior is consistent with the observations of Hu and Yuill [36], who reported that refrigerant superheating may remain comparatively insensitive to several fault combinations because of the compensating action of TXV. Similarly, the suction (or evaporating) pressure exhibited limited sensitivity to the combined CF + EF condition. Since the comparison was performed at equivalent sensible cooling capacities, corresponding to operating conditions where the RTU was still capable of maintaining the SAT_{sp} , the variable-speed CMP continuously adjusted its rotational speed to compensate for the degradation induced by the faults, resulting in comparatively small suction-pressure variations. Conversely, discharge pressure and refrigerant subcooling were found to be predominantly governed by CF, as the residual trends associated with the CF + EF condition remained close to those observed under CF alone. Under CF conditions, the reduction in outdoor airflow degrades CND heat rejection, thereby increasing condensing pressure. At the same time, the higher condensing pressure promotes a larger refrigerant inventory retained within the condenser, enlarging the liquid-filled region and consequently increasing refrigerant subcooling.

EF mainly affected IDF power consumption because of the increased airflow resistance across the EVP coil. As a result, IDF power consumption emerged as a suitable decoupling feature for discriminating between CF-only and CF + EF scenarios.

4.2. Results for Scenario No. 2: Evaporator Fouling, Condenser Fouling, and Refrigerant Undercharge

The performance of the unit for the CF + EF + UndCH scenario is discussed here. The following test condition $IDT = 26\text{ }^{\circ}\text{C}$, $RH_{ID} = 50\%$, and $ODT = 30\text{ }^{\circ}\text{C}$ is first considered. To better understand the effects of multiple faults on RTU, it is useful to include the results found for the case of UndCH [22] and the ones from the CF + EF scenario.

Fig. 8(a) compares the RTU sensible cooling capacity as a function of the IDF speed for the fault-free, CF + EF, UndCH, and CF + EF + UndCH scenarios. At the high IDF torque, the fault-free scenario (point A) achieved approximately 14.1 kW. Under the UndCH condition (point A'), the sensible cooling capacity decreased to nearly 13.5 kW, corresponding to a reduction of about 4%. A significantly larger reduction was observed for the CF + EF condition (point A''), where the capacity dropped to approximately 11.4 kW, corresponding to nearly 19.1%

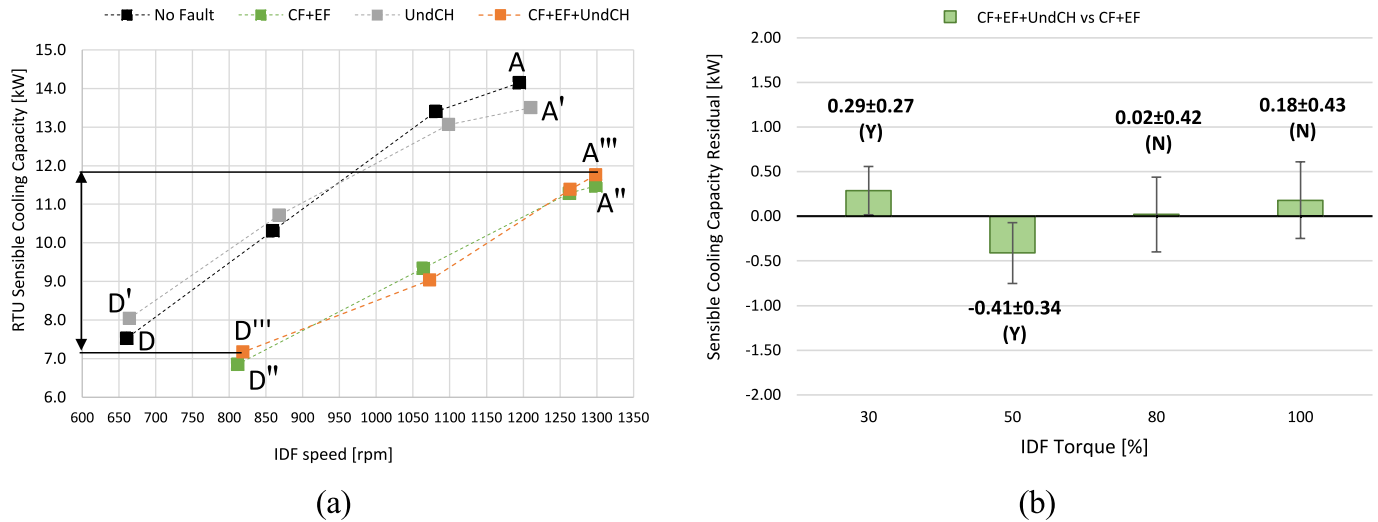


Fig. 8. Experimental results for IDT = 26 °C- $RH_{ID} = 50\%$ -ODT = 30 °C in the case of CF + EF + UndCH: (a) sensible cooling capacity; (b) residuals of sensible cooling capacity relative to CF + EF scenario and statistical significance.

reduction relative to the fault-free case. Similarly, the CF + EF + UndCH condition (point A'') reached approximately 11.7 kW, corresponding to an overall reduction of about 17%. Considering that the CF + EF yields a substantial decrease in the maximum sensible cooling capacity, it can be inferred that the capacity degradation observed in the combined CF + EF + UndCH scenario is driven by EF. In this respect, Fig. 8(b) reports the residuals of sensible cooling capacity for the CF + EF + UndCH scenario relative to the corresponding CF + EF condition at different IDF torque levels, together with the associated uncertainty bounds. The results show that the residuals at 100% and 80% IDF torque remain within the propagated uncertainty range, indicating that the effect of the additional UndCH fault is not statistically distinguishable from the CF + EF condition, especially under high airflow operating conditions. Conversely, larger (although still moderate) residuals were observed at 50% and 30% IDF torque, where the residuals reached approximately -0.41 kW and +0.29 kW, respectively. Notably, the residual sign was not consistent across the operating conditions investigated.

Figs. 9(a-h) provide a picture of experimental data for RTU with CF + EF + UndCH for the test condition IDT = 26 °C- $RH_{ID} = 50\%$ -ODT = 30 °C. Table 4 summarizes the residual analysis performed for the investigated variables under the single-fault (UndCH vs No Fault) and combined-fault (CF + EF + UndCH vs CF + EF) scenarios at the operating conditions placed on the J-line and K-line.

Figs. 9(a-b) show the discharge and suction pressures, respectively. Looking at Fig. 9(a), the discharge pressure in the UndCH scenario (point K'') is approximately 1.4 bar lower than in the fault-free case (point K). In the CF + EF + UndCH scenario, the discharge pressure at maximum capacity (point K''') is approximately 2.3 bar lower than that observed in the CF + EF case at comparable capacity (point K'). The residual analysis reported in Table 4 clearly reveals an interaction among fault effects in the CF + EF + UndCH condition, with weak linear behavior. Specifically, the reduction in discharge pressure under the combined-fault condition relative to CF + EF exceeds the pressure decrease caused by the UndCH fault alone (-1.4 bar) by approximately 0.9 bar. Similar conclusions can also be drawn regarding the operating points located on the J-line.

Regarding suction pressure (Fig. 9(b)), no monotonic trend can be observed. The residual analysis reported in Table 4 reveals only small pressure variations, ranging approximately between -0.3 and -0.2 bar. Moreover, no additive behavior was observed, suggesting that the combined-fault interaction has only a limited influence on suction-side pressure dynamics.

As shown in Fig. 9(c), UndCH leads to a marked decrease in

refrigerant subcooling, reaching approximately -8.0 °C at point K''. In the CF + EF + UndCH scenario (point K'''), the subcooling at maximum capacity remains close to the values observed under the UndCH condition, indicating that this fault predominates in determining the subcooling behavior. Nevertheless, the residual analysis reported in Table 4 reveals that the reduction in subcooling under the CF + EF + UndCH condition (approximately -13.0 °C) is significantly larger than the decrease caused by the UndCH fault alone (8.1 °C), with an additional reduction of approximately 4.9 °C. This result highlights a clear nonlinear interaction among the faults.

Regarding refrigerant superheating (Fig. 9(d)), the previous analysis of the CF + EF scenario showed that this variable is only marginally influenced by these faults. Conversely, the UndCH condition produces a noticeable increase in superheating. The residual analysis reported in Table 4 indicates that the increase in superheating when moving from CF + EF to CF + EF + UndCH (approximately equal to +2.2 °C on the K-line) is smaller than the increase produced by the UndCH fault alone (approximately +3.6 °C). The reduction of the residual magnitude under the combined-fault condition suggests the presence of nonlinear interactions and partial masking effects between simultaneous faults.

Fig. 9(e) presents the CMP power consumption. Under the UndCH condition, CMP power is lower than in the no-fault case, as also confirmed by the residual analysis reported in Table 4. However, the observed trend does not follow a simple additive behavior of the individual faults. Table 4 shows that when moving from the CF + EF condition to the CF + EF + UndCH scenario, an increase in CMP power consumption is observed, in contrast with the reduction produced by the UndCH fault alone. A similar behavior was found for the refrigerant mass flow rate (see Fig. 9(f) and Table 4).

As shown in Fig. 9(g), the IDF power increases by approximately 54.4% in the CF + EF + UndCH scenario (point K''') compared to the fault-free case (point K), consistent with the airflow resistance introduced by EF. In addition, IDF curves for the CF + EF + UndCH and CF + EF almost overlap, confirming the predominance of EF. Finally, Fig. 9(h) shows an increase in ODF power consumption in the CF + EF + UndCH, mainly associated with the higher discharge pressure and CMP power demand. However, the increase does not strictly follow an additive pattern. Conversely, as reported in Table 4, ODF power consumption was only marginally affected under the UndCH-only scenario. However, when comparing CF + EF + UndCH with CF + EF, an increase in the ODF power residual was also observed.

A similar analysis was carried out for the test condition IDT = 24 °C, $RH_{ID} = 50\%$, and ODT = 40 °C. Fig. 10(a) shows that the sensible

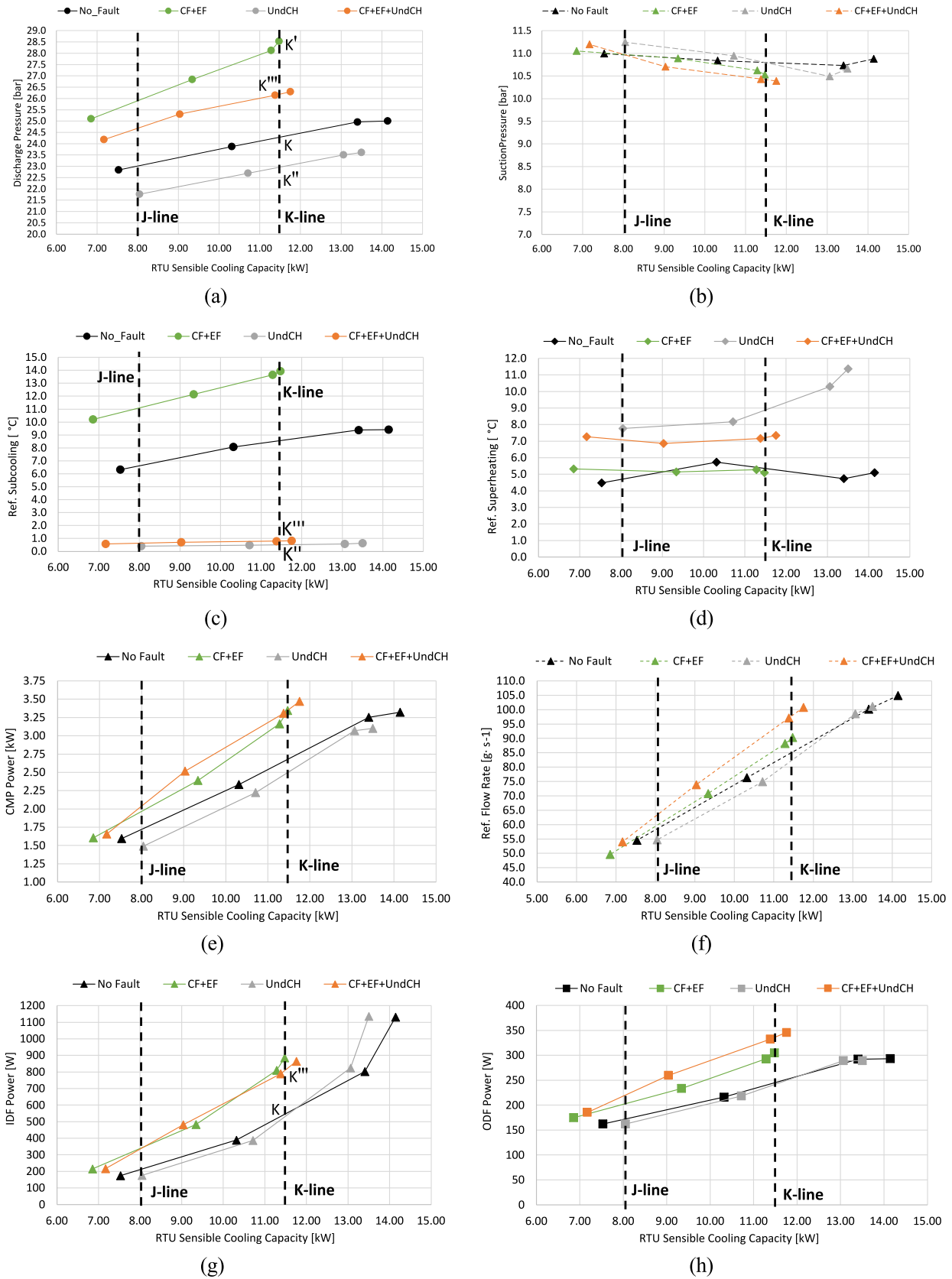
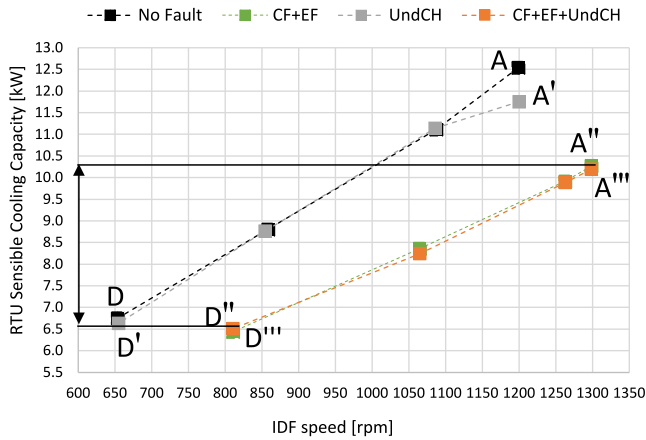


Fig. 9. Experimental results for the CF + EF + UndCH case, assuming $IDT = 26\text{ }^{\circ}\text{C}$, $RH_{ID} = 50\%$, $ODT = 30\text{ }^{\circ}\text{C}$: (a) discharge pressure; (b) suction pressure; (c) refrigerant subcooling; (d) refrigerant superheating; (e) CMP power; (f) refrigerant mass flow rate; (g) IDF power, and (h) ODF power.

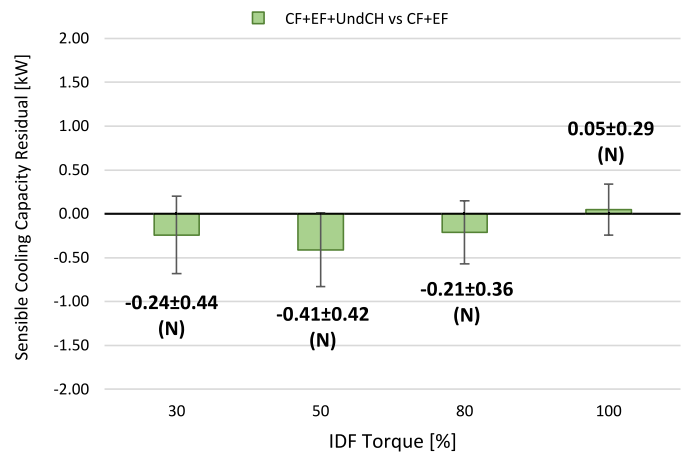
Table 4

Results of residual analysis for single-fault (UndCH vs No Fault) and combined-fault (CF + EF + UndCH vs CF + EF) conditions at the J-line and K-line operating points, assuming $IDT = 26\text{ }^{\circ}\text{C}$ - $RH_{ID} = 50\%$ - $ODT = 30\text{ }^{\circ}\text{C}$.

		$R_{UndCH\ NoFault}$	$R_{UndCH+CF+EF\ CF+EF}$	Comments
Discharge Pressure [bar]	J-line	-1.210 ± 0.122	-1.302 ± 0.122	CF-dominated response with weak linearity
	K-line	-1.413 ± 0.122	-2.312 ± 0.122	
Suction Pressure [bar]	J-line	$+0.202 \pm 0.074$	$+0.152 \pm 0.074$	Low diagnostic sensitivity
	K-line	-0.304 ± 0.074	-0.130 ± 0.074	
Ref. Subcooling [$^{\circ}\text{C}$]	J-line	-6.4 ± 1.0	-10.3 ± 1.0	UndCH-dominated response with NL
	K-line	-8.1 ± 1.0	-13.0 ± 1.0	
Ref. Superheating [$^{\circ}\text{C}$]	J-line	$+3.2 \pm 1.00$	$+1.8 \pm 1.0$	UndCH-dominated response with evident NL
	K-line	$+3.6 \pm 1.0$	$+2.2 \pm 1.0$	
CMP Power [kW]	J-line	-0.221 ± 0.057	$+0.092 \pm 0.057$	Nonlinear interaction effects
	K-line	-0.202 ± 0.057	$+0.103 \pm 0.057$	
Ref. Flow Rate [g·s ⁻¹]	J-line	-3.5 ± 6.1	$+2.7 \pm 6.1$	Nonlinear interaction effects
	K-line	-2.3 ± 6.1	$+8.3 \pm 6.1$	
IDF Power [W]	J-line	-40.2 ± 21.2	-5.6 ± 21.2	EF-dominated response with no superposition
	K-line	-10.3 ± 21.2	-60.9 ± 21.2	
ODF Power [W]	J-line	-10.2 ± 21.2	$+20.3 \pm 21.2$	Affected by NL in CMP Power, with sensitivity to CF
	K-line	-5.7 ± 21.2	$+35.4 \pm 21.2$	



(a)



(b)

Fig. 10. Experimental results for $IDT = 24\text{ }^{\circ}\text{C}$ - $RH_{ID} = 50\%$ - $ODT = 40\text{ }^{\circ}\text{C}$ in the case of CF + EF + UndCH: (a) sensible cooling capacity; (b) residuals of sensible cooling capacity relative to CF + EF scenario and statistical significance.

cooling capacity decreases progressively from the fault-free condition (point A, 12.5 kW) to the CF + EF scenario (point A', approximately 9.9 kW), and finally to the CF + EF + UndCH condition (point A'', approximately 9.9 kW). Compared to the fault-free condition, the combined fault configuration including UndCH leads to an overall reduction of approximately 2.6 kW in sensible cooling capacity. However, the additional degradation introduced by the UndCH fault relative to the CF + EF scenario alone remains limited across all operating points. In this respect, Fig. 10(b) reports the residual analysis of the sensible cooling capacity for the CF + EF + UndCH condition relative to the CF + EF scenario at different IDF torque levels. The residuals are slightly negative at 30%, 50%, and 80% IDF torque, with values ranging between -0.24 ± 0.44 kW and -0.21 ± 0.36 kW, indicating a marginal additional reduction in sensible cooling capacity caused by the UndCH. At 100% IDF torque, the residual becomes slightly positive ($+0.05 \pm 0.29$ kW), although still within the uncertainty interval. Overall, all residuals remain within the propagated uncertainty bounds, indicating that the additional UndCH does not produce statistically significant variations in sensible cooling capacity compared with the CF + EF condition alone. These results suggest that, under the investigated operating conditions, the thermal performance degradation is again

governed by EF.

Figs. 11(a-g) display the main operating variables in fault-free condition and with CF + EF + UndCH imposed, for the case: $IDT = 24\text{ }^{\circ}\text{C}$ - $RH_{ID} = 50\%$ - $ODT = 40\text{ }^{\circ}\text{C}$. Table 5 collects the residual analysis performed for both single-fault and multiple-fault scenarios. Again, the analysis is performed at equivalent sensible cooling capacities indicated by the J-line and K-line. Figs. 11(a-b) show the discharge and suction pressures, respectively. Looking at Fig. 11(a), the discharge pressure in the CF + EF + UndCH scenario is again lower than the CF + EF case. The residual analysis reported in Table 5 clearly reveals an interaction among fault effects in the CF + EF + UndCH condition, with a weak linear behavior. Specifically, the reduction in discharge pressure under the combined-fault condition relative to CF + EF exceeds the pressure decrease caused by the UndCH fault for both the operating points located on the J-line and K-line. Regarding suction pressure (Fig. 11(b)), no monotonic trend can be observed. In this respect, the residual analysis reported in Table 5 reveals small pressure variations with opposite signs.

As shown in Fig. 11(c), UndCH leads again to a marked decrease in refrigerant subcooling, reaching approximately $-11.8\text{ }^{\circ}\text{C}$ at point K''. In the CF + EF + UndCH scenario (point K'''), the subcooling at maximum

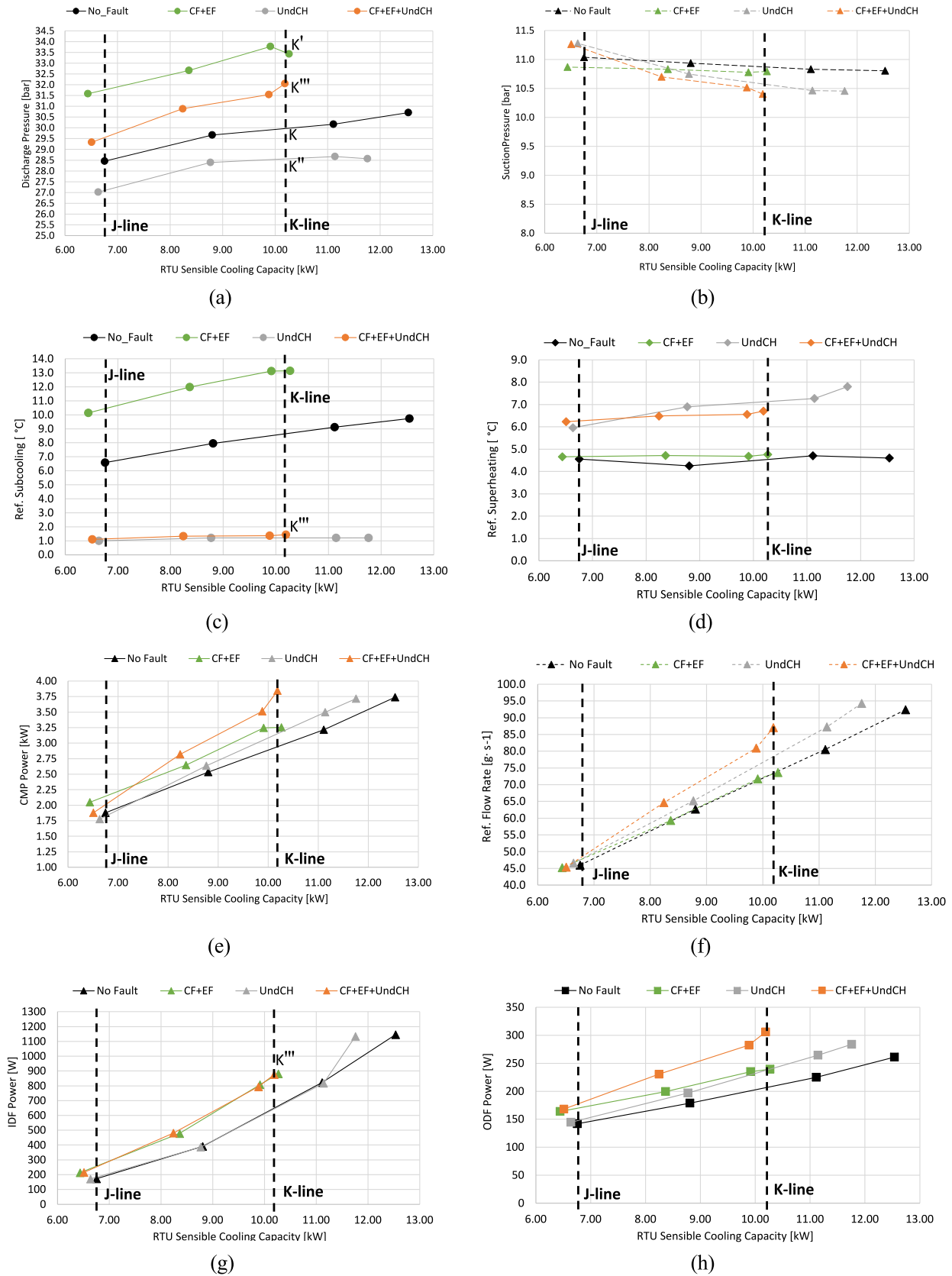


Fig. 11. Experimental results for the CF + EF + UndCH case, assuming $IDT = 24\text{ }^{\circ}\text{C}$ - $RH_{ID} = 50\%$ - $ODT = 40\text{ }^{\circ}\text{C}$: (a) discharge pressure; (b) suction pressure; (c) refrigerant subcooling; (d) refrigerant superheating; (e) CMP power; (f) refrigerant mass flow rate; (g) IDF power, and (h) ODF power.

Table 5

Results of residual analysis for single-fault (UndCH vs No Fault) and combined-fault (CF + EF + UndCH vs CF + EF) conditions at the J-line and K-line operating points, assuming $IDT = 24\text{ }^{\circ}\text{C}$, $RH_{ID} = 50\%$, $ODT = 40\text{ }^{\circ}\text{C}$.

		$R_{UndCH, NoFault}$	$R_{UndCH+CF+EF, CF+EF}$	Comments
Discharge Pressure [bar]	J-line	-1.371 ± 0.122	-2.232 ± 0.122	CF-dominated response with weak linearity
	K-line	-1.408 ± 0.122	-1.567 ± 0.122	
Suction Pressure [bar]	J-line	$+0.244 \pm 0.074$	$+0.373 \pm 0.074$	Low diagnostic sensitivity
	K-line	-0.303 ± 0.074	-0.351 ± 0.074	
Ref. Subcooling [$^{\circ}\text{C}$]	J-line	-5.6 ± 1.0	-9.3 ± 1.0	UndCH-dominated response with NL
	K-line	-7.4 ± 1.0	-11.8 ± 1.0	
Ref. Superheating [$^{\circ}\text{C}$]	J-line	$+1.4 \pm 1.0$	$+1.6 \pm 1.0$	UndCH-dominated response with evident NL
	K-line	$+2.6 \pm 1.0$	$+1.9 \pm 1.0$	
CMP Power [kW]	J-line	-0.071 ± 0.057	-0.167 ± 0.057	Nonlinear interaction effects
	K-line	$+0.235 \pm 0.057$	$+0.486 \pm 0.057$	
Ref. Flow Rate [$\text{g}\cdot\text{s}^{-1}$]	J-line	$+2.21 \pm 0.61$	$+0.12 \pm 0.61$	Nonlinear interaction effects
	K-line	$+4.23 \pm 0.61$	$+13.12 \pm 0.61$	
IDF Power [W]	J-line	$+20.2 \pm 21.2$	$+5.3 \pm 21.2$	EF-dominated response with no superposition
	K-line	$+0.2 \pm 21.2$	-5.5 ± 21.2	
ODF Power [W]	J-line	$+6.3 \pm 21.2$	$+4.1 \pm 21.2$	Affected by NL in CMP Power, with sensitivity to CF
	K-line	$+28.7 \pm 21.2$	$+62.8 \pm 21.2$	

capacity remains close to the values observed under the UndCH condition, indicating that this fault predominates in determining the subcooling behavior. Nevertheless, the residual analysis reported in Table 5 reveals that the reduction in subcooling under the CF + EF + UndCH condition (approximately $-11.8\text{ }^{\circ}\text{C}$) is significantly larger than the decrease caused by the UndCH fault alone, with an additional reduction of approximately $4\text{ }^{\circ}\text{C}$. Regarding refrigerant superheating (Fig. 11(d)), the profile is located below the one found for the UndCH scenario. Again, the residual analysis reported in Table 5 indicates that the increase in superheating when moving from CF + EF to CF + EF + UndCH (e.g., approximately $+1.94\text{ }^{\circ}\text{C}$ for the operating point on the K-line) is smaller than the increase produced by the UndCH fault alone, suggesting the presence of nonlinearity.

Fig. 11(e) presents the CMP power consumption, and an increase is again observed when moving from the CF + EF condition to the CF + EF + UndCH scenario. A similar behavior was found for the refrigerant mass flow rate (see Fig. 9(f) and Table 5). As shown in Fig. 11(g), the IDF power increases by approximately 32.3% in the CF + EF + UndCH scenario (point K'') compared to the fault-free case. In addition, IDF curves for the CF + EF + UndCH and CF + EF almost overlap. Residual value in Table 5 indicates the predominant impact of EF again.

Finally, Fig. 11(h) shows an increase in ODF power consumption in the CF + EF + UndCH, mainly associated with the higher discharge pressure and CMP power demand. However, the increase does not strictly follow an additive pattern. Instead, as shown in Table 5, in the UndCH alone scenario, the variation in the ODF power consumption is,

however, an increase is lower than the one observed when comparing CF + EF + UndCH with CF + EF.

4.2.1. Discussion on key findings from scenario No. 2

Overall, the results obtained for Scenario no. 2 reveal stronger nonlinear interactions compared to the CF + EF case. In most of the investigated variables, the residuals generated under the CF + EF + UndCH condition did not follow a linear superposition of the corresponding single-fault residuals. Focusing on CND-related variables, refrigerant subcooling was strongly affected when UndCH was also imposed, whereas the discharge-pressure increase caused by CF was partially mitigated. Indeed, when UndCH is simultaneously imposed, the refrigerant inventory and liquid filling degree within the CND decrease significantly. Therefore, the pressure buildup induced by CF is partially mitigated, and the effective heat-transfer area available for liquid subcooling is substantially reduced.

Refrigerant superheating was largely affected by UndCH, indicating that, despite the maximum TXV opening, the reduced refrigerant inventory prevented the valve from properly controlling EVP feeding conditions. Although UndCH alone produced a significant increase in superheating, the corresponding residuals under CF + EF + UndCH conditions were smaller, revealing a markedly nonlinear behavior. This reduction in superheating increase compared to the UndCH-only scenario is partially associated with the higher pressure difference between the CND and the EVP induced by CF. The increased pressure differential promotes refrigerant flow through the TXV toward the EVP, partially

Table 6

“Extended Symptom Matrix” for fault detection in variable-speed RTU.

	p_{suct}	p_{disch}	ΔT_{SH}	ΔT_{SubC}	P_C	P_{ODF}	P_{IDF}	Overall Response
UndCH [22]	–	↓	↑	↓	↑	↑	↑	Slight variation in the sensible CC. Large impact on subcooling/superheating.
CF [22]	–	↑	–	↑	↑	↑	–	Very slight variation of sensible CC. Large impact on the CND operating variable.
EF [37]	–	–	–	–	–	–	↑	Air-side isolated effect. Decrease in Sensible CC at higher IDF speed.
CF+EF	–	↑L (CF)	–	↑L (CF)	↑L (CF)	↑L (CF)	↑L (EF)	Quasi-additive but thermodynamically CF-dominated. Decrease in Sensible CC dominated by EF.
CF+EF+UndCH	–	↑NL	↑NL (UndCH)	↑NL (UndCH)	↑NL	↑NL	↑L (EF)	Non-additive interaction. Decrease in Sensible CC, still dominated by EF.

compensating for the reduced refrigerant inventory and mitigating the superheating rise expected under UndCH conditions alone.

The results also showed an increase in CMP power consumption (and consequently in ODF power consumption) together with an increase in refrigerant mass flow rate when moving from CF + EF to CF + EF + UndCH conditions. In this regard, the controller continuously modulates CMP speed to maintain the SAT close to the imposed setpoint, while partially compensating for the reduced capability of the TXV to properly regulate refrigerant flow from the CND under UndCH conditions.

Despite the presence of UndCH, suction pressure again exhibited limited sensitivity. Unlike fixed-speed systems, the variable-speed CMP continuously adapts its rotational speed to preserve cooling delivery and maintain the SAT_{sp}. Therefore, even under combined-fault conditions, the EVP does not undergo the pronounced refrigerant starvation typically observed in constant-speed systems, resulting in slight variations in evaporating pressure.

4.3. Extended symptom matrix and analysis of multiple-fault effects

It is insightful to summarize and compare the deviations observed in the RTU operating variables under single- and multiple-fault scenarios. Table 6 presents an “extended” version of the symptom matrix originally developed in [22] for single-fault cases and here extended to multiple-fault scenarios based on the present experimental analysis. In addition to variation ($\uparrow$, $\downarrow$, $-$), the matrix specifies the nature of the interaction among concurrent faults. The symbols L and NL denote, respectively, *linear dominance* and, *nonlinear contribution*. More specifically, linear dominance indicates that the variable response under multiple-fault conditions is primarily governed by one fault and remains comparable in trend and magnitude to the corresponding single-fault behavior. Nonlinear contribution refers to deviations from linear superposition, whereby the combined response differs from the algebraic sum of the individual effects.

Looking at Table 6, for single-fault scenarios, the system response is characterized by well-defined and predominantly linear signatures [22,37]. UndCH mainly affects thermodynamic variables, producing a decrease in discharge pressure, a reduction in subcooling, and a marked increase in superheating [22]. The associated variations in CMP and ODF power are consistent with this thermodynamic imbalance. Similarly, CF exhibits a clear CND-side dominance, with a linear increase in discharge pressure, subcooling, CMP power, and ODF power, while leaving suction pressure and superheating largely unaffected [22]. EF, in contrast, behaves as an air-side isolated disturbance, with its effect confined almost exclusively to the increase in IDF power [37].

Moving to a multiple-fault scenario, the interaction mechanisms become more articulated. Specifically:

- In the CF + EF scenario, the resulting behavior remains largely quasi-additive from a diagnostic standpoint. Thermodynamic variables such as discharge pressure and subcooling remain dominated by CF ($\uparrow$ L), whereas IDF power continues to be governed by EF ($\uparrow$ L). Although the faults coexist, their respective signatures remain largely separable, and no strong cross-coupling effects emerge. This indicates that the combination of component-level disturbances does not substantially alter the individual dominance mechanisms observed under single-fault operation.
- A markedly different behavior emerges in the CF + EF + UndCH scenario. In this case, several variables exhibit non-linear or competing responses. Specifically, (i) the discharge pressure increase remains present but is lower than in the CF-only case, indicating partial mitigation by UndCH and then a deviation from linear superposition; (ii) superheating increases is mainly due to UndCH; however, its magnitude is smaller than under single UndCH, confirming non-additive coupling; and (iii) subcooling is fully dominated by UndCH. These results demonstrate that the introduction of

a system-fault fundamentally alters the interaction mechanisms, generating nonlinear and compensating effects.

- Sensible cooling capacity degradation remains primarily governed by EF, with UndCH contributing a very slight reduction. The absence of strict additivity confirms that, in variable-speed RTUs, capacity degradation is shaped by the interplay between thermodynamic disturbances and control action rather than by independent summation of fault effects.

These findings highlight that, while single faults generate distinct and largely linear diagnostic signatures, the simultaneous occurrence of multiple faults in variable-speed RTUs leads to coupled and non-additive system responses. Although strict additivity is lost, the dominant influence of specific faults on selected variables (indicated by light red in Table 6) can still be exploited for qualitative fault discrimination. More specifically, under the CF + EF condition, the concurrent increase in discharge pressure (typically associated with CF) and IDF power consumption (typically associated with EF) may serve as qualitative indicators of the simultaneous presence of these faults. In the CF + EF + UndCH scenario, the additional increase in refrigerant superheating — which remains negligible under CF + EF — provides a further distinguishing feature, allowing this triple-fault condition to be differentiated from the CF + EF combination.

In practical applications, the proposed extended symptom matrix may be integrated within rule-based or hybrid FDD architectures by comparing real-time deviations of selected variables against the interaction patterns identified experimentally. For instance, the concurrent increase in discharge pressure and IDF power may indicate simultaneous CF + EF, while an additional increase in refrigerant superheating may suggest the presence of refrigerant UndCH. In this context, the matrix can support feature selection, residual interpretation, and decision-rule construction for automatic FDD systems operating under variable-speed control. Unlike conventional symptom matrices, which are often developed under fixed-speed operation or under conditions where faults directly result in unmet cooling demand, the proposed framework is specifically intended for variable-speed systems operating under active closed-loop control. The matrix, therefore, synthesizes the fault-interaction patterns observed under operating conditions in which the RTU remains capable of satisfying the imposed supply-air-temperature setpoint despite the presence of significant underlying degradations. As demonstrated throughout this study, controller-induced compensation can substantially modify, attenuate, or even mask conventional fault signatures. Consequently, the proposed matrix is specifically designed to support fault diagnosis in these “hidden degradation” scenarios, where the system appears to operate correctly from the building-control perspective while multiple faults simultaneously affect its thermodynamic behavior.

Although the proposed matrix is presently intended as a physics-informed qualitative diagnostic framework, the identified interaction patterns provide a basis for the future development of automated multi-fault FDD algorithms and quantitative classification strategies. It should also be noted that the conclusions drawn from the proposed symptom matrix are inherently linked to the fault magnitudes investigated in this study. Although the analysis is performed by comparing operating conditions characterized by comparable sensible cooling capacities, the observed fault signatures and interaction patterns may still depend on the severity of the underlying faults. Therefore, additional studies covering a wider range of fault magnitudes would be required to assess the generality of the identified interaction mechanisms.

5. Conclusions

This study experimentally analyzed the interaction of EF, CF, and UndCH in a 17.5 kW variable-speed rooftop unit under both humid and near-dry operating conditions. Results show that sensible cooling capacity degradation is always primarily governed by EF. Thermodynamic

variables exhibited different interaction regimes depending on fault combinations. In the CF + EF scenario, discharge pressure and subcooling were almost entirely governed by CF, while IDF power was dominated by EF. The resulting behavior can therefore be described as quasi-additive and diagnostically separable, since each fault preserves its dominant signature. A markedly different interaction pattern emerged when the system-level fault (UndCH) was introduced. In the CF + EF + UndCH scenario, several variables showed nonlinear and competing effects. The discharge pressure increase induced by CF was partially mitigated (up to 2.4 bar relative to CF-only), superheating increased due to UndCH but with reduced magnitude compared to the single-fault case, and subcooling reflected opposing CF–UndCH contributions, with the prevailing UndCH effect. These results clearly demonstrate that fault signatures in variable-speed systems do not simply superimpose but are reshaped by the interaction between thermodynamic disturbances and automated capacity control. The extended symptom matrix proposed in this work provides a structured classification of linear dominance, nonlinear contribution, and competing interaction mechanisms under multi-fault conditions. The results show that diagnostic rules derived under single-fault conditions cannot be directly extended to variable-speed systems operating under concurrent disturbances. Instead, multi-fault FDD strategies must explicitly account for control-induced compensation and non-additive system responses. Overall, this study contributes experimental evidence on multi-fault interactions in variable-speed RTUs and establishes a methodological framework for improving diagnosability under realistic degradation scenarios.

Future work will extend the present investigation to additional refrigerant-related faults, including refrigerant overcharge, in order to assess its interaction with heat-exchanger fouling and its impact on multi-fault diagnostic behavior under variable-speed operation. Meanwhile, further experimental investigations covering a wider range of fault severities are needed to assess the extent to which the observed interaction mechanisms remain valid under less severe degradation conditions. Finally, future work should validate the proposed matrix within an automatic diagnostic framework, using independent datasets, broader fault severities, and additional fault combinations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The author gratefully acknowledges Prof. James E. Braun for his invaluable guidance and support throughout the experimental activities conducted at the Herrick Laboratories, Purdue University (Indiana, USA).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.applthermaleng.2026.132028>.

Data availability

No data was used for the research described in the article.

References

- [1] European Parliament, Council of the European Union, Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast), 2024.
- [2] International energy agency (IEA), Space Cooling, 2022.
- [3] J. Cai, J.E. Braun, Assessments of variable-speed equipment for packaged rooftop units (RTUs) in the United States, *Energ. Buildings* 164 (2018) 203–218, <https://doi.org/10.1016/j.enbuild.2018.01.007>.
- [4] A.P. Rogers, F. Guo, B.P. Rasmussen, A review of fault detection and diagnosis methods for residential air conditioning systems, *Build. Environ.* 161 (2019) 106236, <https://doi.org/10.1016/j.buildenv.2019.106236>.
- [5] B. Llopis-Mengual, D.P. Yuill, E. Navarro-Peris, Time series analysis of field data for soft faults detection and degradation assessment in residential air conditioning systems, *Appl. Therm. Eng.* 269 (2025) 126104, <https://doi.org/10.1016/j.applthermaleng.2025.126104>.
- [6] L. Yang, J.E. Braun, E.A. Groll, The impact of fouling on the performance of filter–evaporator combinations, *International Journal of Refrigeration* 30 (2007) 489–498, <https://doi.org/10.1016/j.jirefrig.2006.08.006>.
- [7] Z. Du, P.A. Domanski, W.V. Payne, Effect of common faults on the performance of different types of vapor compression systems, *Appl. Therm. Eng.* 98 (2016) 61–72, <https://doi.org/10.1016/J.APPLTHERMALENG.2015.11.108>.
- [8] F. Pelella, L. Viscito, A.W. Mauro, Combined effects of refrigerant leakages and fouling on air-source heat pump performances in cooling mode, *Appl. Therm. Eng.* 204 (2022) 117965, <https://doi.org/10.1016/j.applthermaleng.2021.117965>.
- [9] Y. Hu, D.P. Yuill, Non-condensable gas in the refrigerant of air-source heat pumps: interactions between detection features, charge level, and temperature, *International Journal of Refrigeration* 153 (2023) 378–384, <https://doi.org/10.1016/J.IJREFRIG.2022.10.006>.
- [10] A.W. Mauro, A.F. Passarelli, F. Pelella, L. Viscito, Life-cycle thermo-economic-environmental analysis of a PV-driven heat pump with and without refrigerant leakages, *Energy* 323 (2025) 135894, <https://doi.org/10.1016/j.energy.2025.135894>.
- [11] J. Chen, L. Zhang, Y. Li, Y. Shi, X. Gao, Y. Hu, A review of computing-based automated fault detection and diagnosis of heating, ventilation and air conditioning systems, *Renew. Sustain. Energy Rev.* 161 (2022) 112395, <https://doi.org/10.1016/J.RSER.2022.112395>.
- [12] T.M. Rossi, J.E. Braun, A statistical, rule-based fault detection and diagnostic method for vapor compression air conditioners, *HVAC&R Res* 3 (1997) 19–37, <https://doi.org/10.1080/10789669.1997.10391359>.
- [13] V. Singh, J. Mathur, A. Bhatia, A comprehensive review: fault detection, diagnostics, prognostics, and fault modeling in HVAC systems, *International Journal of Refrigeration* 144 (2022) 283–295, <https://doi.org/10.1016/j.jirefrig.2022.08.017>.
- [14] Y. Guo, J. Wang, H. Chen, G. Li, R. Huang, Y. Yuan, et al., An expert rule-based fault diagnosis strategy for variable refrigerant flow air conditioning systems, *Appl. Therm. Eng.* 149 (2019) 1223–1235, <https://doi.org/10.1016/j.applthermaleng.2018.12.132>.
- [15] S. Keshavarzian, M.V. Rocco, E. Colombo, Thermo-economic diagnosis and malfunction decomposition: methodology improvement of the Thermo-economic input-output analysis (TIOA), *Energ. Convers. Manage.* 157 (2018) 644–655, <https://doi.org/10.1016/J.ENCONMAN.2017.12.021>.
- [16] T. Zhao, J. Yang, J. Zhu, M. Peng, C. Lu, Z. Shi, Quantitative detection of refrigerant charge faults in multi-unit air conditioning systems based on machine learning algorithms, *International Journal of Refrigeration* 169 (2025) 184–193, <https://doi.org/10.1016/j.jirefrig.2024.10.026>.
- [17] W. Kim, J.E. Braun, Development, implementation, and evaluation of a fault detection and diagnostics system based on integrated virtual sensors and fault impact models, *Energ. Buildings* 228 (2020) 110368, <https://doi.org/10.1016/j.enbuild.2020.110368>.
- [18] P. Barandier, A.J. Marques Cardoso, A review of fault diagnostics in heat pumps systems, *Appl. Therm. Eng.* 228 (2023) 120454, <https://doi.org/10.1016/J.APPLTHERMALENG.2023.120454>.
- [19] Sholahudin, N. Giannetti, K. Saito, K. Tanaka, W. Kowa, Nasruddin, et al., Refrigerant leakage detection during field operation of air conditioners using neighborhood component analysis and artificial neural network, *J. Build. Eng.* 119 (2026) 115293, <https://doi.org/10.1016/j.jobe.2026.115293>.
- [20] F. Pelella, L. Viscito, A.W. Mauro, Soft faults in residential heat pumps: possibility of evaluation via on-field measurements and related degradation of performance, *Energ. Convers. Manage.* 260 (2022) 115646, <https://doi.org/10.1016/J.ENCONMAN.2022.115646>.
- [21] B.A. Qureshi, S.M. Zubair, The impact of fouling on the condenser of a vapor compression refrigeration system: an experimental observation, *International Journal of Refrigeration* 38 (2014) 260–266, <https://doi.org/10.1016/j.jirefrig.2013.08.012>.
- [22] Catrini A. Piacentino, Experimental analysis of the effects of condenser fouling and refrigerant charge faults on the performance of variable-speed rooftop units, *Appl. Therm. Eng.* 279 (Part B) (2025), <https://doi.org/10.1016/j.applthermaleng.2025.127578>.
- [23] M.S. Breuker, J.E. Braun, Common faults and their impacts for rooftop air conditioners, *HVAC&R Res* 4 (1998) 303–318, <https://doi.org/10.1080/10789669.1998.10391406>.
- [24] F. Pelella, A.F. Passarelli, B. Llopis-Mengual, L. Viscito, E. Navarro-Peris, A. W. Mauro, State-of-the-art methodologies for self-fault detection, diagnosis and evaluation (FDDE) in residential heat pumps, *Energies (Basel)* 18 (2025), <https://doi.org/10.3390/en18133286>.
- [25] I. Bellanco, F. Belío, M. Vallés, R. Gerber, J. Salom, Common fault effects on a natural refrigerant, variable-speed heat pump, *International Journal of Refrigeration* 133 (2022) 259–266, <https://doi.org/10.1016/J.IJREFRIG.2021.10.017>.

- [26] H. Li, J.E. Braun, Decoupling features and virtual sensors for diagnosis of faults in vapor compression air conditioners, *International Journal of Refrigeration* 30 (2007) 546–564, <https://doi.org/10.1016/j.ijrefrig.2006.07.024>.
- [27] H. Li, J.E. Braun, Decoupling features for diagnosis of reversing and check valve faults in heat pumps, *International Journal of Refrigeration* 32 (2009) 316–326, <https://doi.org/10.1016/j.ijrefrig.2008.05.005>.
- [28] H. Li, J.E. Braun, Virtual refrigerant pressure sensors for use in monitoring and fault diagnosis of vapor-compression equipment, *HVAC&R Res* 15 (2009) 597–616, <https://doi.org/10.1080/10789669.2009.10390853>.
- [29] Y. Hu, Y. Chen, D.P. Yuill, Experimental study of liquid line temperature drop as a fault feature for detecting severe liquid line restrictions in residential air conditioning systems, *International Journal of Refrigeration* 152 (2023) 293–302, <https://doi.org/10.1016/j.ijrefrig.2023.04.029>.
- [30] B. Llopis-Mengual, E. Navarro-Peris, Selection of relevant features to detect and diagnose single and multiple simultaneous soft faults in air-source heat pumps, *Appl. Therm. Eng.* 238 (2024) 121922, <https://doi.org/10.1016/J.APPLTHERMALENG.2023.121922>.
- [31] B. Llopis-Mengual, E. Navarro-Peris, Effects of simultaneous soft faults in a reversible and variable-speed air-to-water heat pump, *Appl. Therm. Eng.* 254 (2024) 123883, <https://doi.org/10.1016/j.applthermaleng.2024.123883>.
- [32] B. Llopis-Mengual, D.P. Yuill, E. Navarro-Peris, Fault detection and diagnosis algorithm for multiple simultaneous faults in residential air-conditioning systems: development, validation study and critical analysis, *Appl. Therm. Eng.* 269 (2025) 125975, <https://doi.org/10.1016/j.applthermaleng.2025.125975>.
- [33] Z. Zhou, H. Chen, L. Xing, G. Li, W. Gou, An experimental study of the behavior of a model variable refrigerant flow system with common faults, *Appl. Therm. Eng.* 202 (2022) 117852, <https://doi.org/10.1016/j.applthermaleng.2021.117852>.
- [34] Wu J, Xu Z, Jiang F. Analysis and development trends of Chinese energy efficiency standards for room air conditioners. *Energy Policy* 2025;343:115838. doi:<https://doi.org/10.1016/j.enpol.2018.10.038>.
- [35] Y. Hu, D.P. Yuill, Multiple simultaneous faults' impacts on air-conditioner behavior and performance of a charge diagnostic method, *Appl. Therm. Eng.* 215 (2022) 119015, <https://doi.org/10.1016/j.applthermaleng.2022.119015>.
- [36] Y. Hu, D.P. Yuill, Effects of multiple simultaneous faults on characteristic fault detection features of a heat pump in cooling mode, *Energ. Buildings* 251 (2021) 111355, <https://doi.org/10.1016/J.ENBUILD.2021.111355>.
- [37] P. Catrini, A. Piacentino, Experimental performance characterization of variable-speed packaged rooftop units with fouled evaporator, *Appl. Therm. Eng.* 233 (2023) 121159, <https://doi.org/10.1016/j.applthermaleng.2023.121159>.
- [38] M. Kim, S.H. Yoon, P.A. Domanski, W. Vance Payne, Design of a steady-state detector for fault detection and diagnosis of a residential air conditioner, *Int. J. Refrig.* 31 (2008) 790–799, <https://doi.org/10.1016/j.ijrefrig.2007.11.008>.
- [39] S.A. K. Engineering equation solver, 2010.
- [40] B.N. Taylor, C.E. Kuyatt, Guidelines for evaluating and expressing the uncertainty of NIST measurement results: appendix D1. Terminology, 2001.
- [41] I.H. Bell, E.A. Groll, Air-side particulate fouling of microchannel heat exchangers: experimental comparison of air-side pressure drop and heat transfer with plate-fin heat exchanger, *Appl. Therm. Eng.* 31 (2011) 742–749, <https://doi.org/10.1016/j.applthermaleng.2010.10.019>.
- [42] L. Yang, J.E. Braun, E.A. Groll, The impact of evaporator fouling and filtration on the performance of packaged air conditioners, *Int. J. Refrig.* 30 (2007) 506–514, <https://doi.org/10.1016/j.ijrefrig.2006.08.010>.
- [43] Y. Hu, D.P. Yuill, Impacts of common faults on an air conditioner with a microtube condenser and analysis of fault characteristic features, *Energ. Buildings* 254 (2022) 111630, <https://doi.org/10.1016/J.ENBUILD.2021.111630>.