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A review of common faults in large-scale heat pumps

José Joaquín Aguilera [a,*], Wiebke Meesenburg [a], Torben Ommen [a], Wiebke Brix Markussen [a], Jonas Lundsted Poulsen [b], Benjamin Zühlsdorf [b], Brian Elmegaard [a]

[a] *Section of Thermal Energy, Department of Civil and Mechanical Engineering, Technical University of Denmark, Nils Koppels Alle 403, 2800 Kgs. Lyngby, Denmark*
[b] *Danish Technological Institute, Energy and Climate, Kongsvang Allé 29, 8000, Aarhus, Denmark*

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ABSTRACT

Large-scale heat pumps can contribute towards the decarbonisation of district heating systems and industrial processes. Unidentified faults can have a negative impact on the availability, performance and maintenance costs of heat pump systems. This study provides a description of faults related to the operation of 53 heat pumps based on a vapour compression cycle. Faults were characterized according to potential causes, mitigation or prevention implications as well as detection and diagnosis methods. Faults in the compressor, evaporator and source heat exchanger were more recurrent than in other components of large-scale heat pumps. Overall, the most common faults were fouling of heat exchangers and refrigerant leakage. Faults related to negative impacts like system shutdown, performance reduction and release of refrigerant into the environment, were mainly described to be originated in the compressor. Several directions for future research were identified, which included developing specific fault detection and diagnosis methods for large-scale heat pump applications, proposing methods to detect and diagnose multiple and simultaneous faults, and integrating performance degradation monitoring with fault detection and diagnosis.

1. Introduction

The Heat Roadmap Europe [1] estimated that about 50% of the European residential heating demand can potentially be provided by district heating, in which approximately 25%–30% can be delivered by large-scale heat pumps. Pieper et al. [2] suggested that large-scale heat pumps are those with heating capacities equal or above 0.2 MW, which are often used in district heating systems and industrial applications. Large-scale heat pump units and systems (i.e. arrangement of single units) are able to recover excess heat and leverage renewable energy sources, which may contribute to the decarbonisation of district heating systems and industries in Europe, as suggested by Kosmadakis [3] and Sayegh et al. [4]. Wolf and Blesl [5] stated that large-scale heat pumps can contribute to a 15% reduction of the final energy consumption of the EU-28 industrial sector, corresponding to 17% of its CO_2 emissions, which can be even larger with an increased share of renewables for electricity production.

A significant share of commercially available large-scale heat pumps are based on an electricity-driven vapour compression cycle [6]. A number of studies [7–9] proposed that large-scale electric heat pumps can provide an integration between the heating and power sectors, improving their operational flexibility and increasing the use of renewable energy sources. In this context, it is expected that large-scale heat pumps will have a significant role in future smart energy systems [10,11].

Different heat sources may be related to various types of faults affecting large-scale heat pump systems. For instance, extracting heat from sewage water often leads to the deposition of organic material on heat exchanger surfaces [12], whereas geothermal heat pumps can be exposed to corrosion as a result of underground minerals reacting with metal elements in the system [13]. According to Storesund [14], the first components in large-scale heat pumps to be affected by mechanical wear are linked to the compressor (e.g. bearings, shaft seals and impellers). Storesund also described that material debris from a compressor breakdown may damage other components in the system, particularly the condenser.

Previous studies have summarized technical challenges that can occur in large-scale heat pumps. Schlosser et al. [15] summarized operational experiences from 155 large-scale heat pumps, which included heat pump characteristics, applications and performance indicators. They developed a framework to assess economic and ecological break-even temperature lifts for heat pump industrial integration. Arpagaus et al. [16] provided an overview of high-temperature heat

* Corresponding author.
E-mail address: jojap@mek.dtu.dk (J.J. Aguilera).

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Nomenclature

Abbreviations

BHS	building heating supply
CFC	chlorofluorocarbons
COP	coefficient of performance
CPR	capacity and/or performance reduction
DA	defrosting application
DCP	district cooling
DH	compressor damage
FDD	fault detection and diagnosis
GWP	global warming potential
HFC	hydrofluorocarbons
HP	heat pump
HVAC	heating, ventilation and air-conditioning
HX	heat exchanger
NS	not specified information outdoor air
OA	process heat
RL	refrigerant leakage
SHX	source heat exchanger
SSD	system shutdown

pumps, where 20 systems available in the market were described. They characterized the theoretical and experimental performance of high-temperature heat pumps, focusing on the operational challenges from experimental studies.

A number of studies focused on large-scale heat pumps in Scandinavian countries. Averfalk et al. [17] provided a summary of experiences from Swedish large-scale heat pumps operating in district heating systems. The authors described that electrical motors in such heat pumps may be affected by mechanical wear when operated dynamically to accommodate large shares of variable power. Aguilera et al. [18] performed a survey study where operators, manufacturers and maintenance providers of large-scale ammonia heat pumps characterized technical challenges that occur in those systems during operation. This study indicated that the most critical faults described by large-scale heat pump operators were identified in the compressor, evaporator and condenser as well as source heat exchangers and intake filters. Moreover, the authors identified a potential to develop frameworks that leverage existing supervisory systems for large-scale heat pumps to identify abnormalities in their operation.

Fault detection and diagnosis (FDD) is the task of timely recognizing the inability of an element to perform a required function, localizing it and identifying its causes [19]. FDD methods applicable for heat pumps and refrigeration systems have been assessed in previous review studies. Two studies [20,21] focused on faults in supermarket refrigeration systems as well as detection and diagnosis methods applicable for such systems. Other studies [22–25] presented a review of FDD methods for heating, ventilation and air-conditioning (HVAC) systems, where heat pumps are used for space conditioning applications. Mirnaghi and Haghighat [26] performed a review of FDD methods applicable for large-scale HVAC systems. The authors suggested that data-driven methods are accurate, less costly and time consuming than model-based methods, can adapt to different operating conditions and leverage existing sensing devices.

Some of the faults occurring in large-scale heat pumps can also be observed in other vapour compression systems, such as refrigeration systems. Other faults are heat pump specific, especially faults related to the heat source, e.g. evaporator fouling or clogging of source stream filters. Compared to small-scale heat pumps for domestic heat supply, large-scale heat pumps typically have a higher level of complexity, higher reliability requirements as well as a larger number of components. Because of these differences, it makes sense to focus on faults occurring in large-scale heat pumps to derive recommendations for the improvement of the operation of existing and future heat pump systems.

To the best of the authors' knowledge, none of the articles found in literature provide an overview of common faults that may affect large-scale heat pumps, where different system characteristics and boundary conditions are described. Moreover, there is no publicly available review article that collected and contrasted fault specifications described in large-scale heat pumps during their operational life. The aim of the present study is to characterize faults that were described in large-scale heat pumps in operation, regarding potential causes, implications, prevention or mitigation strategies as well as detection and diagnosis methods.

First, Section 2 describes the methods used in the present literature review. Section 3 introduces case studies where faults were identified in large-scale heat pump systems. The most frequently identified faults are described in Section 4. The discussion is presented in Section 5. Finally, the main conclusions are provided in Section 6.

2. Methods

The publications included in this review study were compiled through an extensive search in digital libraries, search engines and journal web pages such as Web of Science, Google Scholar, Science Direct, Scopus, the International Institute of Refrigeration, the in-house libraries of R&D institutes, and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). The method "reference by reference" was also applied to find relevant studies. The following procedure was employed throughout the review:

- **General topic research and evaluation:** Research and technical publications that described large-scale heat pumps in operation (case studies hereafter) and that identified faults in such systems, were summarized. The keywords applied were: "heat pump" (standalone or in combination with "large-scale", "large", "industrial", "high temperature", "district heating", "sewage", "air source", "geothermal", "seawater", "excess heat", "solar"), "fault" (standalone or in combination with "mechanism", "incident"), "operation" (standalone or in combination with "experience", "challenge").
- **Subtopic research and evaluation:** After identifying faults affecting large-scale heat pumps, articles describing the characteristics of such faults were reviewed. Faults were characterized according to potential causes, detection and diagnosis methods, implications on the system performance, and prevention or mitigation strategies. The keywords applied were: "fault" (standalone or in combination with "mechanism", "impact", "detection", "diagnosis", "mitigation", "prevention"), "refrigeration" (standalone or in combination with "fault detection"), "fouling", "frosting", "leakage", "vibrations", "control", "noise", "corrosion", "monitoring".
- ***Description and analysis of topic and subtopic research:*** An analysis of the reviewed case studies was performed, where fault characteristics and different types of FDD methods were assessed.

3. Case studies on large-scale heat pumps

Faults that can affect the operation of large-scale heat pumps were analysed based on documented case studies. The term *fault* applied in this study corresponds to the state of an item characterized by its partial or complete inability to perform an expected function, as defined in EN 13306:2017 [19]. The case studies included in this review corresponded to electricity-driven heat pumps based on a vapour compression cycle whose faults during operation were documented. As presented in Tables 1–4, 53 case studies were found in the literature. These were characterized by refrigerant type, location, nominal capacity, heat sink and source, and compressor type. The inlet and outlet temperature from the sink and source streams were also added in the description as average design values. The case studies were divided into four groups (A

Table 1
General characteristics of the case studies using R-717.

Index	Refrigerant	Location [−]	Reference Sources [−]	Nominal Capacity [MW]	Heat Source/Sink [−]	Start-up Year [−]	Compressor Type [−]	Source Inlet/Outlet Temp. [°C]	Sink Inlet/Outlet Temp. [°C]
A1	R-717	Drammen, Norway	[28,29]	13.0	seawater/DH	2011	screw	8/4	60/90
A2	R-717 (R-22)	United Kingdom	[29,30]	1.2	excess heat/PH	2010	screw	5/0	10/60
A3	R-717	France	[29]	6.4	excess heat/PH	2011	screw	NS	25/65
A4	R-717	Grønnesby, Norway	[31]	4.8	groundwater/DH	1998	NS	30/20	40/70
A5	R-717	Lausanne, Switzerland	[32]	3.9	freshwater/DH	1986	screw	7/4	35/50
A6	R-717	Skjern, Denmark	[33]	4.0	excess heat/DH	2012	screw	55/30	37/70
A7	R-717	Vejen, Denmark	[33]	1.1	flue gas/DH	2013	reciprocating	40/20	45/55
A8	R-717	Høje Taastrup, Denmark	[33]	2.3	DC/DH	2016	screw	−1/−8	48/75
A9	R-717	Rødkærsbro, Denmark	[33]	1.6	sewage water/DH	2017	reciprocating	22/5	35/70
A10	R-717	Kalundborg, Denmark	[33,34]	10.0	sewage water/DH	2017	reciprocating	25/15	57/72
A11	R-717	Broager, Denmark	[33]	4.0	groundwater/DH	2016	reciprocating	11/2	35/75
A12	R-717	Copenhagen, Denmark	[35]	0.8	groundwater/DH	2019	reciprocating	10/4	35/70
A13	R-717	Sig, Denmark	[34]	0.8	OA/DH	2017	reciprocating	NS	34/64
A14	R-717	Germany	[36]	2.4	sewage water/DH	2019	NS	NS	NS
A15	R-717	Bodø, Norway	[37]	3.8	seawater/DH	1992	reciprocating	7/3	60/68
A16	R-717 + R-12*	Helsingborg, Sweden	[38]	1.3	cold storage/DA	1985	screw	NS	NS
A17	R-717 + R-12*	Copenhagen, Denmark	[39]	0.5	excess heat/PH + BHS	NS	reciprocating + screw	18/NS	NS/65

* System with provision of heating and cooling: Refrigerant in use before the system was converted to R-717.

Table 2
General characteristics of the case studies using R-134a.

Index	Refrigerant	Location [−]	Reference Sources [−]	Nominal Capacity [MW]	Heat Source/Sink [−]	Start-up Year [−]	Compressor Type [−]	Source Inlet/Outlet Temp. [°C]	Sink Inlet/Outlet Temp. [°C]
B1	R-134a	Bergen, Norway	[42]	0.5	seawater/DH	1993	NS	7/NS	NS/65
B2	R-134a	Melhus, Norway	[43]	0.4	groundwater/DH	2003	NS	7/4	NS
B3	R-134a	Sollentuna, Sweden	[44]	5.0	groundwater/DH	1992	centrifugal	8/2.5	60/80
B4	R-134a	Dalian, China	[45]	0.8	sewage water/ BHS	NS	screw	8/4	40/45
B5	R-134a	Oslo, Norway	[46]	18.4	sewage water/DH	2006	centrifugal	10/6	60/90
B6	R-134a (R-12)	Stokmarknes, Norway	[47]	0.8	seawater/BHS	1987	reciprocating	7/6	NS/65
B7	R-134a (R-500)	Stockholm, Sweden	[40]	25.0	sewage water/DH	1986	centrifugal	NS	NS
B8	R-134a (R-22)	Stockholm, Sweden	[48]	30.0	sewage water/DH	1986	NS	NS	NS
B9	R-134a	Stockholm, Sweden	[49]	50.0	flue gas/DH	NS	NS	NS	NS
B10	R-134a*	Stockholm, Sweden	[50]	36.0	DC/DH	NS	NS	NS	NS
B11	R-134a*	Västerås, Sweden	[51]	15.0	sewage water + DC/DH	1993	NS	NS	NS
B12	R-134a	Rya, Sweden	[52]	160.0	sewage water/DH	NS	NS	12/3	45/80
B13	R-134a	Stockholm, Sweden	[53]	12.0	freshwater/DH	NS	NS	NS	NS

* System with provision of heating and cooling: Refrigerant in use before the system was converted to R-134a.

to D) depending on the type of refrigerant used, namely R-717 (A), R-134a (B), R-12 and R-22 (C), and other refrigerants (D). Information that was not provided in the case studies was categorized as not specified information (NS).

3.1. Systems using R-717

Ammonia (R-717) is a widely used refrigerant because of its excellent thermodynamic properties and low cost [27]. As seen in Table 1, the largest fraction of ammonia large-scale heat pumps (13 out of 17 systems) were applied for district heating (DH) supply. Ammonia systems were also applied for the provision of process heat (PH) and building heat supply (BHS). One case study (A2) was indicated to use R-22 before it was retrofitted to use ammonia.

3.2. Systems using R-134a

The HFC refrigerant R-134a has been used as a replacement of CFC refrigerants like R-12 in different refrigeration and heat pump applications due to its lower environmental impact and similar thermodynamic

Table 3
General characteristics of the case studies using R-12 and R-22.

Index	Refrigerant	Location [–]	Reference Sources [–]	Nominal Capacity [MW]	Heat Source/Sink [–]	Start-up Year [–]	Compressor Type [–]	Source Inlet/Outlet Temp. [°C]	Sink Inlet/Outlet Temp. [°C]
C1	R-22	Oestersund, Sweden	[54]	11.0	sewage water/DH	1984	centrifugal	8/2	60/72
C2	R-22	Budva, Montenegro	[55]	0.9	seawater/BHS	1984	reciprocating	15/10	45/55
C3	R-12*	Södertälje, Sweden	[56]	0.3	ice rink/DA	1980	reciprocating	28/21	45/56
C4	R-12	Falun, Sweden	[57]	1.3	sewage water/DH	1983	screw	5/2	55/70
C5	R-12	Motala, Sweden	[58]	4.5	freshwater/DH	1985	centrifugal	NS	65/75
C6	R-12	Ejby, Denmark	[59]	1.3	freshwater + OA/DH	1984	reciprocating	12/NS	38/60
C7	R-12	Kungälv, Sweden	[60]	3.2	OA/DH	1984	screw	NS	NS
C8	R-12	Bjuv, Sweden	[61]	2.5	groundwater/DH	1983	centrifugal	9/2	55/70
C9	R-12	Ålesund, Norway	[62]	6.0	seawater/DH	1989	centrifugal	NS	57/67
C10	R-12	Skøyen, Norway	[63,64]	2.1	sewage water/DH	1983	screw	10/NS	65/85
C11	R-12	Lidingö, Sweden	[65–67]	11.0	seawater/DH	1982	centrifugal	11/NS	55/70
C12	R-12	Lidingö, Sweden	[66,67]	3.0	seawater/DH	1983	screw	11/NS	55/63
C13	R-12	Helsinki, Finland	[68]	6.8	excess heat/DH	1984	centrifugal	38/30	50/71
C14	R-12	Sala, Sweden	[59,65,69]	3.3	sewage water + freshwater/DH	1981	screw	8/2	55/63
C15	R-12	Loudden, Sweden	[65,67]	5.5	sewage water/DH	1982	centrifugal	17/NS	NS
C16	R-12	Uppsala, Sweden	[65,67]	39.0	sewage water/DH	1982	centrifugal	13/8	52/60
C17	R-12	Visby, Sweden	[65,67,70]	11.0	sewage water + seawater/DH	1983	screw	11/9	55/80
C18	R-12	Gothenburg, Sweden	[71]	1.2	ice rink + OA/DH	1982	screw	NS	55/90

* System with provision of heating and cooling.

Table 4
General characteristics of the case studies using R-114, R-500 and R-410A.

Index	Refrigerant	Location [–]	Reference Sources [–]	Nominal Capacity [MW]	Heat Source/Sink [–]	Start-up Year [–]	Compressor Type [–]	Source Inlet/Outlet Temp. [°C]	Sink Inlet/Outlet Temp. [°C]
D1	R-114	Ontario, Canada	[72]	0.5	excess heat/PH	1982	NS	41/37	37/52
D2	R-114	Quebec, Canada	[72]	0.4	excess heat/PH	1982	centrifugal	35/32	29/72
D3	R-500 + R-12	Belledune, Canada	[72]	0.2	excess heat/BHS	1982	reciprocating	38/36	37/71
D4	R-410A*	Leicester, United Kingdom	[73]	0.4	geothermal heat/BHS	2010	scroll	NS	50/55
D5	R-500*	Sandvika, Norway	[74]	13.2	sewage water/DH	1988	centrifugal	13/5	60/85

* System with provision of heating and cooling.

properties [40]. The largest share of heat pumps using R-134a shown in Table 2 (11 out of 13 systems) were employed for district heating supply and building heat supply. Three systems (B6, B7 and B8) were described to be reconverted from CFC refrigerants to R-134a.

3.3. Systems using R-12 and R-22

As seen in Table 3, heat pumps using CFC refrigerants such as R-12 and R-22 were put into operation before 1990. This occurred before CFC refrigerants were phased out as agreed in the Montreal Protocol [41]. The largest share of those systems (12 out of 18 systems) were connected to district heating networks, whereas other systems were used for building heat supply and defrosting applications (DA).

3.4. Systems using other refrigerants

The case studies shown in Table 4 used CFC refrigerants R-500, R-114 and R-410A. Three systems (D1, D2 and D3) corresponded to heat pumps used for different industrial applications in Canada. In those systems, excess heat was recovered and used for process heat and building heat supply. The other two systems (D4 and D5) were simultaneously used for heating and cooling supply, using geothermal heat and sewage water as heat sources, respectively.

4. Fault characterization

This section provides a description of the faults diagnosed in the case studies presented Section 4. A total of 129 faults were identified in case studies of large-scale heat pumps, which were divided into 48 types of faults. It was considered that faults occurred either at a system level or at a component level. The components considered were the compressor, condenser, control and electronics, lubrication system, source stream, evaporator and source heat exchanger (SHX). The evaporator and SHX were defined as a single component group since the faults identified in such components presented similar characteristics (e.g. faults affecting heat exchangers on the source stream side such as fouling, frosting or corrosion). As shown in Fig. 1, a larger number of faults were identified in the compressor (32) and in the evaporator and SHX (29), whereas the

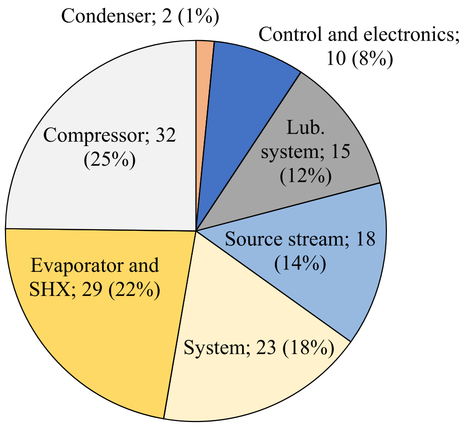

Fig. 1. Number of faults related to each component and to the entire system.

fewest were described in the condenser (2). Fig. 2 indicates that over half of the faults identified in the evaporator and SHX corresponded to fouling, which was the most common type of fault described in the case studies. The second most frequent fault was refrigerant leakage.

The types of faults that were most frequently described in the different heat pump components were characterized based on information provided from the case studies and from the literature. The components included in the characterization were the compressor, evaporator and SHX, lubrication system, condenser as well as control and electronics. A total of 13 types of faults were described and presented in the following sections of this study, which included potential root causes, FDD methods, and fault implications on the system performance. Such implications included system shutdown (SSD), capacity and/or performance reduction (CPR), refrigerant leakage (RL), and compressor damage (DCP). Moreover, strategies that can be applied to prevent or mitigate fault occurrence were also incorporated in the description.

4.1. Compressor

Among the faults attributed to the compressor, the most frequent one was the presence of excessive noise and vibrations. This fault was identified in seven case studies, as seen in Table 5. Other less frequent faults that were described in three (or more) systems were breakdown of the mechanical transmission system, defective capacity control valves, defective electric motor and defective shaft seals.

4.1.1. Excessive noise and vibrations

Operational challenges related to noise and vibrations can be time consuming and expensive, as mentioned in Ref. [75]. As seen in Table 5, excessive noise and vibrations were attributed to the development of constructive interference between the compressor and economiser or due to highly vibrating slide valves, which are used for part load operation in screw compressors. Noise and vibrations may not be the root cause of a faulty operation. Thereby, a number of the systems where such faults were described might have been affected by unidentified faults in the compressor. Excessive vibrations were described to affect different components negatively (e.g. gears, bearings, pipes, valves, and oil pumps) and potentially lead to refrigerant leakage or even to a shutdown of the heat pump (see Table 5). A report that gathered the operational experiences from heat pumps for district heating supply [76], mentioned that heat pumps installed in residential areas can be difficult to operate since vibrations from the compressor can propagate in the ground as low-frequency noise. Wachel and Tison [77] described that excessive vibrations and noise generally occur when a mechanical natural frequency of a piping section or the compressor manifold is excited by a pulsation source. This fault mechanism was characterized in screw compressors [78–80] and reciprocating compressors [81–83], which can generate high levels of pressure pulsation. High vibration levels can also originate from defective bearings, misalignment of the compressor and motor, curved axles, eccentricity of rotating parts and friction [14]. Johnson [84] investigated the characteristics of vibrations coming from the compressor of an air-conditioning chiller with 4.4 MW of cooling capacity. Johnson used portable accelerometer sensors mounted on bearing housings to measure vibrations, characterizing their amplitude and frequency to detect anomalies. Another study [85] applied stationary vibration sensors to verify the existence of excessive vibrations from a heat pump compressor.

Potential solutions to excessive vibrations and noise described in the case studies include the replacement of the entire compressor unit or the installation of a resonator to reduce vibrations and noise (see Table 5). The use of Helmholtz resonators were suggested in different studies [80,83,86,87] to attenuate pressure pulsations originated from the compressor. This type of resonator has a chamber where standing waves

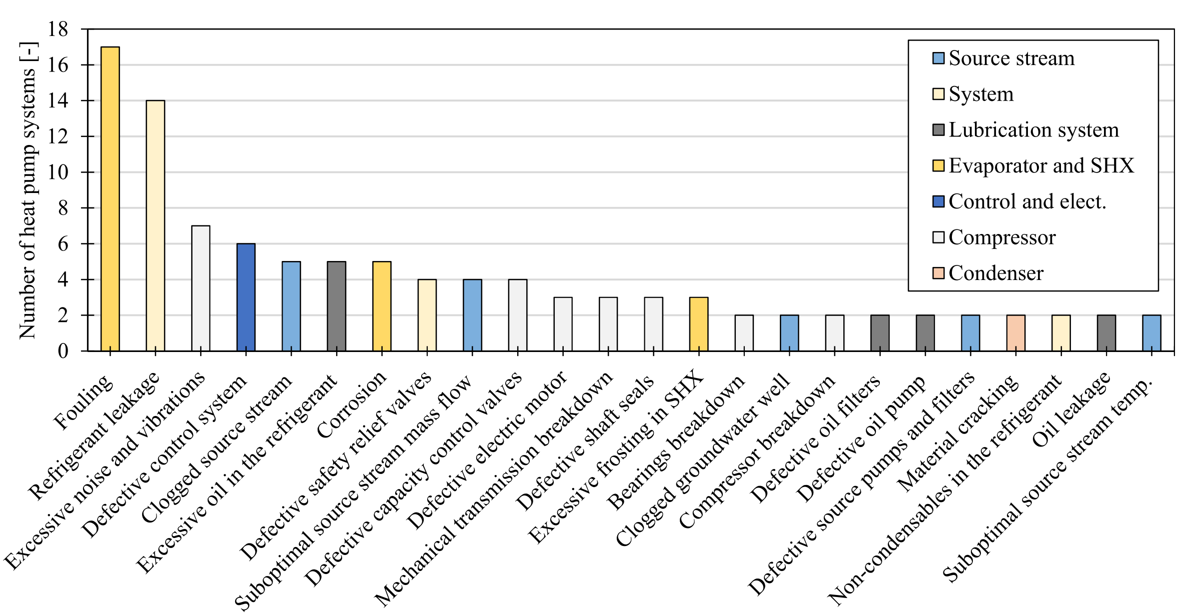

Fig. 2. Frequency of faults that were observed in more than one heat pump system.

Table 5
Characteristics of faults described in the compressor. SSD: System shutdown, CPR: Capacity and/or performance reduction, RL: Refrigerant leakage (RL), DCP: Compressor damage.

Fault	Case studies [–]	Potential causes [–]	Detection [–]	Implications [–]				Prevention or mitigation [–]
				SSD	CPR	RL	DCP	
▪ Balance piston corrosion	(A1)	▪ Ammonia/oil mixture corroding balance pistons in screw compressor (A1)	NS					▪ Installation of plastic balance pistons (A1)
▪ Bearings breakdown	(C15)(C17)	▪ Excessive vibrations (C17)	NS					NS
▪ Breakdown of the mechanical transmission system	(A1)(C15)(C17)	▪ Fatigue failure of the thrust system induced during assembly (A1) ▪ Broken gears without specified cause (C15) or caused by excessive vibrations (C17)	▪ Breakdown incident (A1)	X			X	NS
▪ Condensation in the suction line	(A12)	▪ Fast ramping operation of the HP (A12)	▪ Wall temperature of the suction line below saturation temperature of ammonia (A12)				X	▪ Increase ramp-up times (A12) ▪ Preheating of the suction line (A12)
▪ Compressor breakdown	(C16)(D5)	▪ Human-induced error in the compressor control during maintenance (D5)	▪ Breakdown incident (D5)	X		X	X	▪ Installation of a new compressor (D5)
▪ Defective shaft seals	(B13)(C11)(C18)	▪ Excessive vibrations (C18)	NS	X		X		NS
▪ Defective capacity control valves	(A1)(A15)(C10)(C14)	▪ Ammonia/oil mixture causing pitting wear on slide valves (A1) ▪ Poor lubrication (A15)(C10) ▪ Excessive vibrations from the valves (C14)	▪ Oil leakage (A15) ▪ Breakdown incident (C14)	X	X	X	X	▪ Installation of valves compatible with the oil in use (A15)(C10) ▪ Installation of suction throttling control (C14)
▪ Excessive noise and vibrations	(A1)(A2)(A3)(A11)(C14)(C17)(C18)	▪ Constructive interference between economisers and compressors (A1) ▪ Vibrations from capacity control slide valves (C14)	▪ Noticeable noise (A1)(A11) ▪ Breakdown incident (C14)	X	X	X	X	▪ Installation of a resonator (A1) ▪ Installation of a new compressor and capacity control system (C14)
▪ Excessive mechanical wear	(A5)(A15)	NS	▪ Decreased isentropic efficiency and refrigerant mass flow (A5)		X		X	NS
▪ Fouling of compressor cooler	(C8)	▪ Material deposition from groundwater used for compressor cooling (C8)	NS					NS
▪ Defective electric motor	(C2)(D1)(D3)	▪ Suboptimal manufacturing (D1) ▪ Voltage drops in the electricity network (C2)	▪ Detected during maintenance inspection (D1)	X			X	▪ Installation of new motors (D1)(D3) ▪ Reparation of motor (C2)

interfere with the vibrations from the entrance of the chamber, reducing the noise and vibration levels [75]. The installation of nozzles in the manifold of compressors is another potential mitigation strategy that was applied in Ref. [79]. The authors of that study described that the flow restriction caused by nozzles leads to a dissipation of energy and pressure pulsations from the compressor, which can attenuate the level of noise and vibrations.

4.1.2. Defective shaft seals

Shaft seals prevent the working fluid inside the compressor to be released to the atmosphere. Schwerdtfeger [88] stated that the performance of shaft seals is characterized by three parameters: lifespan under design specifications, leakage behaviour and frictional torque. In the reviewed case studies, excessive vibrations were indicated as a potential cause of defective shaft seals. Moreover, faulty shaft seals were described as possible contributors to refrigerant leakage and system shutdown incidents (see Table 5). Storesund [14] mentioned that it is common that shaft seals need to be replaced more frequently than the scheduled interval for maintenance services in large-scale heat pumps. Here, it was indicated that the lifetime of shaft seals can be lower than expected due to suboptimal oil selection and frequent start/stop operation of the compressor, particularly due to unplanned stops of the system. According to Ref. [89], shaft seals exposed to high temperatures can break due to thermal expansion, depolymerise or become brittle, whereas high pressures may cause extrusion or stress failure. They proposed to improve seal design and material selection when operating at high pressure and temperature conditions. Granryd et al. [90] indicated that the thin oil film that is normally present between the seal surfaces can disappear after long stand-still periods. This lack of lubrication can damage the seals when the system is started up again. The authors recommended to rotate the compressor periodically for short intervals, even during off-periods, to keep the seals lubricated. Refrigerant gas detectors can be used to identify leakage that may be originated from defective shaft seals [88]. However, stationary refrigerant gas sensors commonly used in heat pump applications cannot identify the exact source of a leak [91]. As a solution to this, one study [92] used ultrasonic detection systems to detect the collapse of the lubricating film between surfaces that may cause a failure of shaft seals.

4.1.3. Defective capacity control valves

Three of the four systems with faulty capacity control valves (A1, C10 and C14) were equipped with screw compressors. According to Stosic et al. [93], the motion of slide valves for capacity control in screw compressors leads to suction volume variations that can result in additional thermodynamic losses when operating at part load. In C14, it was described that excessive vibrations originated from the slide valves were identified when the heat pump was operating at part load conditions. This fault caused defective part load operation, fractured pipes and valves as well as system shutdown. Defective slide valves were described in A1 to be affected by pitting corrosion originating from the mixture between ammonia and oil. Faulty capacity control valves were also identified in the high-pressure reciprocating compressors from A15. In this case study it was indicated that the existing housing of a magnetic valve was not compatible with the synthetic oil used, leading to oil leakage.

In C14, slide valves were replaced by a suction throttling capacity control mechanism. This mechanism operated by increasing the pressure drop at the compressor inlet, which reduced the vibrations when operating at part load conditions. In two case studies (A10, C10) it was suggested that the design of capacity control valves should be compatible with the oil in use to mitigate lubrication-related faults. Another alternative to avoid the negative effects of capacity control valves could be the use of variable-speed capacity control, suggested as an energy efficient alternative for reciprocating compressors [94] and screw compressors [93].

4.1.4. Defective electric motors

Faulty electric motors were described in three cases studies (C2, D1 and D3), all of which proposed poor manufacturing and voltage drops in the electricity grid as potential causes (see Table 5). This fault was indicated in the case studies to potentially cause a shutdown of the system and compressor damage. Storesund [14] described that in large-scale heat pump applications, induction motors are the preferred option when the required nominal power uptake is up to 8 MW. For a higher nominal power uptakes, the author indicated that synchronous motors are often used and thereby such motors are exposed to higher loads when the heat pump is started up. As a result, elements like rotor keyways or winding insulation can be damaged due to the high temperatures reached during start-up of synchronous machines. Asad et al. [95] stated that the most frequent mechanical fault in induction motors is cracking of the rotor bar, whereas the most common electrical fault is unbalanced supply voltage. They described three common methods to detect mechanical faults in electric motors, namely mechanical vibration detection [96], finite element analysis [97] and motor current signature analysis [98]. The latter may also be applied to detect electrical faults, which could also be identified by using signals from relays and switches [95]. Kudelina et al. [99] observed that two-phase soft starters in heat pump induction motors caused current imbalance and harmonic components in the motors. Consequently, the insulation inside the motors melted, leading to a thermal breakdown process. The starter mechanism also caused excessive vibrations that deteriorated the lubricant layer on the shaft bearings. Kudelina et al. suggested to install three-phase soft starters for induction motors to avoid motor burnout caused by an inadequate start-up of the system.

4.1.5. Mechanical transmission breakdown

The mechanical transmission system involves components that enable the power transmission between electric motors and compressors such as gears and thrust elements. In the case study A1, the bolts holding the thrust bearing were over-torqued during installation, which was described to induce a fatigue failure after 400 h of operation. In systems C15 and C17, several gear breakdowns were identified, where one of the potential causes was attributed to be high vibrations in the compressor. In the case studies where mechanical transmission breakdown was identified, mentioned system shutdown and compressor damage as possible outcomes of such a fault. Storesund [14] indicated that transmission components such as rotor shafts can be worn during assembly or disassembly, which may limit their lifespan. The author also indicated that imbalanced shafts can break due to fatigue and cause vibrations that may affect other components negatively such as bearings and shaft seals. Therefore, vibration monitoring strategies such as those used in Refs. [85,96] coupled to specific mechanical elements can be applied to monitor the status of mechanical transmission components.

4.2. Evaporator and source heat exchanger (SHX)

All the faults described in evaporators and SHXs from the case studies presented in Section 4 where attributed to the source stream side of the HXs, as shown in Table 6. SHXs were only present in systems with a secondary refrigerant or brine loop installed between the source stream and the evaporator. The most frequent fault in SHX and evaporators was fouling, followed by corrosion and excessive frosting.

4.2.1. Fouling

Fouling was described to affect the operation of the case study heat pumps extracting heat from sewage water (A9, A10, A14, B4, B5, B7, C1, C10, C14, C15, C17), seawater (C17), freshwater (A5, C14), groundwater (B2, C8), geothermal heat (D4) and excess heat (A5, D2). Here, fouling is defined as the undesirable accumulation of deposits on a heat transfer surface. This fault may affect the thermal performance and pressure drop across HXs, and increase the probability of shutdown for cleaning processes [100]. As indicated in Table 6, fouling was frequently identified in large-scale heat pumps by observing a cumulative reduction of the heating capacity. However, non-intrusive sensing techniques may be applied to identify the development of fouling in operating HXs. Such techniques include direct weighing of HXs [101], heat transfer estimations [102] and pressure drop estimations [103]. Studies have also estimated the thickness of the deposited material by means of ultrasound measurements [104] or infrared measurements [105]. According to ASHRAE RP-1275 [106], the UA-value of an evaporator is a useful indicator to identify fouling in heat exchangers. However, the UA-value might also be affected by over-charge or under-charge of refrigerant as well as variations in the source stream mass flow. Gjengedal et al. [43] detected fouling from a ground source heat pump by measuring the pressure difference between the evaporator inlet and outlet in the source stream. Their framework used a step-test procedure to decouple the influence of the pressure drop variation caused by fouling from the variation attributed to a variable-speed pump in the source stream. Pelet and Favrat [32] identified the presence of fouling in the evaporator of a lake-water source heat pump by observing an increase of the pinch-point temperature difference. The existence of fouling was also detected in Refs. [36,45,107], by observing an increase of the thermal resistance of the evaporator and/or a COP and capacity reduction.

The most frequently described mitigation strategy for evaporator fouling is the use of cleaning-in-place (CIP) systems, which enables to clean heat transfer surfaces automatically without the need to disassemble a HX. Awais and Bhuiyan [108] indicated that variables such as flow velocity, bulk temperature and particle concentration in the source stream as well as roughness of the heat transfer surface, influence significantly the deposition process. A higher flow rate leads to an increase of shear stress along the heat transfer surface, decreasing the fouling resistance and enhancing the heat transfer performance at higher pressure drops. Awais and Bhuiyan also stated that a higher concentration of impurities increases particle deposition due to the fouling solution reaching supersaturated levels. Moreover, low velocity regions on the heat transfer surface were observed to be more sensitive to develop fouling.

4.2.2. Corrosion

The metal surface of a HX can react chemically with some fluids and become corroded. This type of fault was described in systems using heat sources such as excess heat (with humid air as working medium) (A6), sewage water (A10 and C17), freshwater (C5) and seawater (C11 and C17). As shown in Table 6, potential causes of corrosion included the use of inappropriate manufacturing techniques or specific design considerations of HXs, high chlorine content in the treated sewage water and the air stream with high humidity from a paper factory. Corrosion was indicated to be detected after HXs were cracked, causing a leakage of refrigerant to the atmosphere (C11) or to a secondary brine loop (C5). Bott [109] described that the products from a corrosion process can deposit on the heat transfer surface and lead to fouling. Kiessling and Hägerstedt [110] identified failure mechanisms in tube HXs for large-scale heat pumps. Their survey study indicated that tube HXs with

Table 6
Characteristics of faults described in the evaporator and source HX. SSD: System shutdown, CPR: Capacity and/or performance reduction, RL: Refrigerant leakage (RL), DCP: Compressor damage.

Fault	Case studies [−]	Potential causes [−]	Detection [−]	Implications [−]				Prevention or mitigation [−]
				SSD	CPR	RL	DCP	
■ Corrosion	(A6) (A10) (C5) (C11) (C17)	■ Humid air as well as oil and grease residues from a paper factory (A6) ■ High chlorine content in treated sewage water (A10) ■ Steel tubes used in the evaporator not able to withstand corrosion (C5) ■ Manufacturing techniques (C11)(C17)	■ Alarm from the control system caused by refrigerant in the brine circuit (C5) ■ Refrigerant leakage (C11)	X		X		■ Sprinkle the SHX periodically with distillate water (A6) ■ Installation of a SHX made with a higher grade steel (A10) ■ Installation of titanium tubes in the evaporator and a cathodic protection system (C5) ■ Replacement of the evaporator plates (C11)(C17)
■ Defective CIP system	(D1) (C10)	■ Defective thermistor in the fouling guard cleaning system (D1)	■ Alarm from the control system regarding the faulty thermistor (D1)	X				■ Replacement of thermistor (D1) ■ Reparation of the CIP system (C10)
■ Fouling	(A5)(A6) (A9) (A10) (A14)(B2) (B4)(B5) (B7) (C1)(C8) (C10) (C14) (C15) (C17) (D2)(D4)	■ Deposition of material from a paper mill (A6) ■ Deposition of material from sewage water (A9)(A14)(B4)(B5)(C1)(C15) ■ Deposition of black material on the refrigerant side after a conversion of refrigerant (B7) ■ Deposition of material from groundwater (B2)(C8) ■ Defective CIP system (C10) ■ Deposition of clay minerals from freshwater (C14) ■ Deposition of algae (C17)(D2)	■ Heating capacity reduction (A14)(C14)(C15) ■ Increase in the pressure drop of the source stream (B2) ■ Inspection during maintenance after refrigerant conversion (B7)	X	X			■ Installation of a CIP system (A6)(A9)(C10) ■ Retrofit of the filtering system (A14) ■ Cleaning of the SHX with an organic acid treatment (B2) ■ Reversing the flow of the source stream (B5) ■ Repairs of the CIP system (C10) ■ Application of freezing water on the evaporator surface (C14) ■ Modification of cleaning measures applied in the evaporator (C14)(C15)(C17)(D2)
■ Excessive frosting	(A13) (C3)(C7)	■ Late activation of defrosting system (A13) ■ Excessive frost on the fan blades of the SHX caused by water leakage during stand-still (C3)	■ Performance reduction (A13)		X			■ Improvement of the defrosting control strategy (A13)(C3) ■ Replacement of the fans and the motor (C3)
■ Excessive noise	(A13)	■ Fan operation of the SHX placed outdoors (A13)	■ Noticeable noise (A13)					NS
■ Pressure increase during stand-still	(A6)	■ Continuous operation of the paper factory used as heat source (A6)	NS					■ Improvement of the control strategy (A6)

copper alloy tubes can last a longer period without developing corrosion-related problems compared to carbon steel. Moreover, the authors recommended to use titanium-made tubes for HXs exposed to difficult environments such as geothermal water. According to ASHRAE [111], copper-made tubes should be avoided in ammonia HXs, as they may develop corrosion when ammonia is exposed to water. Cracks in HXs resulting from a corrosion process or other fault mechanisms can be detected by using eddy current measurements, as indicated in Refs. [14, 110]. Eddy current testing is a non-destructive testing method that can be applied to identify cracks in metals by using electromagnetic induction [112].

4.2.3. *Excessive frosting*

The formation of frost on the surface of air-source HXs can lead to a reduction of the performance and heating capacity of heat pump systems. Excessive frosting was the third-most frequent fault identified in evaporators and SHXs, as indicated in Table 6. According to the reviewed case studies, the potential causes of excessive frosting were a late activation of the defrosting system and an accumulation of water in air-source HXs during stand-still. Yao et al. [113] observed that at a constant ambient air temperature, a higher relative humidity leads to increased frost formation and to shorter defrosting intervals. They also identified that at a constant air relative humidity, frost formation was higher at a higher air temperature than at a low air temperature, as long as the air temperature is below a specific limit in which frost is likely to form. This is expected since the air humidity ratio is higher at higher air temperatures for constant relative humidity. Air-source heat pumps that are prone to frosting require periodic defrosting to minimize the impact of frost formation on the performance of the system. However, no studies were found in the literature that describe specific defrosting methods applied to large-scale air-source heat pumps. Song et al. [114] provided a review of frost retarding and defrosting methods for residential and commercial air-source heat pumps. They characterized five types of defrosting methods, namely compressor shutdown defrosting, electric heating defrosting, hot water spraying defrosting, hot gas bypass defrosting, and reverse cycle defrosting. Regardless of the type of defrosting method applied, Song et al. suggested that a defrosting operation can be initiated based on time intervals (usually every 60 min–90 min of frosting time) or demand start defrosting. Demand defrosting involves detecting the presence of frost by using methods such as determining the thermal conductivity of ice [115], determining the refrigerant superheat temperature difference [116], measuring the fan power uptake [117] or estimating the pressure drop across the evaporator [118].

4.3. *System*

System faults refer to faults that were not attributed to any specific component or were described to affect multiple components. The most frequent system fault was refrigerant leakage, which was identified in 14 case studies, as shown in Table 7.

4.3.1. Refrigerant leakage

Multiple potential causes were described in the case studies that could lead to refrigerant leakage. Defective safety relief valves, defective shaft seals and corrosion in the evaporator were the most frequent causes (see Table 7). The consequences of refrigerant leakage depend on the type of refrigerant used. EN 378–1:2016 [91] defines that gas-state refrigerant emissions from heat pumps and refrigeration systems should be monitored based on the CO_2 equivalent charge, flammability and toxicity level of the refrigerant. Leakage of CFC and HFC refrigerants is required to be monitored due to the significant environmental consequences when released to the atmosphere. Ammonia is among the refrigerants that need to be monitored due to its high toxicity and flammability [111]. Unidentified refrigerant leakage can significantly reduce the amount of refrigerant charge in heat pump systems and thereby affect their performance. One observational study [119] characterized the effects of charge reduction on the performance of a heat pump with a heating capacity of 125 kW. This study identified that, for constant capacity, a refrigerant charge reduction of 10% led to a relative COP reduction of around 3%, whereas a reduction of 40% in the charge reduced the relative COP by about 45%.

As shown in Table 7, none of the reviewed case studies specified how refrigerant leakage was identified except from its detection once a breakdown incident occurred. The leakage detection systems described in EN 378–1:2016 [91] are able to identify if a leak occurred without necessarily locating the source of the leak. Experimental and simulation results from vapour compression chillers [106,120] indicated operational variables that are sensitive to refrigerant leakage. In such studies, refrigerant leakage led to an increase of the condenser UA-value, a decrease of the refrigerant subcooling and a decrease of the condenser approach temperature. The effect of refrigerant undercharge in an air-source cascade cycle heat pump system was analysed experimentally by Ref. [121]. Here, it was observed that the heating capacity was more sensitive to variations on the high stage charge (R410A), than on the low stage charge (R134a). However, the relationship between refrigerant charge, the COP of the system and the optimal subcooling, depended on boundary conditions such as sink/source stream temperatures and compressor speed.

Several studies focused on the identification of refrigerant leakage in large-scale refrigeration systems by means of data-driven methods. Such studies focused on the detection of refrigerant leakage without the identification of the exact root cause that led to a release of refrigerant to the atmosphere. Some of the methods found more frequently incorporate neural networks [122–126] and/or principal component analysis [106,127–129]. The first corresponds to a subgroup of machine learning that defines a connection between inputs and outputs through an arrangement of nodes or neurons, whereas the second is a method for dimensionality reduction of a dataset based on its variability.

4.3.2. Defective pressure relief valves

Table 7 shows that defective pressure relief valves were the most frequent cause of refrigerant leakage and also the second-most common fault at a system level in the case studies. Pressure relief valves are elements that prevent critical failures of refrigeration systems and heat pumps caused by operating at overpressure conditions [130]. One of the potential causes of defective pressure relief valves indicated in Table 7 was excessive vibrations coming from motors, gears or compressors in system A15, a one-stage ammonia system with screw compressors. In A15, it was observed that the pressure difference in the compressor reached higher values than estimated during the design stage and thereby the valves were opening at lower pressures than desired. In C17, faulty relief valves were detected after the breakdown incident already occurred. Standards like ASHRAE 15–2019 [131] provide guidelines for the installation of pressure relief devices in pressure vessels and positive displacement compressors. However, Reindl and Jekel [132] suggested that pressure relief valves are often installed in other system components like HXs or oil separators, without following specific guidelines for their sizing and selection. They suggested that such design decisions can lead to potential safety risks when high pressure is reached during abnormal operating conditions. Dempster and Elmayyah [133] stated that pressure relief valves exposed to two-phase flows may operate defectively when local two-phase flow conditions were not correctly estimated in their design.

4.4. Lubrication system

The lubrication system includes all the elements that keep the

Table 7
Characteristics of faults described in the system. SSD: System shutdown, CPR: Capacity and/or performance reduction, RL: Refrigerant leakage (RL), DCP: Compressor damage.

Fault	Case studies [−]	Potential causes [−]	Detection [−]	Implications [−]				Prevention or mitigation [−]
				SSD	CPR	RL	DCP	
▪ Defective expansion valve	(B3)	▪ Defective sensors (NS) leading to poor regulation of the expansion valve (B3)	▪ Excessively low evaporation pressure (B3)					▪ Replacement of defective sensors (B3)
▪ Defective safety relief valves	(A15)(B9)(B11)(C17)	▪ Excessive vibrations (C17)	▪ Valves opening for lower differential pressures than expected (A15) ▪ Breakdown incident (C17)	X		X		▪ Replacement of the defective safety relief valve (A15)(B9) ▪ Periodic calibration and monitoring of safety mechanisms (C17)
▪ Non-condensables in the refrigerant	(A5)(A16)	▪ Presence of air leaks in the system (A16)	NS		X			▪ Installation of an air purge and reparation of piping connections (A16)
▪ Refrigerant leakage	(A1)(B8)(B9)(B10)(B11)(B12)(B13)(C5)(C6)(C7)(C11)(C17)(D2)(D5)	▪ Condenser cracking (A1) ▪ Defective safety relief valves (B9)(B11)(C17) ▪ Broken O-ring (B10) ▪ Defective shaft seals (B13)(C11) ▪ Defective gaskets in reciprocating compressor (B13) ▪ Poorly welded pipes (C6) ▪ Corroded evaporator (C5)(C11) ▪ Defective oil separator (C11) ▪ Compressor breakdown (D5)	▪ Breakdown incident (C17)(D5)	X		X		▪ Replacement of defective O-rings and safety relief valves (B9)(B10) ▪ Reduction of service interval (B10) ▪ Installation of titanium-made condensers (C5) ▪ Periodic calibration and monitoring of safety mechanisms (C17)

moving parts of the compressor and motor lubricated. Excessive oil in the refrigerant was the most frequently observed problem in lubrication systems, as shown in Table 8. This fault was attributed to the lubrication system because it corresponds to the undesired lubricant/refrigerant mixture that affects the operation of vapour compression systems. Excessive oil may lead to the deposition of oil on the refrigerant side of heat exchangers, causing oil fouling and a deterioration of the thermal performance of the heat exchangers.

4.4.1. Excessive oil in the refrigerant

In the ammonia heat pump A1, excessive oil was found in the refrigerant as a result of the failure of the coalescer element inside the oil separator. It was described that the coalescer element broke as a result of the mixture between ammonia and oil changing its glass transition temperature and thereby turning it brittle. Excessive oil in the refrigerant was also mentioned to be caused by a defective oil separator in C10, whereas in B3 it was blamed to a faulty check valve in the pipe line between the compressor and the oil tank. In both systems B3 and C10, oil accumulated in the evaporator, which was detected as an abnormal formation of foam. Bandarra Filho et al. [134] provided a review on the characteristics of oil mixed with refrigerants such as R-12, R-22, R-134a and R-717, under flow boiling conditions. According to the authors, there is no agreement among studies on whether the oil-refrigerant mixture causes a decrease or increase on the heat transfer coefficient in HXs. This discrepancy was described to apply mainly at weight-based concentrations of oil equal to or below 3%. However, the review suggested that all studies found an increase of two-phase pressure drops with the addition of oil at any concentration. Oil flow in vapour compression systems can be described by two parameters: oil retention and oil circulation ratio [135]. Oil retention refers to the amount of oil mass that deposits in specific sections of the system (e.g. HXs, pipeline sections), whereas oil circulation ratio corresponds to the mass flow rate ratio between oil and the oil-refrigerant mixture. Experimental studies have determined oil circulation ratios by using Coriolis density flowmeters [136], ultra-violet light detectors [137], ultrasonic sensors [138], photosensors [139] and laser displacement sensors [140]. One study [135] applied high-speed cameras and video processing techniques to experimentally measure the oil circulation ratio and oil retention in different components of a refrigeration system. As a measure to control oil flow, oil separators such as coalescing separators can effectively decrease oil circulation and retention in refrigeration and heat pump systems [141]. However, Pearson [29] indicated that coalescer materials should be selected according to the compressor discharge temperature and pressure to prevent a failure of the separator.

4.5. Control and electronics

Faults in control and electronics include malfunctions that occur in the control and surveillance system, sensor, actuators and electrical connections. A survey study [142] identified that faults in control and electronics were among the most common and costliest faults in heat pump systems during the warranty period. The authors suggested that malfunctions linked to a control unit or sensors may cause component damage and performance degradation. For instance, defective control and/or sensors could lead to the breakdown of air-source evaporators caused by a defrosting process performed incorrectly. Among the case studies included in this review, defective control and surveillance was the most frequent fault related to control and electronics.

4.5.1. Defective control and surveillance

Six case studies were affected by a faulty control and surveillance system, as seen in Table 9. Two systems (C9, D5) were not correctly adjusted to variations in the return temperature from the DH system. Another system using excess heat (D3), had a faulty operation due to variations in the sink stream mass flow, which was also poorly monitored. Applying thermal energy storage units such as water tanks as a complement of heat pumps was proposed by Refs. [18,143,144] to handle variable loads from sink or source streams. This strategy could

Table 8
Characteristics of faults described in the lubrication system. SSD: System shutdown, CPR: Capacity and/or performance reduction, RL: Refrigerant leakage (RL), DCP: Compressor damage.

Fault	Case studies [–]	Potential causes [–]	Detection [–]	Implications [–]				Prevention or mitigation [–]
				SSD	CPR	RL	DCP	
▪ Defective oil filters	(A1)(C12)	▪ Faulty degreasing process during manufacturing leading to a detachment of main filter element (A1)	NS					▪ Installation of an additional filter element (A1)
▪ Defective oil pressure valve	(A15)	▪ Suboptimal manufacturing (A15)	▪ Compressor shutdown shortly after start-up due to high oil pressure (A15)	X				▪ Replacement of the oil pressure valve (A15)
▪ Defective oil pump	(A1)(C6)	▪ Damaged oil pump shaft seals and bearings caused by vibrations from the compressor (A1) ▪ Cavitation in oil pumps (C6)	▪ Premature bearing failure and shaft seal leakage in oil pump (A1)					▪ Modification of the pump mounting arrangement (A1)
▪ Excessive oil in the refrigerant	(A1)(B3)(C10)(D1)(C11)	▪ Broken oil separator caused by ammonia/oil mixture (A1) ▪ Defective check valve between compressor and oil tank (B3) ▪ Suboptimal design of oil separator (C10)	▪ Excessive oil level in the evaporator (B3)(C10)	X				▪ Installation of metal coalescer elements in oil separator (A1) ▪ Replacement of a check valve in a draining pipe (B3) ▪ Replacement of the oil separator (C10)
▪ Fouling of oil cooler	(C8)	▪ Deposition of material from groundwater (C8)	NS					NS
▪ Lubricant dilution	(A1)	▪ Ammonia/oil mixture damaging oil seals (A1)	▪ Damaged oil seals (A1)					▪ Use a lubricant with a higher viscosity grade (A1)
▪ Oil leakage	(A1)(A15)	▪ Defective oil pump caused by excessive vibrations (A1) ▪ Defective capacity control valves in piston compressors (A15)	▪ Oil leakage (A15)					▪ Installation of valves compatible with the oil in use (A15)
▪ Oil pump motor burnout	(A15)	NS	NS					NS

Table 9
Characteristics of faults described in control and electronic components. SSD: System shutdown, CPR: Capacity and/or performance reduction, RL: Refrigerant leakage (RL), DCP: Compressor damage.

Fault	Case studies [−]	Potential causes [−]	Detection [−]	Implications [−]				Prevention or mitigation [−]
				SSD	CPR	RL	DCP	
▪ Defective control and surveillance system	(A15) (B3)(C9) (C10) (D3)(D5)	▪ Defective connection between the main control system and compressor control (A15) ▪ Control system not correctly adjusted to the DH return temperature (C9)(D5) ▪ Imprecise measurements of a highly variable sink stream flow rate (D3) ▪ Intermittent error in the surveillance system caused by defective hardware (C10)	▪ Error signal between control system and compressor control unit (A15) ▪ Shutdown incident (D3) ▪ Suboptimal temperatures in sections of the DH network (D5)	X				▪ Upgrade of the control software (A15)(C9)(D5) ▪ Replacement of the defective hardware (C10) ▪ Relocation of sensors in the sink stream to minimize flow rate variations (D3)
▪ Defective bearing temp. Sensor	(C11)	NS	NS					NS
▪ Defective high voltage switch	(D5)	NS	▪ Breakdown incident (D5)	X		X	X	NS
▪ Defective pressure sensor	(C1)	▪ Leakage from the membrane of a pressure transmitter used for refrigerant level control (C1)	▪ Shutdown incident. Low evaporation pressure alarm was misinterpreted as fouling (C1)	X				NS
▪ Defective electrical wiring	(D5)	▪ Installation of a thermocouple that affected the electric supply to the lubrication system (D5)	▪ Breakdown incident (D5)	X			X	NS

minimize the negative effects of variable thermal loads over the performance of large-scale heat pumps.

4.6. Condenser

Material cracking was the only fault mechanism reported in condensers, as shown in Table 10. Another fault affecting condenser performance was the presence of non-condensables in the refrigerant. Non-condensables are gases trapped within the refrigerant loop, which are generally trapped in the condenser. Non-condensables may be introduced during maintenance service [145] or by leaks in piping, shaft seals and parts of the system operating below atmospheric pressures [146]. The latter has been indicated by Buehler [146] and characterized by Chamoun et al. [147] for a water source large-scale heat pump. Given that the presence of non-condensables in the refrigerant cannot be attributed to a single component, this problem was considered to occur at a system level.

4.6.1. Material cracking

Two case studies (A1 and C2) were mentioned to be affected by material cracking. In the first system, the fault was caused by poor manufacturing of stainless-steel tubes in an ammonia condenser. The tubes in the condenser were not correctly annealed to withstand thermal stress conditions. The problem was detected after refrigerant started to leak from the condenser during the testing phase of the system. In the second system, copper-made tubes in a Freon condenser broke after the system had been 14 years in operation. In both systems, A1 and C2, material cracking led to a system shutdown and either the condenser or the entire heat pump was replaced.

Stress corrosion cracking is one of the fault mechanisms that can affect heat pumps and refrigeration systems. Pearson [148] suggested that stress corrosion cracking in ammonia systems can develop rapidly after a condenser has been set into operation. This fault mechanism is generally not detected until cracking has penetrated the full thickness of the condenser, leading to refrigerant leakage. According to Pearson, the only feasible method to detect stress corrosion cracking in operating systems is by using ultrasound over the outer face of the condenser. This detection method was mentioned to apply for a periodic monitoring of crack growth rather than for its initial identification. Kiessling and Hägerstedt [110] indicated that carbon steel tubes in condensers for district heating applications can fail by pitting corrosion. The authors stated that this fault may occur just a few years after a heat pump is commissioned. Unlike stress corrosion, pitting corrosion is the localized form of corrosion that produces cavities in the material. Kiessling and Hägerstedt as well as Storesund [14] indicated that eddy current testing can be used to detect cracks caused by pitting corrosion or by other fault mechanisms that lead to material cracking.

5. Discussion

This section presents a discussion about faults identified in large-scale heat pumps regarding their frequency, root causes, implications and prevention or mitigation strategies. In addition, fault detection and diagnosis methods applied in large-scale vapour compression systems

Table 10
Characteristics of faults described in the condenser. SSD: System shutdown, CPR: Capacity and/or performance reduction, RL: Refrigerant leakage (RL), DCP: Compressor damage.

Fault	Case studies [−]	Potential causes [−]	Detection [−]	Implications [−]				Prevention or mitigation [−]
				SSD	CPR	RL	DCP	
▪ Material cracking	(A1)(C2)	▪ Suboptimal manufacturing of condenser tubes (A1) ▪ Broken copper pipes due to fatigue (C2)	▪ Refrigerant leakage (A1)	X			X	▪ Installation of titanium-made tubes in the condenser (A1) ▪ Replacement of the entire HP unit (C2)

are compared and analysed.

5.1. Faults affecting large-scale heat pumps

According to the reviewed case studies, faults were most frequently described in the compressor as well as in the evaporator and SHX. Overall, the most common faults identified in the case studies were fouling of the evaporator and SHX as well as refrigerant leakage. Those faults reported in the literature may not represent the most frequent faults that actually occurred in the reviewed large-scale heat pumps. Other faults that do not affect the operation of the system significantly, described as soft faults in a related study [145], may be more frequent than the faults described in most of the case studies. Examples of soft faults that were included in this review are defective bearing temperature sensor or excessive noise from the compressor. Soft faults were described in fewer case studies compared to faults that may lead to a performance reduction, damage components or cause a shutdown of the system. Madani and Roccatello [149] identified that the most frequent faults in heat pump systems were defective fans in the evaporator as well as faulty control and electronics. However, their survey-based study was not only focused on large-scale heat pumps and considered only faults that occurred during the warranty period. Therefore, faults that can be caused by component aging were probably not incorporated in such a study. For example, mechanical wear of a compressor may occur during the last stages of the lifetime of this component. This particular fault may lead to a decrease of the isentropic efficiency of the compressor before a severe failure occurs like a breakdown incident. The identification of such a fault during the performance degradation stage may prevent the occurrence of severe failures. Thereby, this may have positive implications on the system regarding its lifetime duration, availability and maintenance costs.

A description of potential causes of faults in large-scale heat pumps was provided in Section 5. However, the root causes of the faults identified in those systems were not necessarily described. For instance, one of the causes of refrigerant leakage corresponded to defective shaft seals. This fault may also have been caused by another fault such as excessive vibrations, which could have occurred due to defective slide valves in screw compressors. The identification of the root causes can be a complex task since a fault can propagate among components depending on the interconnections between them. EN 13306:2017 [19] stated that a fault is often caused by a failure, i.e., an event that prevents an item from performing an expected function. In this context, a primary failure corresponds to an event that only originated from a single component and not by the influence from other components. Thus, the identification of a primary failure requires to distinguish the relationships between components. However, the effort of finding the root cause of a fault may exceed the additional benefits of doing so. In the previous example, determining that refrigerant leakage occurs due to defective shaft seals, rather than identifying that the root cause was faulty slide valves, may lead to the same suggestion that the compressor needs to be inspected. Therefore, detecting a fault without determining its exact origin can still provide meaningful insights about the actions that need to be taken for its mitigation. For example, the result of a fault detection method given as a decision table may represent valuable information for plant operators, which is also described in Ref. [106].

5.2. Fault implications

Fault implications such as system shutdown, capacity and/or performance reduction and refrigerant leakage were more frequent in the compressor than in the other components considered in this study (see Table 5). Storesund [14] suggested that moving parts in the compressor such as bearings, shaft seals and impellers, are among the first components in large-scale heat pumps to be affected by mechanical wear. The author suggested that compressor breakdown can generate material debris that may damage other components in the system, particularly the condenser. The survey study from Aguilera et al. [18] described that faults related to the compressor were among the most commonly indicated faults by operators of large-scale ammonia heat pumps. This was due to the significant impact of compressor faults over the performance and availability of the system. Faults in other components described in the reviewed studies (e.g. fouling in the evaporator or SHX, defective safety relief valves or excessive oil in the refrigerant) may also lead to a shutdown of the system and thereby a significant impact over the system availability. However, faults in the compressor can be more costly than those in other heat pump components, as indicated by Madani and Roccatello [149].

The negative implications of the faults summarized in this review considered mainly the degradation over the expected performance of large-scale heat pumps. However, the impact on the environment and human health should also be considered when characterizing fault mechanisms. In particular, refrigerant leakage can have shattering consequences on the environment when refrigerants with nonzero GWP (e.g. HFC and CFC refrigerants) are released. Moreover, the release of toxic refrigerants like ammonia may impose a risk for human health. The assessment of fault impacts should include a comprehensive overview of the consequences that a fault has on the system operation regarding performance, availability, economy as well as on the environment and human health.

5.3. Prevention or mitigation strategies

Fault prevention or mitigation strategies described in Section 5 included cleaning, replacement and reparation of defective components, which are activities performed during maintenance services. Maintenance corresponds to planned and unplanned actions applied to a system to retain it in, or restore it to, a state in which it can perform a required function. Koster [150] proposed that suitable inspection and maintenance in refrigeration systems can reduce electricity costs and production losses due to breakdown events. Pham and Wang [151] described that maintenance can be categorized based on the degree to which the operating conditions of an item are restored. According to this categorization, a system can be restored to as good as new (*perfect maintenance*), to the state it had when it failed (*minimal maintenance*) or a condition between those two states (*imperfect maintenance*). The authors suggested that the degree to which maintenance is applied depends on the application, costs and the required reliability and safety. In this context, the optimal period to perform maintenance can be defined based on a periodic monitoring of the operating conditions of a system. Identifying the presence of a fault before the performance and availability of a heat pump system is significantly reduced, can be achieved by integrating performance monitoring with fault detection and diagnosis methods.

5.4. Fault detection and diagnosis

Venkatasubramanian et al. [152] suggested that it is often challenging to perform fault detection and diagnosis since process measurements may be incomplete, insufficient and/or unreliable. Katipamula and Brambley [153] suggested a classification scheme for fault detection and diagnosis methods, which can either be model-based or process history based, as shown in Fig. 3. Model-based fault detection and diagnosis enables a reduction of visual inspections and additional sensing devices to identify and characterize faults. In the case of quantitative model-based methods, design characteristics should be available for model development, whereas enough measured data ought to be retrieved for model calibration and validation. This can be exemplified by a thermodynamic model that is applied to describe the operation of a system under fault-free conditions, which is compared with measured information by means of residuals. Instead, qualitative model-based methods require that specific knowledge of the system or process is known in advance to correctly identify faults. For instance, a fault

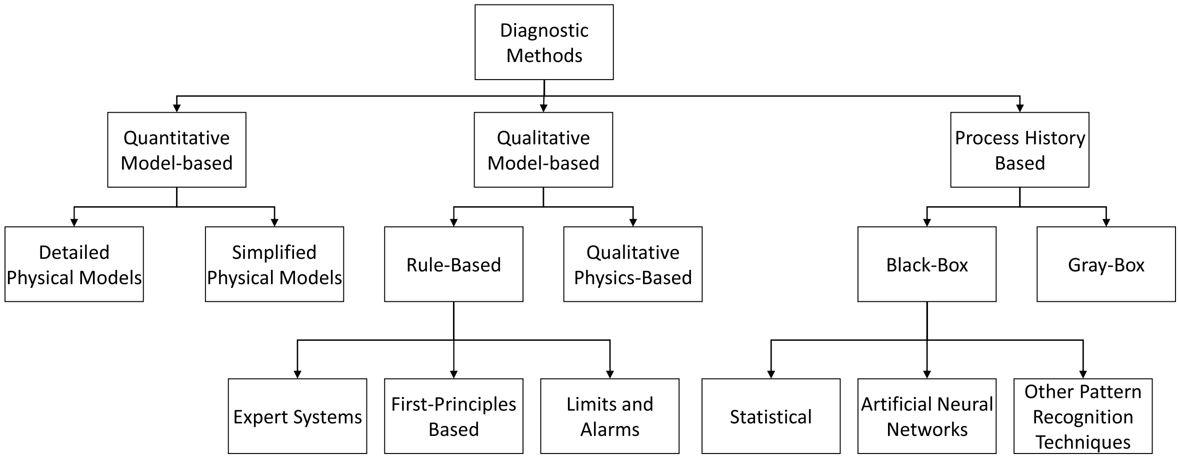

Fig. 3. *Classification of FDD methods (Adapted from work [153]).*

identification strategy characterized by a measurement that is over a specific threshold suggested by a system operator, represents a qualitative model-based method.

Willsky [154] indicated that the more complex the real system is, the more important the robustness of the fault detection and diagnosis method becomes. In this context, robustness corresponds to the ability to provide accurate results regardless of the uncertainties involved in the data collection process (e.g. measurement uncertainties). In large-scale heat pumps, the number of components may be above the component quantity in smaller systems such as residential heat pump units, increasing the number of necessary assumptions to generate the model. Conversely, large-scale systems may have more documentation about their design and historical operation than small units, as well as more sensing devices already installed. This is valuable information to monitor the state of the system that may also be applied for model development.

Process history based methods are those that rely completely (black-box methods) or partially (grey-box methods) on observations. They may be applied when an unexpected operation occurs or when detailed information about a specific fault is not fully available. However, the performance of such methods is highly dependent on the quality and quantity of the data from the real system used for their development, calibration and validation, as indicated by Katipamula and Brambley [153]. If the system is monitored with sensing devices that are defective or inaccurate, as observed in several case studies (see Table 9), it is likely that process history based methods will either not detect a fault correctly or lead to false alarms. Inappropriate method complexity, data availability or estimation performance may lead to oversimplified methods, lack of generalization or poor estimation performance (e.g. high error and/or low accuracy associated with predictions), respectively. Such characteristics should be balanced correctly to develop optimal black-box methods (and data-driven components of grey-box methods).

The faults described in Section 4 may occur simultaneously, increasing the difficulty to identify them and implement suitable corrective measures. A number of studies [155–157] developed fault detection and diagnosis methods for multiple-simultaneous faults in vapour compression systems by using virtual sensors. Virtual sensors can be combined with decoupling features for the detection and diagnosis of multiple faults occurring simultaneously. Other methods for the detection of multiple and simultaneous faults apply thermoeconomic diagnosis. Such methods analyse potential alterations of the relationships between thermodynamic variables in a system. Different methods for thermoeconomic diagnosis were proposed for their application in energy systems [158–160] and a number of them were proposed for vapour compression systems [161–164]. However, no experimental or observational studies found in the literature applied thermoeconomic diagnosis to identify faults in large-scale vapour compression systems and thereby their implementation in this field remains limited.

5.5. Future research

After the development of the present review, possible lines of future research were identified. It was observed that a limited number of studies described the use of fault detection and diagnosis methods in large-scale heat pump systems. Further research is needed to assess the applicability and performance of fault detection and diagnosis methods in such systems and reduce the effort to extend their implementation.

In the reviewed literature, faults in the compressor were frequently described as those that led to severe consequences in the operation of large-scale heat pumps such as system shutdown and capacity reduction. This represents a potential to develop specific detection and diagnosis methods as well as prevention strategies for faults affecting the compressor. Here, new monitoring strategies and devices could be developed with focus on the description of faults in the compressor and their propagation from and to other relevant components.

In many cases, the root causes of the case studies included in the present review were not likely to be described. An example of this would be an incident where excessive vibration were not identified, leading to defective shaft seals and thereby to refrigerant leakage, which was visually detected by the system operator. The use of data from existing supervisory systems in large-scale heat pumps may be complemented with modern data management technologies such as cloud-based services. This may allow to collect data and analyse it in real time to understand the actual causes of faults and prevent potential mechanisms for their propagation.

The present review did not include an assessment of the economic implications related to fault occurrence in large-scale heat pumps. Future studies may investigate historical and potential costs derived from not prevented faults and the effect of predictive maintenance on the reduction of such costs. This analysis may represent the basis to determine the applicability and performance of fault detection and diagnosis methods.

Future studies may analyse the effect of incipient faults, i.e. faults with a slow development over time, over the performance of large-scale heat pumps. This concept can be applied to develop new strategies for predictive maintenance and minimize the effect of faults such as component wear, which may result in severe failures.

6. Conclusions

This study presented a review of faults described in operational large-scale heat pump systems. Faults from 53 case studies were described based on potential causes, effects on the system operation, mitigation or prevention strategies as well as detection and diagnosis methods. The main conclusions of the study were the following:

- Source heat exchangers, evaporators and compressors were described to be affected by faults more frequently than other components in large-scale heat pumps and the most common faults in those systems were fouling of heat exchangers as well as refrigerant leakage.
- The origins of faults leading to system shutdown, capacity and/or performance reduction as well as refrigerant leakage were more frequently described in the compressor than in other components of large-scale heat pump systems.
- The detection and diagnosis of faults in large-scale heat pump systems has the potential to reduce downtime periods, performance degradation and negative environmental and health-related externalities.
- Fault detection and diagnosis methods may leverage existing supervisory systems and the criteria for their design should include data requirement, adaptability, robustness and provision of interpretable results, which can be beneficial for their application in large-scale heat pump systems.

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.

Data availability

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

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