engineering proceedings

Proceeding Paper

# Retrofit of a Heat Pump Unit †

**Miguel Catarino *, Pedro Barandier and Antonio J. Marques Cardoso**

CISE—Electromechatronic Systems Research Centre, University of Beira Interior, Calçada Fonte do Lameiro, 6201-001 Covilhã, Portugal
* Correspondence: miguel.catarino@ubi.pt; Tel.: +351-275-329-902

† Presented at 1st International Electronic Conference on Machines and Applications, 15–30 September 2022; Available online: https://iecma2021.sciforum.net.

**Abstract:** With a constant increase in heat pump (HP) use, it has become of great importance to use the application of fault diagnosis (FD) methods to detect faults at an early stage and thus ensure a proper working condition and improve the reliability of the equipment. The present paper addresses an FD and retrofit of a water-to-water HP unit. The faulty equipment, completely out of operation, was entirely analyzed, and a catastrophic failure in the three-phase compressor was identified. After identifying the faulty component, it was concluded that it should be replaced. Thereby, an adequate solution for this HP is retrofitting with a smaller capacity compressor, which is more suitable for the considered environment. The replacement is also motivated by the fact that the equipment cannot even be started without tripping the circuit breaker. To detect and identify the faults, the electrical part was analyzed first, starting with the verification of the components in the electrical circuits. After that, the resistance of each one of the windings was measured, and it was concluded that they were out of the manufacturer's specification. The process of retrofitting with a new unit followed some steps. First, the thermal loads required for the environment were considered, and then, a suitable compressor capable of fulfilling such requirements was selected. This selection considered the compatibility with the other system components. Finally, to avoid future faults and failures, after retrofitting with the new compressor, temperature sensors shall be installed to be used as a basis for virtual sensors, which enabled an efficient FD approach.

**Keywords:** heat pump (HP); fault diagnosis (FD); compressor; 3-phase motor

check for updates

**Citation:** Catarino, M.; Barandier, P.; Cardoso, A.J.M. Retrofit of a Heat Pump Unit. *Eng. Proc.* **2022**, *24*, 18. https://doi.org/10.3390/IECMA2022-12902

Academic Editor: Dan Zhang

Published: 15 September 2022



## 1. Introduction

A heat pump is a device that uses a vapor-compression cycle to transfer heat from a cold source to a hot one (as long as they are independent). The first studies of HPs were conducted by Carnot and Kelvin in the mid-1800s. However, only in the third decade of the 1900s were more practical and viable models for the public developed [1,2]. Statistics show that between 2005 and 2014 more than 7 million HP units were sold in the EU [3]. The growing tendency of sales is mostly explained by their high efficiency and capability to comply with the new legislations. As an example of their efficiency, for domestic hot water the HP can reduce primary energy consumption (natural gas, uranium, and coal), when compared to a boiler, by 15–20% [2].

Fault diagnosis of the HP is important as it is being progressively more used, not only at the residential level but also in commercial buildings. In the present day, the words "savings" and "low budget" (and others . . . ) are mandatory on a daily basis. So, repairing an equipment part is, sometimes, a more economical option than an entire unit replacement. Although repairing an HP can be viable, the best option is to prevent the faults that may lead to failures by adopting adequate maintenance strategies. This way, the lifespan of an HP may be increased, while the repair costs can be reduced. It can be accomplished by not having costly and catastrophic failures (such as a seizing compressor unit). Moreover, indirect costs can be avoided by the adoption of proper maintenance (for example, places that require a constant temperature due to their sensitivity to variations). Some of the main faults of an HP are mechanical and in regard to: (a) condenser and/or evaporator fouling; (b) refrigerant leakage; (c) improper charge; (d) compressor valve leakage, (e) liquid line restriction, (f) non-condensable gases, and, in reversible systems, (g) 4-way valve leakage and (h) check valve leakage [4–7].

Additionally, there are also control and electronics faults in HP systems, which are the most common and costliest faults. These faults are related to the control unit, electrical faults, the printed circuit board, overcurrent, the motor protection relay, etc. [8]. The present work describes the fault diagnosis of an HP unit, including all the intrinsic aspects, such as detection, localization, identification, and severity assessment [9], and its retrofit based on a corrective maintenance strategy.

## 2. Materials and Methods

In this section, the main components of an HP will be studied in order to understand how the HP works and how some of the faults may occur. Then, the analyzed case study will be presented.

### *2.1. Heat Pumps*

#### 2.1.1. Operation of an HP

Heat pumps move heat from one heat source to another. For example, a heat pump is used for adding heat to a building during the cold season and removing it during the cooling season. In order to have this energy transfer, it is necessary to introduce work into the system.

There are two major groups of HPs: reversible and irreversible HPs. Reversible HPs are the ones that have the capability to cool or heat a place. In other words, during the summer they act as an air conditioner and in the winter as an HP. Meanwhile, the irreversible HP does not have the capability of cooling, only heating (such as an HP used for domestic hot water, for example).

HPs use the refrigeration cycle to transfer heat. This cycle is characterized in the T-s and P-h diagrams. They have four stages:

1. Compression;
2. Condensation;
3. Expansion;
4. Evaporation.

Figure 1 represents the four stages of an ideal refrigeration cycle in a P-h Diagram.

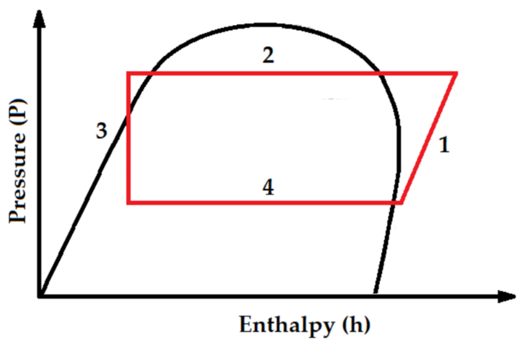


**Figure 1.** P-h diagram for an ideal refrigeration cycle.

From 1 to 2, isentropic compression occurs, where work is introduced to the fluid by the compressor. Then, from 2 to 3, there is an isobaric condensation at the condenser, where heat is removed from the refrigerant. At the expansion valve (stages 3–4), the fluid expands due to a pressure drop, which results, consequently, in a temperature drop. In the last stages, 4 to 3, the refrigerant vaporizes by absorbing heat in the evaporator, and the cycle restarts and repeats constantly while the HP is working [10].

This cycle is valid for an irreversible HP. For a reversible HP, the cycle is mostly the same. However, it has a valve that inverts the refrigerant flow direction and switches the condenser and evaporator functions.

Heat pumps can also be classified according to their heat source. They are divided into two major groups: the air source HP and the ground source HP. The first ones use the outside air as a heat source, and the latter ones use the ground (soil or water) as a heat source.

#### 2.1.2. Components of an HP Unit

HPs have four main components:

1. Compressor;
2. Condenser;
3. Expansion Valve;
4. Evaporator.

There are many types of compressors used in HPs. To choose the right one for an HP, it is necessary to have some requirements, such as thermal load, refrigerant use, application, and so on. A reciprocating compressor is a compressor that uses a piston to compress, driven by a crankshaft. Rotary compressors, instead of an up-and-down motion to compress the fluid, use a rotating piston, eccentric to the cylinder. Screw compressors use two helicoidal rotors parallelly arranged to compress the fluid. Finally, scroll compressors use two scrolls to compress the working fluid where the fluid goes from the outside to the inside of the scroll to be compressed, exiting in the center of the scroll.

The condenser and evaporator are simply heat exchangers which transfer heat from and to the fluid. For the condenser unit, they can be air cooled and, in larger systems, water cooled. The main water-cooled heat exchangers are the shell-and-coil, the shell-and-tube, and the double pipe. For the air-cooled units, the most used heat exchangers are plain or finned tubes. The evaporator units have two general types: dry and flooded. In the dry type, the refrigerant enters as a liquid, and inside the evaporator, the fluid completely evaporates. For the flooded unit, a liquid–vapor mixture of the refrigerant fluid exists inside the evaporator.

Finally, the expansion valve is one major component for the HP. This device rates the flow of refrigerant from the high-pressure side to the low-pressure side. There are some types of expansion valves, such as electronic-controlled and thermostatic-controlled expansion valves. They operate to maintain an adequate refrigerant flow at the evaporator [11].

#### 2.1.3. Faults Presents in HP Units

The main faults that may occur in an HP unit are condenser and evaporator fouling, compressor valve leakage, refrigerant leakage, improper refrigerant charge, liquid line restriction, non-condensable gas, and, for reversing systems, reversing and check valve leakage. Moreover, there are also several electrical faults in HP systems that often occur due to mechanical faults. For example, the most common electrical fault in an HP is the failure of the compressor electrical motor. Such faults may be the result of liquid slugging in the compressor or the deterioration of the motor windings and their insulation due to high operation temperatures; both of these are mechanical faults [12].

All the faults mentioned above are not immediate and, most of the time, not noticeable until the unit stops working or the desired performance is not achieved. These faults can be prevented through a proper maintenance schedule. All these faults are noticed by a reduction of the coefficient of performance (COP) and system capacity, which will drop significantly [4].

2.1.4. Testing Environment

The HP unit under consideration is located at the Guarda International Research Station on Renewable Energies (GIRS-RES) facilities of CISE—Electromechatronic Systems Research Centre. The HP is from AVENIR ENERGIE and is a reversible water-to-water HP with the reference 34T GI IC. The main characteristics of this HP are a heating capacity of 38.46 kW and a cooling capacity of 27.93 kW. It operates with approximately 5 kg of R407C refrigerant fluid, which is an HFC. It works with a scroll compressor with an electric power of 10 kW. Figure 2 represents the analyzed HP unit. The analyzed equipment presented at least an electrical fault to be diagnosed as it was not able to start.

**Figure 2.** Analyzed HP Unit.

## 3. Methods

The methodology applied to this case was the process of an FD. In the first place, the fault was detected as every time the HP tried to start it would trip the breaker. Then, to detect where the fault was, the entire system was checked, starting with the electrical system. The electrical system from this HP has two parts: the power circuit and the control circuit. At an initial stage, all the components from the control side were tested: two contactors, a timer, two flow switches, and the junction box. Then, the continuity was measured in every cable to ensure that there were no short circuits. As the test values were within the specifications, the power circuit was then assessed, and all its continuities were checked.

The last component to be tested was the compressor. According to the service manual, the internal resistance for each phase cannot be more than 0.3 Ω. The resistance obtained (taking into consideration the resistance of the multimeter) was 0.7 Ω for each phase. At this stage, the fault was detected at the compressor unit. The attempt was made to start it from a "soft starter" to ensure it was internally damaged. A spike in current upon the start that kept tripping the brakers was obtained. Thus, it was confirmed that the compressor presented a catastrophic failure and required replacement with a new unit as it was not serviceable.

## 4. Retrofit

To retrofit, the first step was to select a new compressor. As this HP was over-dimensioned for its application, a less powerful compressor had to be chosen to replace the faulty one. Based on that, and considering the required thermal load in the facility, the legislations that resulted from the Paris Agreement in 2015, and the operation parameters, an 18 kW (60,000 BTU) scroll compressor was selected as the best choice; it was half the power of the faulty unit. Such a compressor also accepts the R-134a as the refrigerant, which presents, when compared to R-407C, a lower global warming potential (GWP) and lower operation pressures. Furthermore, the R-134a is not a mixture, whereas R-407C is. Being a zeotropic mixture, the properties of R-407C in case of leakage may be modified, which is implied in the refrigerant total substitution.

As the HP presents a thermostatic expansion valve as an expansion device, it also must be replaced. That is because its operation is directly dependent on the refrigerant parameters. Therefore, if the refrigerant is changed, the thermostatic valve must be changed as well.

The next step to retrofit the equipment is to recover the R-407C of the system. Once recovered, the refrigerant charge must be determined and whether it is approximately at its rated charge must be verified. If the charge is the same, it could be reused; if it is higher, that is probably the cause of the compressor failure. If it is lower, there is a refrigerant leakage in the circuit that must be repaired, and the refrigerant is no longer adequate. Regardless, considering the GWP and the operation pressures of R-134a, it is more suitable for this application.

Then, the current compressor and the thermostatic expansion valve must be replaced in the circuit by the new ones. As the new compressor presents different inlet and outlet diameters, the piping must be adapted to fit it. Before introducing the refrigerant, it is extremely important to verify the system hermeticity to ensure there are no points of leakage.

The adequate charge of the refrigerant in the system is to be determined experimentally. It concerns the charge that enables the maximum COP. Attention to not overcharging the system is required; however, when overcharged, the COP of a system stagnates. Other system parameters should also be constantly monitored. Based on that and following on to the retrofit itself, an on-condition-based maintenance strategy, through virtual sensors based in low-cost sensors, shall be the next step of this work.

## 5. Results and Discussion

Considering the fact that HPs are becoming progressively more popular, the fault diagnosis and retrofit of such equipment should not be disregarded. On the contrary, fault diagnosis is crucial and may result in several savings and in the insurance of the equipment availability. Meanwhile, the HP retrofit presents a profitable opportunity to improve a piece of equipment or even to establish corrective maintenance to make it operational again.

Based on that, a faulty water-to-water HP was analyzed. Through a verification of the control and power circuits, a catastrophic failure in the compressor was diagnosed, and it was determined that the compressor should be replaced. The retrofit of the equipment considered the operational, economic, and environmental aspects. Therefore, this retrofit presents not only the opportunity to achieve economic benefits, but also environmental ones since a lower charge of a lower GWP refrigerant is considered.

Finally, for future work, the retrofit must be totally completed and experimentally assessed. Additionally, in order to monitor the system and to not only prevent but also predict the early stages of such faults, virtual sensors based on low-cost sensors shall be installed.

**Author Contributions:** Conceptualization, M.C. and P.B.; methodology, M.C. and P.B.; investigation, M.C. and P.B.; writing-original draft preparation, M.C. and P.B.; writing-review and editing, P.B. and A.J.M.C.; supervision, A.J.M.C.; project administration, A.J.M.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the Portuguese Foundation for Science and Technology (FCT) under Projects UIDB/04131/2020 and UIDP/04131/2020.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Parise, J.A.R. Simulation of vapour-compression heat pumps. *Simulation* **1986**, *46*, 71–76. [CrossRef]
2. Staffell, I.; Brett, D.; Brandon, N.; Hawkes, A. A review of domestic heat pumps. *Energy Environ. Sci.* **2012**, *5*, 9291–9306. [CrossRef]
3. Thomas, N.; Pascal, W. *European Heat Pump Market and Statistics Report 2015*; Technical Report; The European Heat Pump Association AISBL (EHPA): Brussels, Belgium, 2015.
4. Kim, W. Fault Detection and Diagnosis for Air Conditioners and Heat Pumps Based on Virtual Sensors. Ph.D. Thesis, Purdue University, West Lafayette, IN, USA, 2013; p. 270.
5. Bellanco, I.; Fuentes, E.; Vallès, M.; Salom, J. A review of the fault behavior of heat pumps and measurements, detection and diagnosis methods including virtual sensors. *J. Build. Eng.* **2021**, *39*, 102254. [CrossRef]
6. Li, H.; Braun, J.E. A Methodology for Diagnosing Multiple Simultaneous Faults in Vapor-Compression Air Conditioners. *HVAC&R Res.* **2007**, *13*, 369–395. [CrossRef]
7. Li, H.; Braun, J. Decoupling features for diagnosis of reversing and check valve faults in heat pumps. *Int. J. Refrig.* **2009**, *32*, 316–326. [CrossRef]
8. Madani, H.; Roccatello, E. A comprehensive study on the important faults in heat pump system during the warranty period. *Int. J. Refrig.* **2014**, *48*, 19–25. [CrossRef]
9. Cardoso, A.J.M. *Diagnosis and Fault Tolerance of Electrical Machines, Power Electronics and Drives*; IET: London, UK, 2018.
10. Pimentel de Oliveira, P. *Fundamentos da Termodinâmica Aplicada*, 2nd ed.; LIDEL Publisher: Lisboa, Portugal, 2015.
11. Miller, R.; Miller, M. *Air Conditioning: Home & commercial*, 5th ed.; AUDEL: Hoboken, NJ, USA, 2004.
12. Breuker, M.S.; Braun, J.E. Common Faults and Their Impacts for Rooftop Air Conditioners. *HVAC&R Res.* **1998**, *4*, 303–318. [CrossRef]