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Efficiency characterization of a variable speed compressor

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ABSTRACT

Heat pump systems have been spreading into the heating and air conditioning industry as they offer an affordable, efficient and reliable solution. They are considered by the EU as the solution to follow in heating and cooling in order to reach the objectives in reduction of CO2 emissions.

As a consequence of that, there is a growing interest in the development of more efficient heat pump systems which has motivated the introduction of many technical innovations in the last 10 years. Among these innovations, the introduction of inverter system has been quite popular. This technology could imply a significant improvement when the system has to work at non-design conditions. However, in the standards there is limited information about the characterization procedure of these systems (i.e. EN 13771-1 only refers to fixed speed or vapour injection compressors) and compressor-inverter system are characterized as a single unit. In that context, it is typical to assume a fixed power loss factor of 3-5% in the inverter. That power loss factor is considered when designing a new system but could differ in the final appliance, especially when the system runs at low speed. In conclusion, the knowledge around variable speed compressors is limited and the system is usually studied as a black box.

In this study, the power of a variable speed compressor and its corresponding inverter have been measured separately in a calorimeter test bench according the specifications of the norm EN 13771-1. From these measurements, it has been possible to determine the efficiency of the compressor and the inverter independently. From these results, the aim of the study is to provide a complete analysis of the performance of a variable speed compressor system.
The experimental analysis was carried out using the same compressor with two different models of inverter with the same commutation technology. The study consisted in a battery of tests in which the same compression conditions were maintained while the rotation speed of the compressor were modified from 30rps to 120rps.

The results of the paper show that the speed of the compressor and the chosen inverter brand has a high effect on the efficiency. Moreover, these results can be applied to get the efficiency curve of an inverter and point out the error that can be made by designers when considering a fixed 3-5% power loss. And last but not least, the study can also set the bases for other investigations involving the reduction of the number of measurements required to completely characterize a variable speed compressor.

Keywords: *Inverter, heat pump, VFD, variable speed compressor, efficiency*

1. Introduction

As thermal loads are highly variable, heat pumps tend to work under part load in order to adapt to the load and ensure comfort. Therefore, capacity control techniques have to be applied, among which, variable speed capacity control using inverters stands out [4, 9]. Variable speed capacity control is not a new technology, it has been spread and consolidated in other applications as water pumps or ventilation, and it is following that tendency in HVAC since 1981, when Toshiba introduced that technology in the sector.

However, variable-speed technology in HVAC systems suffers from a lack of information from manufacturers in terms of performance [3]. There is not a standard efficiency equation in these systems equivalent to the ahri equation in the fixed speed compressors[1]. The power loss of the inverter is rarely clearly provided by manufacturers and in modelling and simulation software it is often estimated as a constant value of 5-3% not considering the variations over the full range of operating conditions.

Moreover, the correct characterization and modelling of heat pumps using variable speed compressors is challenging mainly as a consequence of two facts. The first one is related with the increase of the variables to take into account, circumstance that expands dramatically the rating test matrix. The second one is associated with the difficulty of measuring correctly the efficiency of the inverter[5], as the necessary electrical equipment to carry this measurement is a high performance and expensive tool. Because of that limitation, this measurement is usually avoided and, in the open literature, the calorimetric method is often applied in the inverter to determine its thermal power losses [2, 3] although it is difficult to carry out high precision measurements using this approach. "*For the inverter, the calorimetric thermal balance is preferred to any measurement of output power, due to the electrical disturbances created by the inverter itself that exclude the use of conventional power transducers*"[2].

This paper shows the preliminary experimental campaign of a wider study whose main objective is to propose viable procedures to analyse and correctly rate variable speed heat pumps. The general scope of this experimental campaign is to provide real performance data of a commercial heat pump, paying attention to the performance of the inverter-compressor subsystem.

The particular goal of this study is to obtain an order of magnitude of the nominal efficiency and its dependence with speed of standard commercial inverters used in variable speed heat pumps. To do so, the efficiency of the compressor and the efficiency of the inverter has been measured in an independent way, solving the challenges of measuring electrical power in the bus connecting both devices.

2. Experimental setup

In order to achieve the mentioned objectives, a compressor-inverter system extracted from a commercial variable speed heat pump was tested in a test bench capable of measuring power in the bus connecting inverter and compressor.

The experimental campaign consists of calorimetric tests of the compressor-inverter system performed in a test bench (Figure 2) according to the European Standard EN 13771-1[11] for compressor rating. This calorimetric bench performs the typical compression cycle (Figure 1) and was designed to maintain the desired condition of evaporation and condensation pressure, subcooling, superheat and speed of the compressor. A set of PID control loops were configured to adjust the desired pressures with a precision of 1kPa allowing the setting of the desired conditions without manual adjustments. The information of pressure and temperature of the main points of the compression is provided by a Fisher-Rosemount 3051 pressure transducer (accuracy 0.02%) and a RTD-PT 100 (±0.05ºC). The rest of thermophysical properties are retrieved from the NIST REFPROP database [8] using the readings from the sensors described previously.

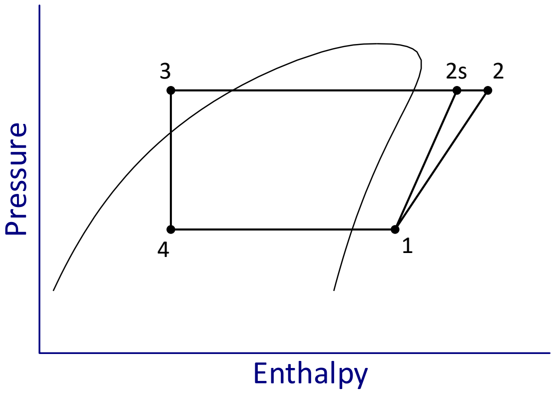

Figure 1. Compression cycle

The principal result of the test is the determination of the refrigerant mass flow. According to the standard, it has to be measured in a stable window of 30 minutes and using two different methods in order to have confirmation data. In our case, the first estimation of the mass flow was carried out with method E (refrigerant flow meter in the liquid line) using a Coriolis-technology mass flow meter installed after the condenser (Fisher-Rosemount Micro-Motion CMF025M with uncertainty of $\pm 0.025 gs^{-1}$). As a validation data, method A (secondary fluid calorimeter on the suction side) was chosen in which a Sineax power meter measure the power delivered to the electric resistance with a precision of 0.2%,. In order to consider the results as valid, both estimations must have discrepancies below 4%. Note that, in our experimental campaign, it has been achieved discrepancies always below 2%.

Regarding the variable speed compressor studied, it has been chosen a Propane (R290) rotary compressor model TPB306F for medium temperature using POE oil. It has a BLDC 1300W electric motor with 2 pole pairs that can be operated from 30 to 120rps. In order to compare the effect of the chosen inverter in the performance of the compressor-inverter system the compressor has been tested with two different commercial inverters (AKO PF1 and APY F003i-2PHB) both using Sensorless Vector Control method with carrier frequency of 8kHz and 4kHz respectively.

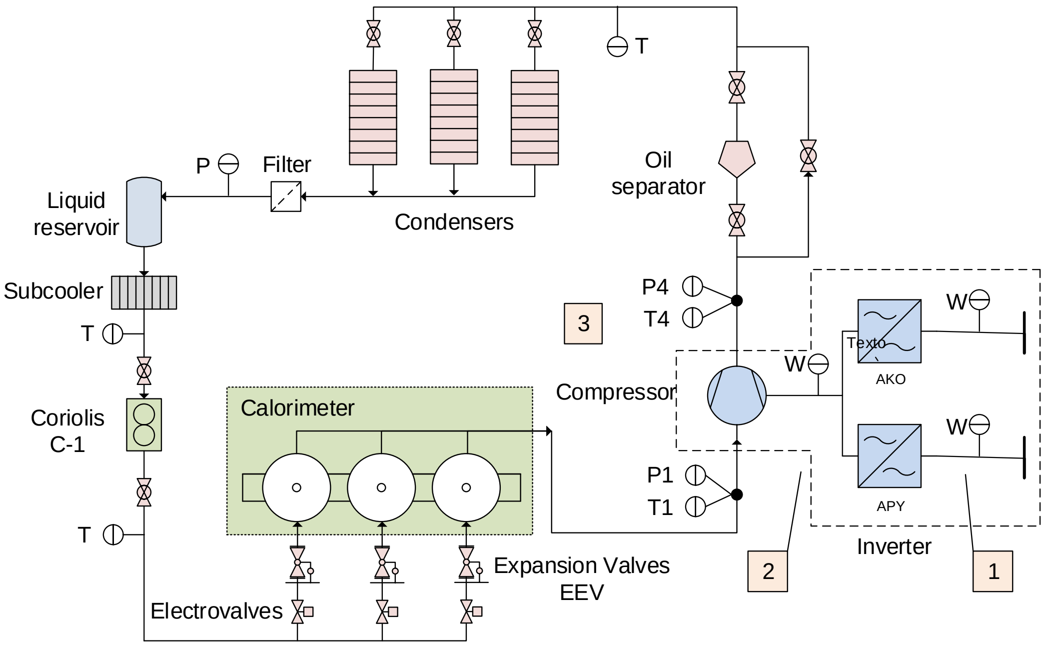

Figure 2. Diagram of calorimetric test bench

To estimate the efficiency of the compressor and the inverters, power measurements were carried out in three different positions (see points (1), (2) y (3) in Figure 2 and Figure 3)

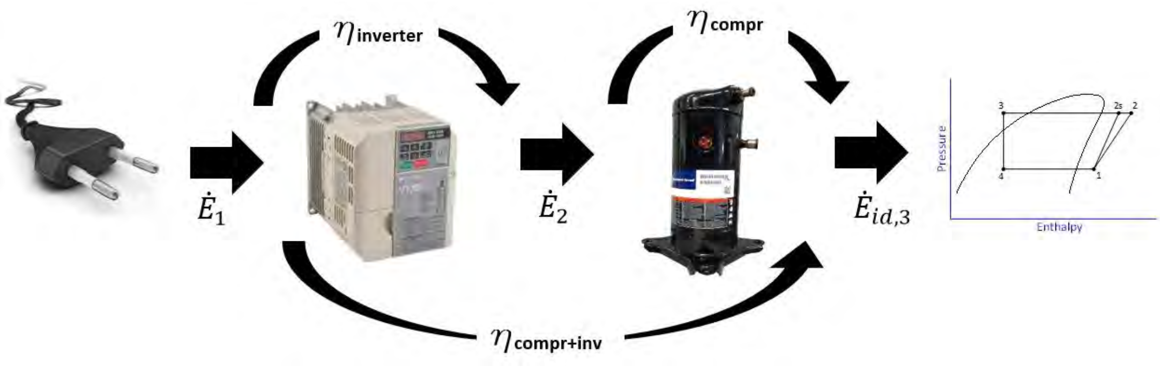

Figure 3. Scheme of the different efficiencies

- In point 1, power measurement ($\dot{E}_1$) was carried out at the source line at 50Hz and 230V with one power meter of the inverter analyser YokogawaWT1030.

- In point 2, power measurement ($\dot{E}_2$) was carried out at the line connecting the inverter with the compressor. This measurement is challenging due to technical limitations of standard power meters and grid analysers. Measurements in this point are characterized by a non 50Hz signal (reaching frequencies of several thousand Hz[5]) with high THD so the chosen power meter must have great bandwidth and a minimum sample period. The required equipment is a high-end tool with a significant higher cost compared with standard power meters and, that is why, power measurement in the linking bus is often avoided when rating variable speed heat pumps. The equipment used has been the other two power meters of the inverter analyser YokogawaWT1030[6, 7] which fulfils the requirements exposed previously (accuracy of 0.1% rdg + 0.2% rng measuring signals with frequency between 1kHz and 10kHz).

- In point 3, power estimation ($\dot{E}_{id,3}$) was carried out with the cycle parameters using Equation 1. The enthalpies were retrieved from the compression cycle (Figure 1) considering isentropic compression from injection conditions. Regarding the mass flow, the value considered is the one shown by the Coriolis mass flow meter. Resulting in an uncertainty in the $\dot{E}_{id,3}$ estimation of 0.3%.

$$\dot{E}_{id,3} = \dot{m}_{coriolis}\,(h_{2s} - h_1) \tag{1}$$

Once the power is estimated in the different locations, retrieving the efficiencies is a direct operation consisting of the ratio between the out and in power. Remark that, in point 3 it has been chosen the estimation of the ideal isentropic compression power instead of the power transmitted to the fluid in order to retrieve in a direct operation the equation of the efficiency of the compressor (Equation 2).

$$\eta_{\text{compr}} = \frac{\dot{m}_{coriolis}\,(h_{2s} - h_1)}{\dot{E}_2} \tag{2}$$

Reasoning in a similar way, the efficiency of the inverter is defined as $\eta_{\text{inverter}} = \dot{E}_2/\dot{E}_1$ and the overall efficiency $\eta_{\text{inverter+compr}} = \dot{m}_{coriolis}\,(h_{2s} - h_1)/\dot{E}_1$.

Respecting the test matrix, it consisted of 18 independent test in which the two different inverters where tested over their speed span (from 30 to 120 rps) keeping fixed the compression conditions (evaporation temperature of -7ºC and compression temperature of 50ºC with 10 and 4 degrees of superheat and subcooling respectively). Remark that all the results are computed with the average of all the measurements obtained in the 30 minutes stable window of each test.

3. Results

An extract of the results obtained from the tests can be retrieved from Table 1. The results are separated in 2 chunks of data and contain the measured mass flow, electrical power drawn from the grid and all measured efficiencies:

- In the first chunk of data, the results of the sweep in speed for the APY inverter are presented with a step in speed of 5rps.
- In the second chunk, in turn, the results of the AKO inverter are displayed with 20 rps speed step.

Additionally the exact values of superheat, condensing and evaporating temperatures measured in the tests are displayed in order to give an idea of the deviation from the chosen condition.

Imposed					**Results**					
Inverter (-)	**Tevap (ºC)**	**Tcond (ºC)**	**SH (K)**	**speed (rps)**	$\dot{M}_{coriolis}$ **(g/s)**	$\dot{E}_1$ **(W)**	η_{volum} **(%)**	η_{compr} **(%)**	η_{invert} **(%)**	$\eta_{invert+compr}$ **(%)**
APY	-7.0	50.0	9.9	**30.0**	6.02	814	82.24	61.64	89.09	54.92
APY	-7.2	50.0	10.1	**34.6**	7.01	927	83.22	62.68	90.09	57.45
APY	-7.0	50.0	10.0	**40.6**	8.32	1076	84.43	63.45	90.94	58.54
APY	-7.1	50.0	10.1	**50.4**	10.51	1336	85.84	63.79	92.13	59.49
APY	-7.0	50.0	9.9	**60.0**	12.83	1610	87.84	63.78	93.04	59.94
APY	-6.9	50.0	9.9	**70.3**	15.25	1904	88.63	63.45	93.66	59.42
APY	-7.0	50.0	10.0	**79.8**	17.43	2196	89.52	62.83	94.11	59.13
APY	-7.0	50.0	10.0	**90.4**	20.17	2550	91.55	62.40	94.48	58.95
APY	-7.0	50.0	10.1	**100.2**	22.65	2884	92.62	61.74	94.68	58.45
APY	-7.0	50.0	10.1	**105.0**	23.80	3070	93.03	60.90	94.87	57.77
APY	-7.0	50.0	10.0	**110.0**	25.32	3285	94.18	60.50	94.74	57.32
APY	-6.9	50.0	10.0	**115.2**	26.43	3495	93.70	59.17	94.82	56.10
APY	-7.0	50.0	10.0	**120.0**	27.39	3692	93.43	58.23	94.77	55.18
AKO	-7.1	50.0	10.1	**30.0**	6.00	759	82.17	62.99	93.49	58.89
AKO	-6.9	50.0	9.7	**50.0**	10.56	1280	85.54	64.19	95.08	61.03
AKO	-7.1	50.0	9.9	**70.2**	15.10	1839	88.32	63.75	95.87	61.11
AKO	-7.0	50.0	10.0	**90.0**	20.11	2502	91.31	62.19	95.92	59.66
AKO	-7.1	50.0	10.0	**117.6**	26.71	3505	93.27	59.37	95.80	56.87

Table 1. Obtained results

In Figure 6 the variation of performance with the speed is displayed for the two tested inverters. The maximum efficiency is 94.8% and 95.8% for the AKO and APY inverters respectively. This maximum is found at the higher tested frequencies and a decay with the diminution of speed is observed. This decay is more important in the case of APY inverter reaching a diminution in efficiency of 6 points. Regarding the two analysed inverters, the AKO inverter performs better than APY with improvements varying from 1% at maximum speed to 4% at minimum speed. The main conclusion retrieved from the results in Figure 6 is the high effect of the speed and the chosen inverter over the efficiency.

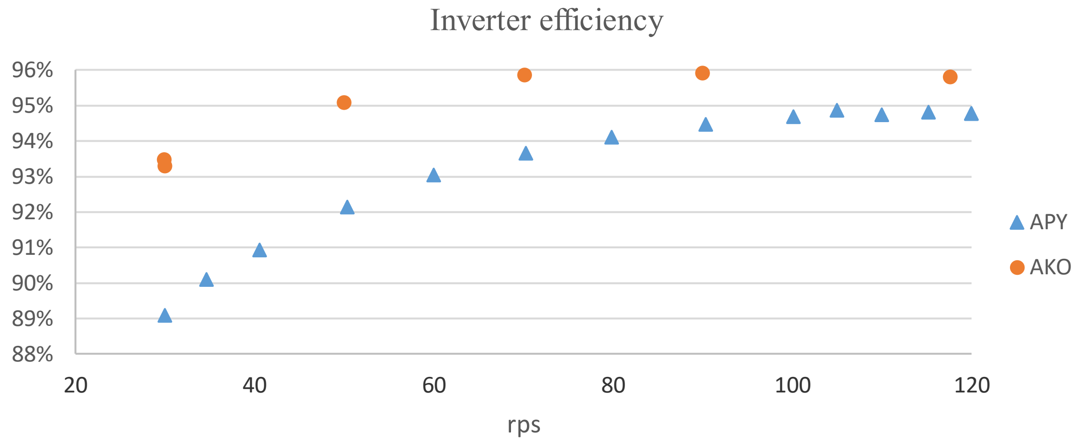

Figure 4. Variation of the inverter efficiency with speed

In Figure 5 the variation of the compressor efficiency with the speed and with the chosen inverter is displayed. The compressor efficiency shows a curve with a maximum of 64% at 50rps. The chosen inverter plays a secondary role and it appears to affect the compressor efficiency only at low speeds. At these speeds, the compressor driven by the AKO inverter seems to perform slightly better showing an improvement of 1.3 points. A higher total harmonic distortion (THD), produced by the low performance APY inverter, could explain this effect as its influence is higher at low speeds.

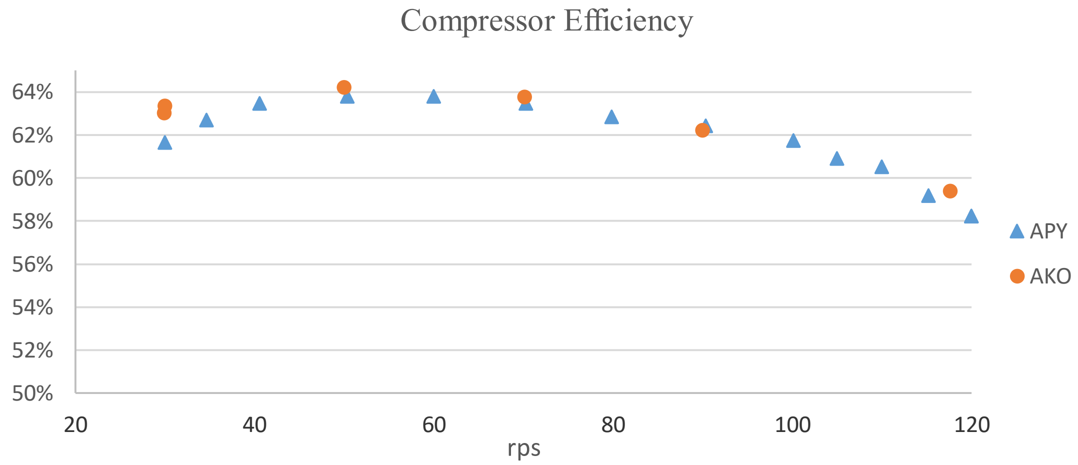

Figure 5. Variation of the compressor Efficiency with speed

In the Figure 6, the system compressor+inverter efficiency variation with speed is displayed. This graph would be the only result obtained in case standard EN 13771-1 would be rigorously applied. The result is a combination of the two preceding graphs and gives few information about the performance of the different elements separately.

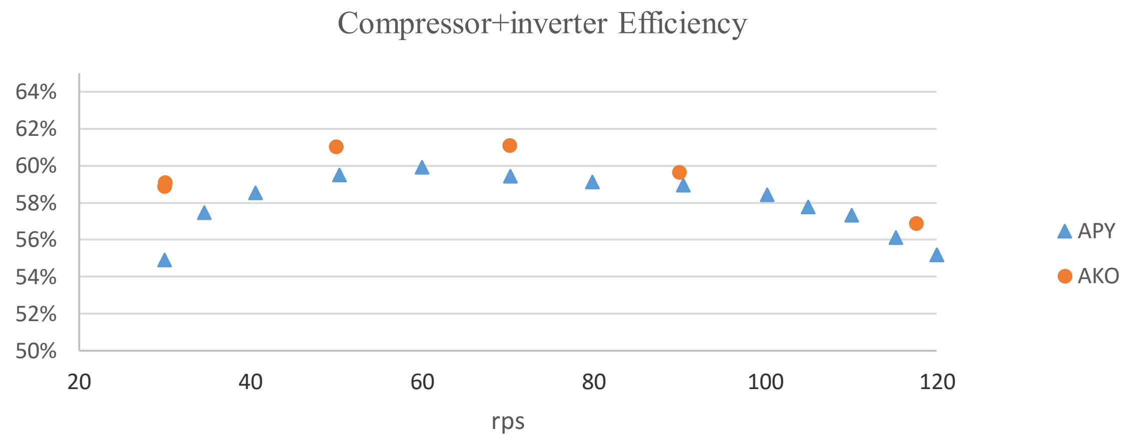

Figure 6. Variation of the compressor-inverter subsystem with speed

A better overview of the performance variation is displayed in Figure 7. In this graph, both the compressor efficiency and the system efficiency (inverter + compressor) are displayed in the same axis so it can be easily checked the effect of the inverter performance in the general performance of the system.

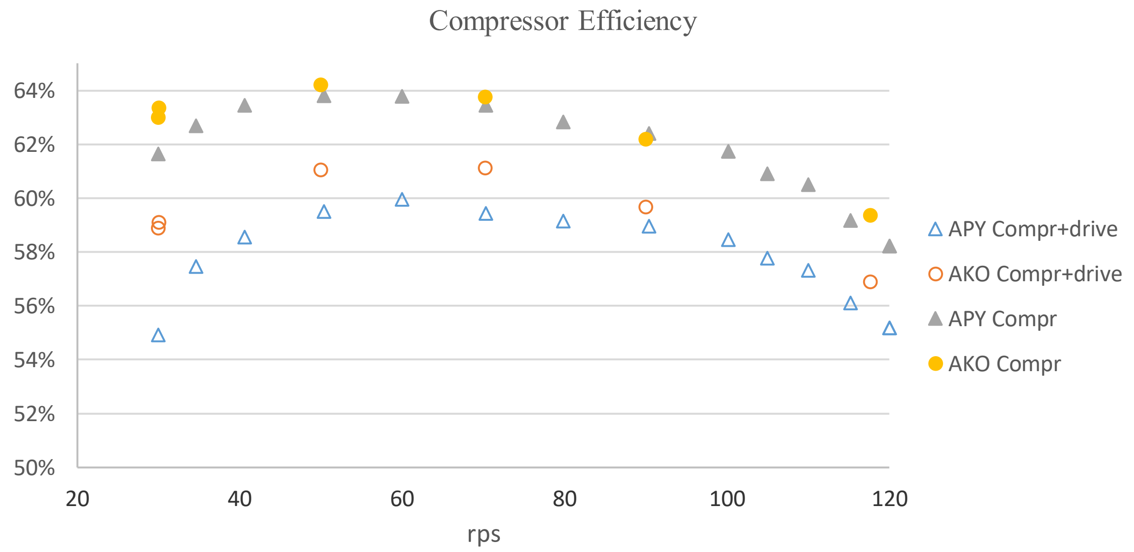

Figure 7. Variation efficiency vs System efficiency using both in

Regarding other characteristics parameters of the heat pump, as discharge temperature or volumetric efficiency of the compressor, results in Figure 8 and Figure 9 shows that, as expected, they are not influenced by the performance of the chosen inverter.

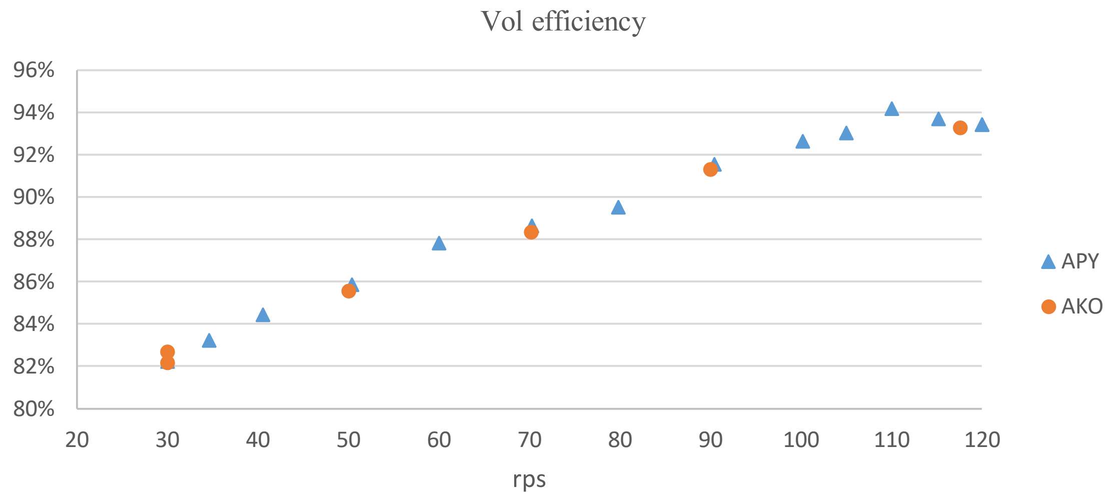

Figure 8. Variation of volumetric efficiency with speed and inverter

Concerning the variation of volumetric efficiency with speed, Figure 9 shows, for a pressure ratio of 4.5, a linear increase from 82% at the minimum speed until 94% at 110rps. At 110rps the volumetric efficiency reaches the maximum and for higher speeds there is not a further increase and even a decrease can be observed.

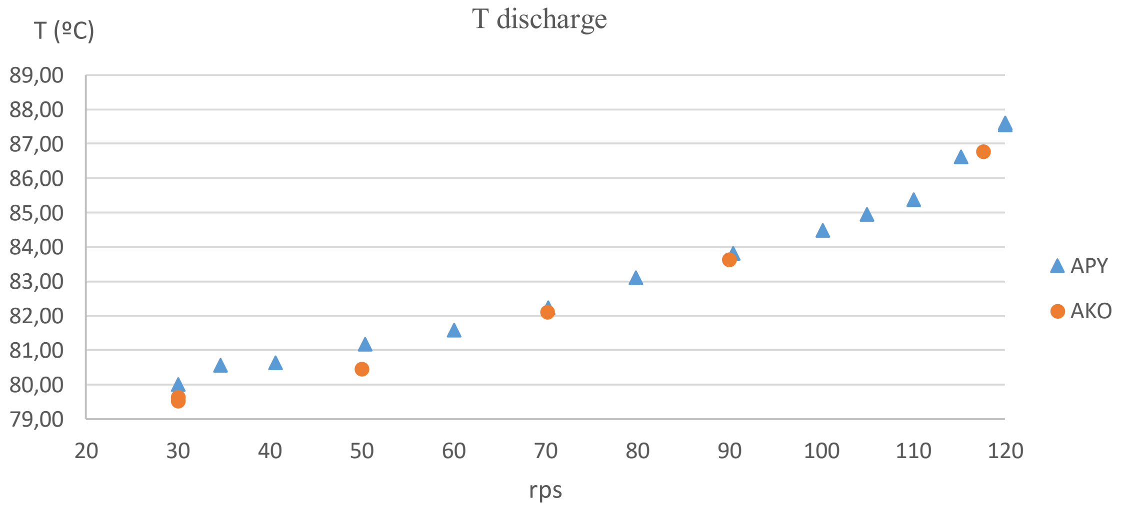

Figure 9. Variation of discharge temperature with speed and inverter

In Figure 9 the dependence of the discharge temperature with speed can be checked. A continuous increase of the discharge temperature is observed and it is accentuated as speed rises. In the speed band analysed there is an increment of temperature of 8ºC (from 80ºC at minimum speed to 87.5ºC at maximum speed).

4. Conclusion

The most relevant variables of the performance of a variable speed compressor have been studied in this experimental campaign using calorimetric tests. In particular, their variation with speed and the influence of the chosen inverter.

The chosen inverter does not affect volumetric efficiency and discharge temperature and only seems to affect the compressor efficiency at low speeds. Regarding the effect of the speed in the studied variables, volumetric efficiency and discharge temperature increase with the increase in speed (maintaining constant all the other variables). On the other hand, compressor efficiency shows a maximum at 50rps.

The independent analysis of the efficiency of the inverter using a high performance equipment has provided a clear vision of the performance of commercial inverters. The results point out the importance of the correct selection of a drive for a heat pump application showing how the performance of the inverter can vary significantly from one unit to other.

Concerning the dependence of the inverter efficiency with speed, the results display a diminution of 6 points in the case of the APY inverter. Consequently, considering constant losses in the inverter of 3-5% is realistic only when the heat pump is working at design conditions. As heat pumps tends to work at part load most of the time, a model including the variability of efficiency with load is highly recommended in order to have accurate results.

This paper shows preliminary results that will be used in a later study to model the behaviour of variable speed compressors, which, in turn, will help to:

- Minimize the required amount tests to characterize completely a variable speed compressor.
- Stablish criteria for a correct design and selection of heat pumps containing variable speed compressors.

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