# A Critical Analysis of the Characterization of Reciprocating Compressors Energy Consumption

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## ABSTRACT

This paper presents the analysis of the energy consumption in reciprocating compressors. The study has included the data of several AHRI reports: (especially AHRI 30 and AHRI 59). A total of 9 different reciprocating compressors of different sizes, some of them tested with various refrigerants (R134a, R32, R410A, R404A, …) have been considered in the study.

The values of the compressor consumption and the shape of the corresponding response surface as a function of working conditions, for all the studied compressors and refrigerants, have been analyzed and compared with the obtained for other compressors designs like scroll. Based on that, an analysis of the significance for the different coefficients of the AHRI polynomial has been determined. The main results of this analysis have been that pressure-dependent correlations converge the energy consumption response surface for different refrigerants, and this response surface has two types of shapes depending on the application range of the compressor.

## 1. INTRODUCTION

Nowadays, simulation tools are increasingly being used by manufacturers in the industry with the aim of improving the quality of their products. In addition, the need to stand out from the competition has led the companies to invest more financial resources in the development of their own simulation software.

In heating and air-conditioning applications for buildings, due to the growing importance and the current role of Heat Pumps (HP), it becomes essential to develop accurate models to characterize their internal components and performance. The main component in these units is the compressor, which largely fixes the global performance in HPs. Thus, the development and improvement of compressor technologies can lead to a reduction of more than 80% in the electricity consumption of HPs (Chua et al., 2010). Therefore, many authors and technical reports focus on compressors characterization, giving researchers powerful tools to assist the design stage and systems' control. Regarding the compression process, scroll and reciprocating compressors are two of the most used technologies. For example, in light commercial refrigeration appliances (like freezers and refrigerators), hermetic reciprocating compressors are commonly the most widely used technology.

There are hundreds of papers and technical reports regarding compressor modelling with different modelling approaches. Shaping the meaning of compressor model term, it could be defined as the mathematical transcription of the thermodynamic processes inside the compression chamber. These models have the main objective of predicting the compressor performance, i.e., the energy consumption and refrigerant mass flowrate, and they can be classified depending on the detail level of knowledge (Rasmussen & Jakobsen, 2000).

On the one hand, theoretical and semi-empirical models are generated from physical and chemical laws, being the second one completed through experimentation (it may also contain numerical relations based on statistics to simplify the compression process). However, these types of models can require a higher level of knowledge of the compressor's boundary conditions and geometric measurements of its internal components, only available by manufacturers. Some examples of these models are reported in Corberan et al. (2000); Navarro et al. (2007); Winandy et al. (2002).

On the other hand, empirical models, for instance polynomial models, include only numerical relations between the response variable (*what we want to characterize*) and independent variables (*control factors in the experiment*). Therefore, they do not directly describe any physical phenomena, and they are constructed by regression analysis of performance tests providing more flexibility to reproduce an objective response surface. Moreover, as reported in (Cheung & Wang, 2018), if sufficient experimental data are available, and they completely cover the experimental domain of the analyzed compressor, empirical models always result in a lower prediction error if we compare them with other approaches like theoretical or semi-empirical models.

Due to these advantages, although many theoretical and semi-empirical models have been proposed over the years, empirical models are still in use, and it is the most commonly approach used by manufacturers to perform their catalog data. The classical empirical model to characterize the compressor performance is the 10-term and 3rd-degree AHRI polynomial included in the AHRI-540 standard (ANSI/AHRI 540, 2015). It considers that the unknown function to reproduce the compressor performance can be substituted by a polynomial according to the Taylor theorem approach. However, there is no a clear explanation about using a 3rd-degree polynomial to reproduce the compressor performance. That point is specially critical, considering that the cubic exponent introduces a very sensible term to the location of the experimental information and could introduce significant deviations when the amount of data is not high or is not appropriately placed over all the operating range as it is in (Jähnig et al., 2000).

Against this background, this study aims to analyze the dependence and shape of the response surfaces obtained for the compressor consumption in reciprocating compressors in order to evaluate the required terms to include in the AHRI polynomial and get a proper characterization. This will allow to reduce the time dedicated to characterizing a compressor and avoid undesired deviations in the results obtained from using this kind of model to extrapolate data. For this purpose, it was necessary to have access to a massive and reliable database on compressor calorimeter data. In a previous study (Marchante-Avellaneda et al., 2022), a similar analysis was performed on scroll compressors using the experimental data reported in the project *"Low-GWP Alternative Refrigerants Evaluation program"*. These reports also include experimental data for reciprocating compressors working with different refrigerants and suction conditions and they have been used to develop the present work.

## 2. COMPRESSOR PERFORMANCE DATA

A few years ago, AHRI disclosed a series of performance data for different compressors (scroll and reciprocating), with conventional and new refrigerants and mixtures. These experimental results are included in several reports within the AHRI *"Low-GWP Alternative Refrigerants Evaluation Program"*. This study has considered all those AHRI reports containing reciprocating compressor tests:

AHRI 17 (Borges Ribeiro & Marchi Di Gennaro, 2013a), AHRI 18 (Borges Ribeiro & Marchi Di Gennaro, 2013b), AHRI 28 (Sedliak, 2013a), AHRI 29 (Sedliak, 2013b), AHRI 30 (Sedliak, 2013c), AHRI 35 (Rajendran & Nicholson, 2014a), AHRI 37 (Rajendran & Nicholson, 2014b), AHRI 49 (Sedliak, 2015a), AHRI 50 (Sedliak, 2015b), AHRI 51 (Boscan & Sanchez, 2015), AHRI 59 (Lenz & Shrestha, 2016), AHRI 64 (Pérouffe & Renevier, 2016a), AHRI 67 (Pérouffe & Renevier, 2016b), AHRI 69 (Pérouffe & Renevier, 2016c).

From the analysis of all the compressor consumption data, we have found two different behaviors depending on the application range: at Low/Medium Back Pressure conditions (L/M-BP), the compressor consumption shows a slight dependence on the condensation temperature. While, at higher values of evaporation pressure (HBP), the compressor consumption increases significantly with an increase of the condensation temperature. AHRI 30 is characteristic of the first kind: (L/M-BP), while AHRI 59 is characteristic of the second kind: (HBP). Those reports include a huge amount of refrigerants tested and different suctions conditions. Therefore, the effect of the suction conditions and refrigerant on the compressor consumption are also discussed.

Table 1 summarizes the main characteristics of the reciprocating compressors included in the AHRI reports. AHRI 30 and AHRI 59 compressors were selected as a basis to perform all the current analyses. The results obtained with these compressors were verified with the rest to confirm the general application of the obtained conclusions. Due to the extension limit of this paper, it shows in detail the analysis of the reports mentioned above. However, anyone could check the validity of the obtained conclusions on the rest of the compressors of the database.

**Table 1:** Calorimeter data (AHRI Reports)

| Report | Compressor model | Manufacturer | Displacement $cm^3/rev$ | Refrigerants tested | Test cond.* $°C$ | Test points† | Total tests |
|---|---|---|---|---|---|---|---|
| AHRI 17 | NJ7240F | Embraco | 34.38 | R22/R1270 | a | 12/12 | 24 |
| AHRI 18 | EG80HLR | Embraco | 7.15 | R134a/N13a/ARM42a | b | 12/8/12 | 32 |
| AHRI 28 | NEK2134GK | Embraco | 8.77 | R404A/L40 | c/a/b | 36/36 | 72 |
| AHRI 29 | NEK2134GK | Embraco | 8.77 | DR7 | c/a/b | 36 | 36 |
| AHRI 30 | NEK6214Z | Embraco | 16.80 | R134A/R1234YF | c/a/b | 45/45 | 90 |
| AHRI 35 | CS14K6E-TF5 | Copeland | 47.15 | DR7 | a/b | 52 | 52 |
| AHRI 37 | CS14K6E-TF5 | Copeland | 47.15 | L40 | a/b | 51 | 51 |
| AHRI 49 | NEK2134GK | Embraco | 8.77 | R455A | c/a/b | 36 | 36 |
| AHRI 50 | NEK2134GK | Embraco | 8.77 | DR3 | c/a/b | 36 | 36 |
| AHRI 51 | 4GE-23-40P | Bitzer | 971.26 | R449A/R404A | e | 12/12 | 24 |
| AHRI 59 | H84B223ABC | Bristol | 30.51 | R410A/L41-1/DR5A/ARM71a/D2Y60/R32 | a | 15/15/15/15/17/16 | 93 |
| AHRI 64a | FH2511Z | Tecumseh | 74.23 | R404A/DR7 | d/e | 28/23 | 51 |
| AHRI 64b | FH4540Z | Tecumseh | 74.23 | R404A/DR7 | d/e | 34/27 | 61 |
| AHRI 67a | FH2511Z | Tecumseh | 74.23 | ARM25 | d | 37 | 37 |
| AHRI 67b | FH4540Z | Tecumseh | 74.23 | ARM25 | d | 16 | 16 |
| AHRI 69a | FH2511Z | Tecumseh | 74.23 | ARM20b | d/e | 32 | 32 |
| AHRI 69b | FH4540Z | Tecumseh | 74.23 | ARM20b | d | 16 | 16 |

* Test conditions: **a**. $SH = 11\,K$ ; **b**. $SH = 22\,K$ ; **c**. $T_s = 18\,°C$ ; **d**. $SH = 10\,K$ ; **e**. $T_s = 20\,°C$;
† Total test points: **759**;

## 3. COMPRESSOR PERFORMANCE ANALYSIS

One of the possibilities to characterize the compressor performance has always been to characterize the compressor efficiency. This approach has the advantage of considering a non-dimensional parameter with low dependence on the compressor size and the refrigerant tested:

$$\eta_c = \frac{\dot{m}\Delta h_{is}}{\dot{W}_c} \tag{1}$$

Additionally, some authors have proposed non-dimensional parameters, similar to the efficiencies, which are even more general and provide a slightly better estimate of compressor performance (Navarro-Peris et al., 2013; Pierre, 1982). However, as was already shown in a previous study carried out on scroll compressors (Marchante-Avellaneda et al., 2022), the characterization in terms of efficiency is more complex than in direct terms of electrical consumption. This is still true in reciprocating compressors' characterization. Figure 1 shows an example of the compressor efficiency map for a reciprocating compressor (AHRI 59, left-plot) and for a scroll compressor (AHRI 11, right-plot) at constant suction conditions ($SH$ = 11K).

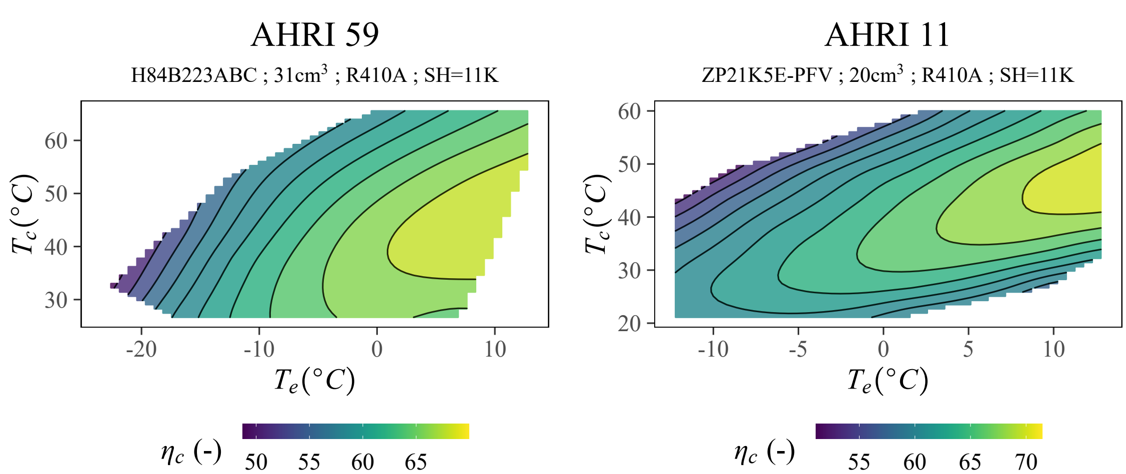


**Figure 1:** Compressor efficiency map of AHRI 59 (left) and AHRI 11 (right) for its reference refrigerant

In the figure above, we can see how the response surfaces have a certain similarity. Both plots show that compressor efficiency depends on the evaporation and condensation temperature, and the zone of maximum efficiency is in both cases at the highest values of evaporation temperature without an absolute maximum. Then, another interesting feature is to analyze the dependence on suction conditions. Figure 2 shows the compressor efficiency and energy consumption vs the pressure ratio and evaporation temperature for the AHRI 30 compressor, including three different suction conditions ($SH$ = 11K, $SH$ = 22K and $T_s$ = 18°C), and the reference refrigerant (R134a). This figure also includes different subplots for each level of condensation temperature to simplify the visualization:

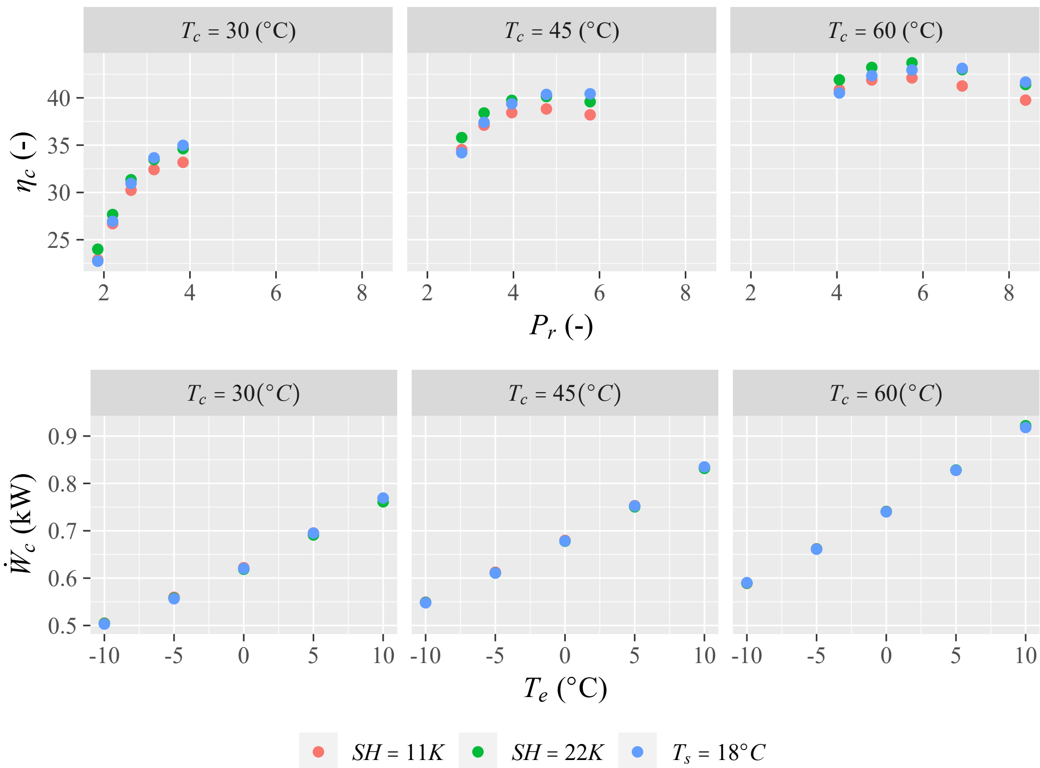


**Figure 2:** Compressor efficiency and energy consumption for different suction conditions (AHRI 30 R134a)

As shown in Figure 2, the suction temperature or $SH$ level only affects the compressor efficiency, with no apparent effect on the energy consumption. For instance, it is possible to observe how the compressor efficiency increases with the $SH$ level. These results agree with those already obtained in scroll compressors. On the other hand, the energy consumption shows a main dependence with the evaporation temperature and a slight dependence on the condensation temperature (it increases for higher values of $T_c$). This is different concerning to the results obtained in scroll compressors.

As reported in Marchante-Avellaneda et al. (2022), the energy consumption in scroll compressors depends mainly on the condensation temperature with a linear trend if we define a polynomial model in terms of pressure ($P_e$, $P_c$) and with a slight curvature if we define it in terms of temperature ($T_e$, $T_c$). Then, the evaporating conditions only include a slight dependence depending on the application range.

On the other hand, for all the reciprocating compressors analyzed, the main independent variable that sets the energy consumption level is the evaporation temperature rather than the condensation temperature like in scroll compressors. Then, the condensation temperature only includes a slight dependence on the major part of the compressors analyzed. Only the reports AHRI 51 and AHRI 59 include a major dependence on the condensation temperature. In order to show these trends, Figure 3 includes the energy consumption maps of several reciprocating reports (left-plot), and the energy consumption maps already analyzed in Marchante-Avellaneda et al. (2022) for scroll compressors (right-plot). This figure is plotted in terms of condensation and evaporation pressure in order to include the pressure ratio isolines. The plot also includes a label to identify the AHRI report:

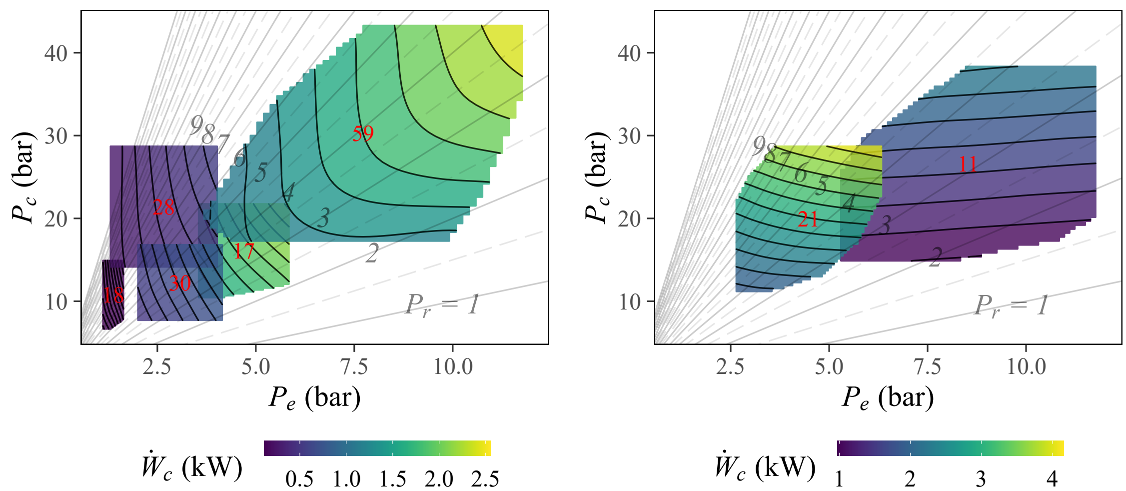


**Figure 3:** Compressor consumption maps of AHRI 17, 18, 28, 30, 59 reports (left) and AHRI 11, 21 reports (right) for its reference refrigerant

As can be observed in Figure 3, the energy consumption in reciprocating compressors has two behaviors depending on the application range of the compressor. The first one only include a main dependence with one of the two independent variables that set the energy consumption, the evaporation temperature. In this case, the response surfaces are simpler, requiring fewer terms to be included in a polynomial model with probably a minor number of terms for the condensation temperature. For example, AHRI 18 and AHRI 28 compressors (LBP) show this main dependency with these trends. Then, if the application range of the evaporation pressure increase, we can observe how the dependence of the energy consumption with the condensation temperature increase, like in the AHRI 30 and AHRI 17 compressors (MBP). Finally, for the higher values of the evaporation pressure, the response surface becomes to the second type of behavior observed, like in the AHRI 59 compressor (HBP). In this case, the energy consumption is fixed in both terms of evaporation and condensation temperature. Due to this, the response surface obtained is more complex when it is characterized by a polynomial model. Therefore, in order to obtain a good characterization, it will be necessary to use a higher number of terms, including terms dependent on the condensation temperature. Regarding scroll compressors, they don't show a significant change in trend.

These differences between reciprocating and scroll compressor may be caused by its difference behavior in terms of mass flowrate. Considering that the energy consumption is related to the level of mass flowrate through the compressor, an important difference between these two technologies is the dependence of the volumetric efficiency on the pressure ratio. On the one hand, the pressure ratio in scroll compressors has a small influence on the mass flowrate. However, in reciprocating compressors (and piston machines) there is a high dependence caused by the influence of the *"dead space"*. If we check the pressure ratio isolines in the figure above, we will notice a lower distance between them at lower values of the evaporation temperature. Therefore, we will have a high variation in the pressure ratio/mass flowrate for the energy maps that shows only a main dependence with the evaporation temperature.

## 4. COMPRESSOR CONSUMPTION CORRELATION

### 4.1 Correlations employed

Once the initial analysis of the dependence and shape of the response surface has been completed, the next step is to define the polynomial model to be used. In scroll compressors, the use of the 10-term AHRI polynomial (ANSI/AHRI 540, 2015) was unnecessary due to the smoothness of the response surfaces. However, as shown in Figure 3, in reciprocating compressors, the use of a larger number of terms in the polynomial may be justifiable.

As mentioned above, this will depend on the application range. For example, we can see that AHRI 17, 18, 28 and 30 compressors (Figure 3) do not need such an extensive polynomial. This allows us to remove some terms like cubic or second-order interaction terms. On the other hand, in the case of the response surface obtained in the AHRI 59 compressor, Figure 3 shows that it will be necessary to include a larger number of terms, especially terms related to the condensation temperature.

Another essential aspect of evaluating, which has already been verified in scroll compressors, is the selection of the independent variables. Should we obtain a polynomial in terms of condensation and evaporation temperature? Is there any advantage of building the model in terms of condensation and evaporation pressure?

In scroll compressors, the authors have found that if alternatively the consumption is plotted as a function of the refrigerant pressure, instead of temperatures, it turns out that the surfaces are much more similar to each other. Making the same assumption for reciprocating compressors, Figure 4 shows a 3D representation of the consumption response surfaces for the AHRI 59 compressor working with different refrigerants at the same SH level.

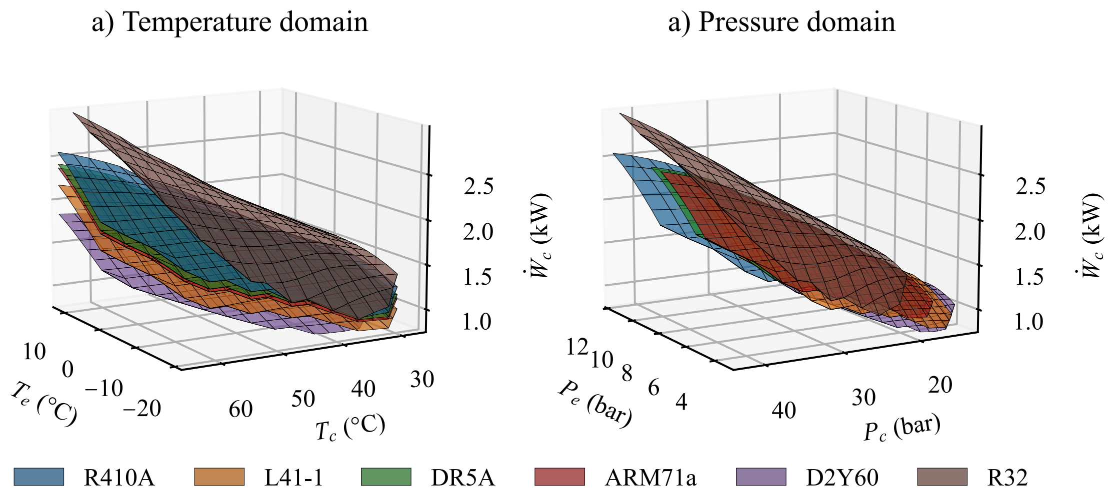


**Figure 4:** 3D plot of compressor consumption vs $T_e/T_c$ and vs $P_e/P_c$ of compressor H84B223ABC (AHRI 59) for 6 different refrigerants.

We can see the same effect in the figure above when using a pressures domain in reciprocating compressors. Only the refrigerant R32 shows a slight difference, converging all the other refrigerants in the same plane. Therefore, selecting the pressure domain rather than the temperature domain is much more universal in both technologies, scroll and reciprocating compressors.

Against this background, and considering that the characterization of reciprocating compressors can be more complicated than scroll compressors, the authors propose to use the original 10-term AHRI polynomial. Moreover, due to some compressors can obtain simpler response surfaces, the use of this model can be complemented with additional term reduction methodologies. With this, we obtain a more robust approach to avoid possible overfitting in the model if 10 terms are excessive for the characterization. The procedure would be as follows:

Consider in a first step the 10-term AHRI polynomial. Then, perform a term elimination procedure to eliminate possible unneeded terms. This step can be performed manually or using automatic procedures like stepwise regression methodologies. In this study, the authors have been selected the backward elimination procedure selecting the *BIC* criterion (Bayesian information criterion). The tool selected has been the open-source programming language R (R Core Team, 2022) and the *stepwise( )* function provided in the *RcmdrMisc* package (Fox, 2022).

Finally, due to the advantages observed in the use of refrigerant pressures, this methodology will be applied considering the AHRI polynomial defined in terms of pressure and temperature:

*Temperature domain (T)*
$$\dot{W}_c = c_0 + c_1 T_e + c_2 T_c + c_3 T_e T_c + c_4 T_e^2 + c_5 T_c^2 + c_6 T_e T_c^2 + c_7 T_e^2 T_c + c_8 T_e^3 + c_9 T_c^3 \quad (2)$$

*Pressure domain (P)*
$$\dot{W}_c = c_0 + c_1 P_e + c_2 P_c + c_3 P_e P_c + c_4 P_e^2 + c_5 P_c^2 + c_6 P_e P_c^2 + c_7 P_e^2 P_c + c_8 P_e^3 + c_9 P_c^3 \quad (3)$$

### 4.2 Comparison of correlations

Table 2 and Table 3 show the fitting results for the models considered using the refrigerant temperatures and pressures. The AHRI (T) and AHRI (P) models are obtained by fitting the full polynomial with 10 terms (Equation 2 and Equation 3). Then, the AHRI (T-SW) and AHRI (P-SW) models are the polynomials obtained after applying the automatic term elimination methodology. These tables include the values of the regression coefficients, as well as the *MRE* and *RMSE* errors. For each compressor and refrigerant, the correlations are fitted to all available tests points, including all different suction conditions (as already seen in Figure 2, $\dot{W}_c$ is independent of suction conditions). The coefficients are meant to provide the energy consumption in kW with temperatures in °C and pressure in bar.

As we can see from the results, the prediction errors are low for both temperature and pressure-fitted models. In the case of the AHRI 30 (L/M-BP) compressor, we can observe that the term elimination methodologies obtain more compact models than in the AHRI 59 (HBP) compressor. Additionally, it has been noticed that, in general, the compressors with LBP and MBP application ranges present large collinearity when trying to fit the 10-term AHRI polynomial. In the case of the AHRI 30 compressor, we can observe that the regression fit has not been able to estimate the cubic term referring to condensation conditions ($T_c^3$ or $P_c^3$) in the AHRI (T) and AHRI (P) models. This reinforces the hypothesis that this type of compressors, with more straightforward response surfaces, do not need such a large polynomial model. Therefore, it is advisable to eliminate terms to avoid overfitting in the model adjustment. Additionally, another possible approach could be generating the compressor performance maps with other more sophisticated tools such as non-parametric regression models like a Thin-Plate-Spline regression model (Green & Silverman, 1993). This allows a smooth interpolation, and accurate results can be obtained regardless of the complexity of the response surface.

## 5. CONCLUSIONS

A thorough analysis of the energy consumption characteristics of reciprocating compressors has been performed. The study has included all reciprocating compressor results included in the AHRI reports corresponding to the *"Low-GWP Alternative Refrigerants Evaluation program"*. The following main conclusions can be drawn from the performed study:

- The analysis of the compressor efficiency response surface shows similar results in both technologies, reciprocating and scroll compressors. The response surface shows a complex shape, and it is sensitive to the suction conditions.
- The energy consumption response surfaces in reciprocating compressors can be more complex than in scroll compressors. This complexity depends mainly on the working range of the compressor and may require the use of more complex polynomial models, being justifiable the inclusion of cubic and interaction terms for the most complicated response surfaces.
- The energy consumption depends mainly on the evaporating temperature and two types of behavior have been identified. The L/M-BP compressors analyzed have simpler response surfaces and depend mainly on the evaporation temperature with a slight dependence on condensation temperature . On the other hand, the HBP compressors obtain more complex response surfaces and depend mainly on the evaporation and condensation temperatures.
- Once the different response surfaces for the energy consumption have been analysed, the authors recommends to use the original 10-term AHRI polynomial in order to characterize reciprocating compressors. Furthermore, the authors have found that the use of automatic term reduction methodologies are adequate in order to simplify the final polynomial model. This allows the elimination of possible collinearity effects in the models in the case of more straightforward response surfaces. Alternatively, other sophisticated strategies can be used to generate the compressor maps by a smooth interpolation. In this sense, non-parametric regression models such as a Thin-Plate-Spline regression model are recommended.
- The prediction errors obtained are low when the model is considered in terms of temperature or pressure. However, the authors have found that if the compressor consumption is correlated versus the condensation and evaporation pressures, the energy consumption surfaces are much more similar for a specific compressor, regardless of the refrigerant used.

**Table 2:** Empirical models $\dot{W}_c$, compressor H84B223ABC (AHRI 59)

| | **AHRI (T-SW)** | **MRE (%)** | **RMSE (W)** | **AHRI (P-SW)** | **MRE (%)** | **RMSE (W)** | **AHRI (T)** | **MRE (%)** | **RMSE (W)** | **AHRI (P)** | **MRE (%)** | **RMSE (W)** | **Fluid** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $c_0$ | 8.272e-01 | | | 2.277e-01 | | | 8.259e-01 | | | 7.319e-02 | | | |
| $c_1$ | -4.112e-02 | | | 3.157e-01 | | | -4.476e-02 | | | 3.260e-01 | | | |
| $c_2$ | 1.176e-02 | | | -3.486e-02 | | | 1.279e-02 | | | -1.998e-02 | | | |
| $c_3$ | 1.475e-03 | | | 1.594e-02 | | | 1.664e-03 | | | 1.685e-02 | | | |
| $c_4$ | -1.168e-03 | 1.87 | 10.80 | -5.184e-02 | 1.97 | 12.91 | -1.477e-03 | 1.92 | 9.86 | -5.502e-02 | 2.01 | 12.35 | R410A |
| $c_5$ | 5.033e-04 | | | -2.261e-04 | | | 4.708e-04 | | | -8.609e-04 | | | |
| $c_6$ | | | | -1.221e-04 | | | -1.914e-06 | | | -1.096e-04 | | | |
| $c_7$ | 1.033e-05 | | | | | | 1.574e-05 | | | -9.845e-05 | | | |
| $c_8$ | | | | 1.399e-03 | | | -6.609e-06 | | | 1.646e-03 | | | |
| $c_9$ | -6.563e-06 | | | | | | -6.304e-06 | | | 5.814e-06 | | | |
| $c_0$ | 3.903e-01 | | | -1.029e-01 | | | 4.616e-01 | | | -1.029e-01 | | | |
| $c_1$ | -4.238e-02 | | | 1.208e-01 | | | -4.044e-02 | | | 1.208e-01 | | | |
| $c_2$ | 3.906e-02 | | | 5.558e-02 | | | 3.353e-02 | | | 5.558e-02 | | | |
| $c_3$ | 1.940e-03 | | | 1.082e-02 | | | 1.846e-03 | | | 1.082e-02 | | | |
| $c_4$ | -2.378e-03 | 1.64 | 7.04 | -1.248e-02 | 1.78 | 8.23 | -2.320e-03 | 1.65 | 6.94 | -1.248e-02 | 1.78 | 8.23 | L41-1 |
| $c_5$ | -3.194e-04 | | | -3.082e-03 | | | -1.866e-04 | | | -3.082e-03 | | | |
| $c_6$ | -7.662e-06 | | | -3.569e-04 | | | -6.608e-06 | | | -3.569e-04 | | | |
| $c_7$ | 3.675e-05 | | | 1.275e-03 | | | 3.537e-05 | | | 1.275e-03 | | | |
| $c_8$ | -3.144e-05 | | | -2.038e-03 | | | -3.106e-05 | | | -2.038e-03 | | | |
| $c_9$ | | | | 5.484e-05 | | | -9.946e-07 | | | 5.484e-05 | | | |
| $c_0$ | 6.378e-01 | | | -2.728e-01 | | | 6.057e-01 | | | -2.728e-01 | | | |
| $c_1$ | -3.622e-02 | | | 2.738e-01 | | | -3.914e-02 | | | 2.738e-01 | | | |
| $c_2$ | 2.351e-02 | | | 3.476e-02 | | | 2.627e-02 | | | 3.476e-02 | | | |
| $c_3$ | 1.366e-03 | | | 1.288e-02 | | | 1.508e-03 | | | 1.288e-02 | | | |
| $c_4$ | -1.770e-03 | 0.73 | 3.83 | -4.188e-02 | 0.96 | 5.56 | -1.857e-03 | 0.63 | 3.68 | -4.188e-02 | 0.96 | 5.56 | DR5A |
| $c_5$ | 1.739e-04 | | | -2.207e-03 | | | 1.031e-04 | | | -2.207e-03 | | | |
| $c_6$ | | | | -1.607e-04 | | | -1.594e-06 | | | -1.607e-04 | | | |
| $c_7$ | 2.290e-05 | | | 3.376e-04 | | | 2.491e-05 | | | 3.376e-04 | | | |
| $c_8$ | -1.481e-05 | | | 6.263e-04 | | | -1.566e-05 | | | 6.263e-04 | | | |
| $c_9$ | -3.968e-06 | | | 2.512e-05 | | | -3.416e-06 | | | 2.512e-05 | | | |
| $c_0$ | 6.062e-01 | | | -1.965e-01 | | | 6.062e-01 | | | -1.946e-01 | | | |
| $c_1$ | -3.960e-02 | | | 2.343e-01 | | | -3.960e-02 | | | 2.322e-01 | | | |
| $c_2$ | 2.614e-02 | | | 3.609e-02 | | | 2.614e-02 | | | 3.636e-02 | | | |
| $c_3$ | 1.617e-03 | | | 1.166e-02 | | | 1.617e-03 | | | 1.159e-02 | | | |
| $c_4$ | -2.016e-03 | 0.53 | 3.05 | -3.376e-02 | 0.76 | 4.25 | -2.016e-03 | 0.53 | 3.05 | -3.329e-02 | 0.73 | 4.25 | ARM71a |
| $c_5$ | 6.141e-05 | | | -2.154e-03 | | | 6.141e-05 | | | -2.157e-03 | | | |
| $c_6$ | -3.325e-06 | | | -2.006e-04 | | | -3.325e-06 | | | -2.031e-04 | | | |
| $c_7$ | 2.839e-05 | | | 5.608e-04 | | | 2.839e-05 | | | 5.747e-04 | | | |
| $c_8$ | -2.067e-05 | | | | | | -2.067e-05 | | | -3.868e-05 | | | |
| $c_9$ | -2.881e-06 | | | 2.887e-05 | | | -2.881e-06 | | | 2.914e-05 | | | |
| $c_0$ | 5.652e-01 | | | 1.719e-01 | | | 6.993e-01 | | | 1.885e-01 | | | |
| $c_1$ | -6.267e-02 | | | 3.368e-01 | | | -5.921e-02 | | | 3.264e-01 | | | |
| $c_2$ | 2.706e-02 | | | -3.258e-02 | | | 1.666e-02 | | | -3.222e-02 | | | |
| $c_3$ | 2.985e-03 | | | 1.644e-02 | | | 2.813e-03 | | | 1.624e-02 | | | |
| $c_4$ | -2.241e-03 | 1.93 | 7.79 | -5.908e-02 | 2.41 | 11.03 | -2.113e-03 | 2.00 | 7.51 | -5.677e-02 | 2.35 | 11.03 | D2Y60 |
| $c_5$ | -2.238e-04 | | | -2.635e-04 | | | 2.561e-05 | | | -2.671e-04 | | | |
| $c_6$ | -2.244e-05 | | | -6.326e-04 | | | -2.049e-05 | | | -6.445e-04 | | | |
| $c_7$ | 3.761e-05 | | | 1.728e-03 | | | 3.467e-05 | | | 1.788e-03 | | | |
| $c_8$ | -2.007e-05 | | | | | | -1.879e-05 | | | -2.030e-04 | | | |
| $c_9$ | | | | 4.260e-05 | | | -1.864e-06 | | | 4.380e-05 | | | |
| $c_0$ | -1.118e+00 | | | 8.057e-01 | | | -1.252e+00 | | | 1.052e+00 | | | |
| $c_1$ | -1.254e-01 | | | 1.022e-01 | | | -1.335e-01 | | | 1.020e-01 | | | |
| $c_2$ | 1.629e-01 | | | -2.498e-02 | | | 1.729e-01 | | | -5.260e-02 | | | |
| $c_3$ | 5.285e-03 | | | 6.127e-02 | | | 5.657e-03 | | | 6.182e-02 | | | |
| $c_4$ | -1.309e-03 | 6.81 | 29.99 | -9.404e-02 | 5.31 | 25.35 | -1.613e-03 | 6.61 | 29.81 | -9.565e-02 | 5.06 | 24.59 | R32 |
| $c_5$ | -3.095e-03 | | | -7.826e-03 | | | -3.322e-03 | | | -6.880e-03 | | | |
| $c_6$ | -4.058e-05 | | | -9.007e-04 | | | -4.443e-05 | | | -7.694e-04 | | | |
| $c_7$ | | | | | | | 5.061e-06 | | | -5.057e-04 | | | |
| $c_8$ | | | | 2.722e-03 | | | -5.690e-06 | | | 3.381e-03 | | | |
| $c_9$ | 2.288e-05 | | | 1.725e-04 | | | 2.455e-05 | | | 1.501e-04 | | | |

**Table 3:** Empirical models $\dot{W}_c$, compressor NEK6214Z (AHRI 30)

| | **AHRI (T-SW)** | **MRE (%)** | **RMSE (W)** | **AHRI (P-SW)** | **MRE (%)** | **RMSE (W)** | **AHRI (T)** | **MRE (%)** | **RMSE (W)** | **AHRI (P)** | **MRE (%)** | **RMSE (W)** | **Fluid** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $c_0$ | 5.292e-01 | | | 9.481e-02 | | | 5.292e-01 | | | 1.481e-01 | | | |
| $c_1$ | 1.517e-02 | | | 1.407e-01 | | | 1.535e-02 | | | 9.525e-02 | | | |
| $c_2$ | 2.639e-03 | | | 2.254e-02 | | | 2.640e-03 | | | 2.002e-02 | | | |
| $c_3$ | -1.543e-04 | | | | | | -1.543e-04 | | | 1.138e-03 | | | |
| $c_4$ | 1.327e-04 | 0.78 | 1.73 | -2.438e-03 | 0.78 | 1.71 | 1.338e-04 | 0.75 | 1.67 | 1.059e-02 | 0.75 | 1.67 | R134A |
| $c_5$ | 1.489e-05 | | | -9.158e-04 | | | 1.489e-05 | | | -8.479e-04 | | | |
| $c_6$ | 2.948e-06 | | | 2.182e-04 | | | 2.948e-06 | | | 1.956e-04 | | | |
| $c_7$ | | | | -3.189e-04 | | | -2.540e-08 | | | -4.119e-04 | | | |
| $c_8$ | | | | | | | -2.022e-06 | | | -1.290e-03 | | | |
| $c_0$ | 5.727e-01 | | | 2.098e-01 | | | 5.727e-01 | | | 1.301e-01 | | | |
| $c_1$ | 1.004e-02 | | | 1.245e-01 | | | 9.293e-03 | | | 1.886e-01 | | | |
| $c_2$ | 2.420e-03 | | | -2.399e-03 | | | 2.420e-03 | | | 9.614e-04 | | | |
| $c_3$ | 8.642e-05 | | | 6.421e-03 | | | 1.226e-04 | | | 4.268e-03 | | | |
| $c_4$ | -1.710e-05 | 0.81 | 2.33 | -7.460e-03 | 0.85 | 2.42 | -1.710e-05 | 0.77 | 2.31 | -2.338e-02 | 0.78 | 2.33 | R1234YF |
| $c_5$ | 9.289e-06 | | | 2.101e-04 | | | 9.289e-06 | | | 2.101e-04 | | | |
| $c_6$ | | | | -1.484e-04 | | | -4.015e-07 | | | -1.484e-04 | | | |
| $c_7$ | 2.422e-06 | | | | | | 2.422e-06 | | | 3.262e-04 | | | |
| $c_8$ | | | | | | | -1.185e-07 | | | 1.216e-03 | | | |

## NOMENCLATURE

| | | | |
|---|---|---|---|
| $SH$ | Superheat (K) | $P_r$ | Pressure ratio (-) |
| $SC$ | Subcooling (K) | $\dot{W}_c$ | Compressor power input (kW) |
| $T_e$ | Evaporation temperature at dew point (°C) | $\dot{m}$ | Refrigerant mass flowrate (kg/h) |
| $T_c$ | Condensation temperature at dew point (°C) | $MRE$ | Maximum Relative Error (%) |
| $P_e$ | Evaporation pressure (bar) | $RMSE$ | Root Mean Square Error |
| $P_c$ | Condensation pressure (bar) | *L/M/H-BP* | Low/Medium/High Back Pressure |
| $T_s$ | Suction temperature (°C) | | |

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