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A CRITICAL ANALYSIS OF THE CHARACTERIZATION OF SCROLL COMPRESSORS MASS FLOWRATE

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ABSTRACT

This paper presents the analysis of the refrigerant mass flowrate of scroll type compressors. The study has included the data of several AHRI reports: (especially AHRI-11 and AHRI-21) as well as data from other sources. A total of 8 different scroll compressors of different sizes, tested with various refrigerants, have been considered in the study. The compressor mass flowrate, the corresponding volumetric efficiency, and the shape of the corresponding response surfaces, have been analyzed with the objective of understanding better the dependence of the compressor mass flowrate on the operating conditions and the refrigerant. One of the study results is that correlation of the mass flowrate as a function of pressures is more universal than as a function of temperatures. Two simple correlation polynomials, based on suction and discharge pressures, are presented, which require less empirical information and have better interpolation-extrapolation characteristics than the standard correlations.

Keywords: Refrigeration, Scroll compressor, Modelling, Mass flowrate

1. INTRODUCTION

Nowadays, mathematical models allow the estimation of a vapor compression system's performance and therefore are very useful in assisting the systems design, analysis, and control. Numerous models have been proposed in the literature to estimate the compressor performance. A thorough review of compressor models has been included in several recent papers/reports, for instance, in Byrne et al., 2014 and Hermes et al., 2019.

Although a good number of semi-empirical models have been proposed over the years, fully empirical models are still in use, and it is the way that most of the compressors manufacturers report their compressor performance. In fact, as reported in Cheung and Wang, 2018, when semi-empirical models have been compared with empirical models in the cases where a large number of experimental data points are available, the fully empirical models show better agreement in the representation of the compressor performance.

The classical fully empirical model employed to characterize the compressor performance is the 10 coefficients third degree AHRI polynomial (ANSI/AHRI, 2015). These polynomials are able to provide a very accurate prediction of the compressor performance: refrigerant mass flowrate and compressor energy consumption across its entire working envelope by fitting 10 coefficients. There has always been a discussion about how many experimental data points and where to place them are necessary to reach a reasonably good accuracy all across the compressor envelope. This topic was recently researched by Aute et al., 2015, Aute and Martin, 2016 and Cheung and Wang, 2018.

A few authors have proposed other empirical modelsto reduce the amount of experimental data points required for their fitting and maybe additionally improving the interpolation and extrapolation capabilities of the functionals in comparison with the AHRI polynomial. Among this, it should be first mentioned the more compact 2nd-degree polynomial proposed by Shao (Shao et al., 2004), the functionals proposed by Aute et al. (Aute et al., 2014) and the proposed by Navarro et al. (Navarro-Peris et al., 2013).

Marchante-Avellaneda et al. studied the characterization of the compressor energy consumption of all scroll compressors tested along with the AHRI Low-GWP Alternative Refrigerants Evaluation Program (Marchante Avellaneda, 2021). This paper presents the analysis of the mass flowrate of the same set of scroll compressors, discussing its dependence on the operating conditions and introducing a new function for its correlation requiring much less adjusting coefficients than the standard AHRI polynomial.

2. COMPRESSOR PERFORMANCE DATA

A few years ago, AHRI disclosed a series of performance results of different compressors, scroll and piston, 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 scroll compressor tests and the performance data published in Cuevas and Lebrun, 2009.

AHRI-11 report (Shrestha et al., 2013a) and AHRI-21 report (Shrestha et al., 2013b) have been selected for discussion in this paper because they include many experimental test points, covering the entire operating domain of the respective compressors. Moreover, these reports show working maps for two different application ranges. The AHRI-11 report includes experimental results at moderate-high evaporation temperatures (M-HT), while the AHRI-21 report includes test results at low evaporation temperatures (LT). Therefore, the possible effect of the application range is also considered.

Table 1 summarizes the main characteristics of the analysed compressors. Table 2 shows the Mass% composition of the tested refrigerant' mixtures.

Table 1. Main compressor characteristics and tested refrigerants

Source	Model	Manufac.	Disp. (freq.) (cm^3) (Hz)	Refrigerants tested	Test points	Conditions by refrigerant test	
AHRI 21	ZS21KAE-PFV	Copeland	50.96 (60)	R404A/ARM31a/ D2Y65/L40	191/186/ 183/173	SH=11 K SH=22 K Tsuc=18ºC	SC=0 K
AHRI 11	ZP21K5E-PFV	Copeland	20.32 (60)	R410A/R32/DR5/ L41a	196/166/ 189/186		SC=8 K
Cuevas(2009)	-	-	54.25 (50)	R134a	18	SH=6.8ºC	

Table 2. New refrigerant's composition (Mass%)

Source	Name	Composition
AHRI 21	ARM-31a	R-32/R-134a/R-1234yf (28/21/51)
	D2Y-65	R-32/R-1234yf (35/65)
	L-40	R-32/R-152a/R-1234yf/R-1234ze(E) (40/10/20/30)
	R-32/R-134a	R-32/R-134a (50/50)
AHRI 11	DR-5	R-32/R-1234yf (72.5/27.5)
	L41a	R-32/R-1234yf/R-1234ze(E) (73/15/12)

3. COMPRESSOR MASS FLOWRATE ANALYSIS

The database considered includes test results for the entire working map of 8 scroll compressors. Additionally, some of the reports include three different conditions at the compressor's inlet: constant superheat with two values (SH=11K and SH=22K) and constant suction temperature (T=18 ºC).

The volumetric efficiency (η_v) has always been the parameter of choice to characterize a compressor's pumping characteristics, Eq. (1).

$$\eta_v = \frac{\dot{m}_{ref}}{\rho_s \cdot V_s \cdot n} \qquad \text{Eq. (1)}$$

Slightly different definitions have been developed trying to better represent the compressor mass flowrate all across its operation envelope; see, for instance (Pierre, 1982) and (Navarro-Peris et al., 2013). However, the developed functionals become more difficult to correlate and only bring a moderate improvement on the predictions. Figure 1 shows the volumetric efficiency of compressors ZS21KAE-PFV (AHRI-21) and ZP21K5E-PFV (AHRI-11) for their corresponding reference refrigerants, R404A, and R410A, respectively, and the three different inlet conditions considered.

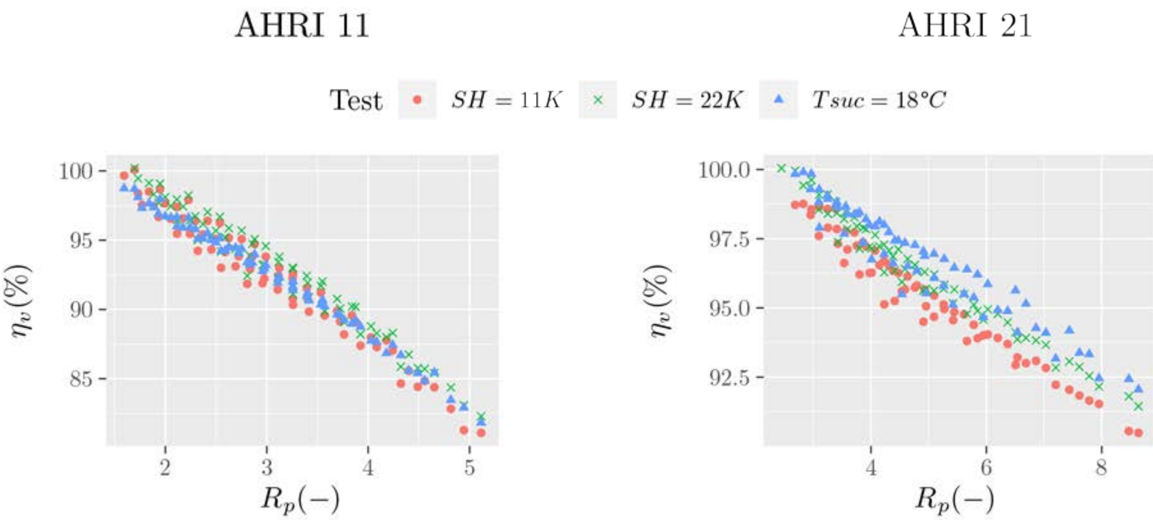

Figure 1: Volumetric efficiency versus pressure ratio of compressors ZP21K5E-PFV (AHRI-11) and ZS21KAE-PFV (AHRI-21) for their corresponding reference refrigerant, R410A and R404A

As can be observed, this figure shows a clear basic dependence of η_v with R_p, as it has been described in many references, with a decreasing trend with increasing the pressure ratio. However, it also becomes clear, first, that the relationship is not exactly linear but more complex and second that there are other influences. The relatively important influence of the inlet conditions on the volumetric efficiency is very visible, with higher volumetric efficiencies at higher superheats. This is also well known, and there exist ways to try to catch up with this effect and correct it in the estimation of the mass flowrate. The most employed correction is the one proposed by Dabiri (Dabiri and Rice, 1981). However, apart from that, it is also clear that the pressure ratio is not the only variable explaining the volumetric efficiency and that there is a clear influence of the evaporation and condensation temperatures, not explained by the pressure ratio. One can clearly see that there are groups of points distinguishable in Figure 1, corresponding to the same evaporation ($T_{e,dew}$) or condensation temperature ($T_{c,dew}$). Therefore, volumetric efficiency is a good parameter to characterize the compressor mass flowrate when a simple correlation is required. However, it is not the right way to characterize it in the general case. In fact, the AHRI standard (ANSI/AHRI, 2015) is based on the direct correlation of the compressor flowrate.

Figure 2 shows the mass flowrate of compressor ZP21K5E-PFV (AHRI-21) in a 3D plot as a function of evaporation and condensation temperatures for the case with constant superheat SH=11K. As it can be observed, at constant superheat, the mass flowrate surface is a quite smooth, mainly dependent on the evaporation temperature, almost linear but with a slight curvature, and a much weaker dependence on the condensation temperature, again almost linear with a slight curvature.

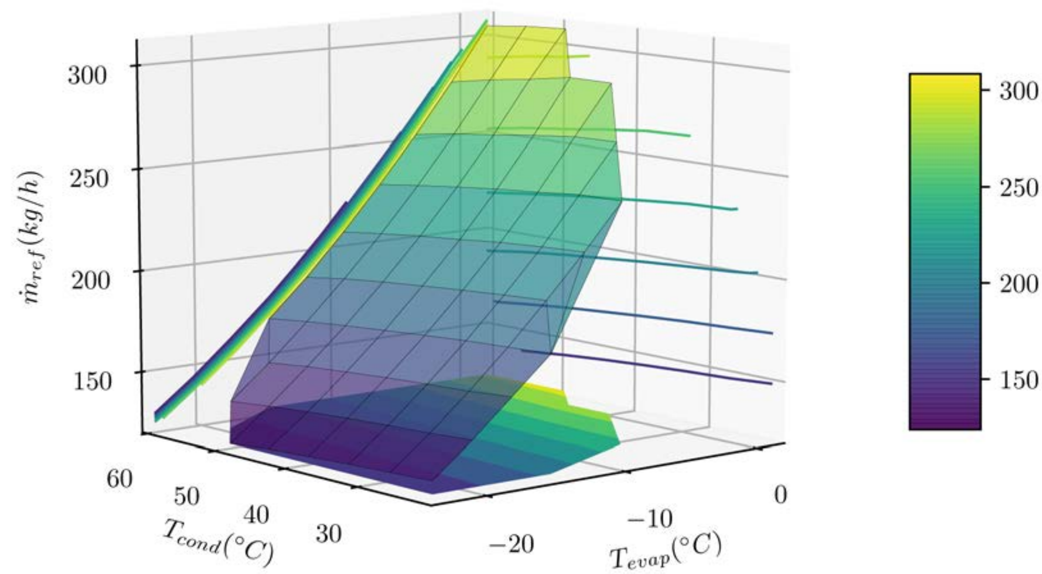

Figure 2: 3D plot of mass flowrate versus evaporation and condensation temperatures of compressor ZS21KAE-PFV with refrigerant R404A (SH=11 K).

The authors have analyzed the mass flowrate data of all AHRI reports referred above and the test data included in (Cuevas and Lebrun, 2009) and have found that the trends observed in Fig. 2 are the same for all compressors and refrigerants.

4. COMPRESSOR MASS FLOWRATE CORRELATIONS

4.1. Correlations employed

If one observes the surface representing the mass flowrate versus the condensation and evaporation temperatures shown in Figure 2, it is easy to understand why the 10 coefficients AHRI polynomial (ANSI/AHRI, 2015) is able to reproduce the response surface so well when enough experimental data points are available for the fitting and they are well distributed all across the operation domain. In fact, the authors have employed the more compact polynomial proposed by Shao et al., 2004 and have found that it provides the same ability to represent the surface with only 6 coefficients. The polynomial proposed by Shao employs only the main terms of the AHRI polynomial, and in the experience of the authors, it can represent very well the mass flowrate of scroll and rotary compressors.

However, when one plots the mass flowrate for different refrigerants versus the evaporation and condensation temperatures, the surfaces show different levels depending on their respective refrigerant properties as shown in Figure 3 (left), which shows the mass flowrate of compressor ZS21KAE-PFV of AHRI-21 for 4 different refrigerants. The authors have found that if alternatively, the mass flowrate is plotted as a function of the corresponding refrigerant pressures, instead of temperatures, it turns out that the surfaces are much more similar with each other, and become more linear, as can be seen in Figure 3 (right). This has also been observed for the other compressors. Therefore, it turns out that the representation versus the pressures is more universal than versus the temperatures and offers an easier correlation.

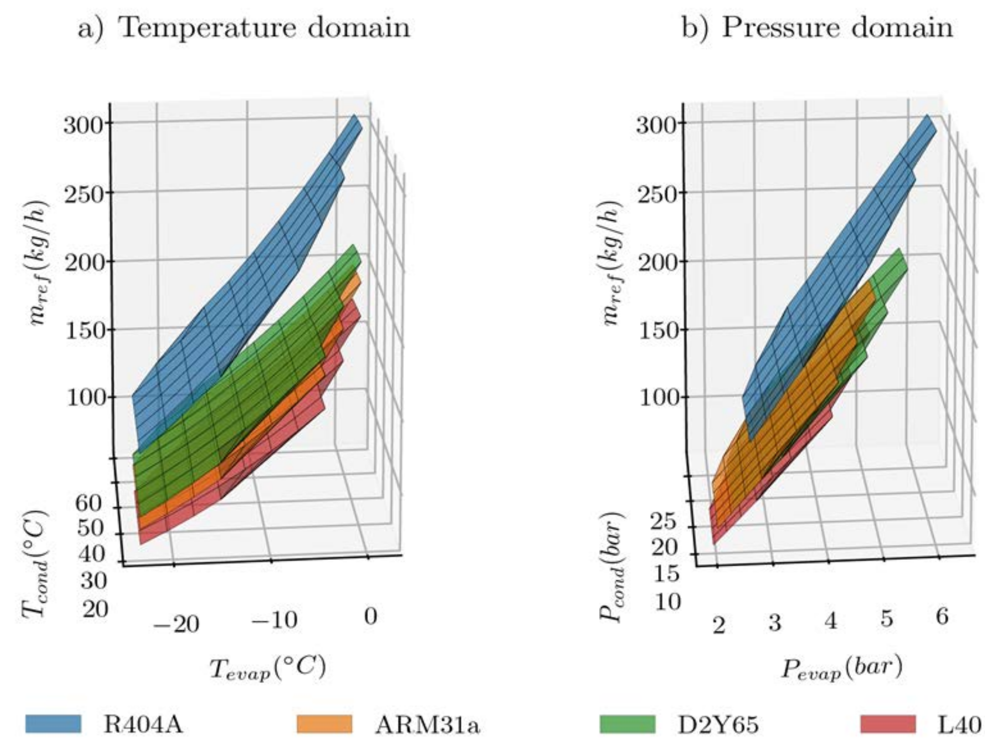

Figure 3: Left side: 3D plot of mass flowrate versus evaporation and condensation temperatures of compressor ZS21KAE-PFV for 4 different refrigerants. Right side: 3D plot of mass flowrate versus evaporation and condensation pressures of compressor ZS21KAE-PFV for 4 different refrigerants (SH=11 K).

As it can be observed in figure 3 right side, the compressor mass flowrate is a quite flat surface when represented versus the evaporation and condensation pressures. The authors have found that a simple linear polynomial, containing only linear terms, leads to a robust correlation with very decent accuracy for all the analyzed compressors and refrigerants. This polynomial will be referred to as Correlation 1 in the following comparison of results.

Correlation 1: $\dot{m}_{ref} = C_0 + C_1P_e + C_2P_c$ Eq. (2)

If one wants to increase the accuracy of the correlation, one should add one crossed term with evaporation and condensation pressures. This polynomial will be referred to as Correlation 2

Correlation 2: $\dot{m}_{ref} = C_0 + C_1P_e + C_2P_c + C_3P_eP_c$ Eq. (3)

Finally, to compare the results of the new proposed correlations with the standard correlation, we will compare the results with the correlation proposed by Shao et al., 2004, which has been commented above retain only the main terms of the AHRI polynomial. This polynomial will be referred to as Correlation 3

Correlation 3: $\dot{m}_{ref} = C_0 + C_1T_c^2 + C_2T_c + C_3T_e^2 + C_4T_e + C_5T_eT_c$ Eq. (4)

4.2. Comparison of correlations

The described correlations, 1 2 and 3, were fitted to the compressor mass flowrate results included in all the available AHRI reports with scroll compressors, mentioned in the first section, and to the set of the test points of Cuevas and Lebrun, 2009 corresponding to 50 Hz constant compressor frequency.

The results of the fitting were very good for all the analyzed compressors and refrigerants. We also did the fitting to the original 10 coefficients AHRI polynomial, but the results did not improve, and a big portion of the coefficients did not have significant enough. Table 3 shows a summary of the correlation results for compressors ZS21KAE-PFV (AHRI-21) and ZS21KAE-PFV (AHRI-11) for 4 different refrigerants each, and for the compressor tested by Cuevas and Lebrun, 2009, for the three correlations mentioned above. The Table includes the values of the coefficients (estimates) for correlation 1, 2, and 3, as well as the maximum relative error (MRE) in (%) and the Root Mean Square Error (RMSE) in kg/h. For each compressor and refrigerant, the correlations are fitted to the data tested at constant SH (SH=11K in AHRI reports and SH=6.8K in Cuevas and Lebrun, 2009). The effect of variable SH will be described in a future publication. The coefficients are meant to provide the compressor mass flowrate in kg/h with temperatures expressed in ºC and pressures in bar.

As can be seen in table 3, both MRE and RMSE are very low with practically all the analyzed correlations, providing a very good representation of the compressor mass flowrate across the entire envelope. The highest accuracy is reached with Correlation 2, proving that the correlation with pressures is better than with temperatures, and as discussed above, less dependent on the employed refrigerant. Correlation 1 is able to predict the results with a very decent accuracy with only 3 coefficients. It should be pointed out that the coefficients of both, Correlation 1 and 2 keep the same order of magnitude and sign independently of the refrigerant, which is not observed for Correlation 3.

Table 3. Correlation results

	Correlation 1			Correlation 2			Correlation 3				
Coeff	**Estimate**	**MRE (%)**	**RMSE (kg/h)**	**Estimate**	**MRE (%)**	**RMSE (kg/h)**	**Estimate**	**MRE (%)**	**RMSE (kg/h)**	**Source**	**Fluid**
C0	4.801E+00	1.09	0.80	-4.720E+00	0.85	0.53	3.056E+02	0.75	0.49	AHRI21	R404A
C1	5.093E+01			5.332E+01			-4.410E-03				
C2	-7.107E-01			-2.385E-01			-1.708E-02				
C3	-			-1.156E-01			9.452E-02				
C4	-			-			9.744E+00				
C5	-			-			-5.005E-03				
C0	1.362E+00	0.73	0.33	-7.923E-01	0.92	0.29	1.966E+02	0.92	0.28	AHRI21	ARM31a
C1	4.077E+01			4.145E+01			-1.931E-03				
C2	-5.273E-01			-4.026E-01			-7.248E-02				
C3	-			-3.794E-02			6.842E-02				
C4	-			-			6.563E+00				
C5	-			-			-1.204E-03				
C0	2.573E+00	1.24	0.55	-6.429E-01	1.62	0.50	2.089E+02	1.33	0.44	AHRI21	D2Y65
C1	3.888E+01			3.977E+01			-3.509E-03				
C2	-5.252E-01			-3.566E-01			5.783E-02				
C3	-			-4.516E-02			6.698E-02				
C4	-			-			6.772E+00				
C5	-			-			2.105E-04				
C0	1.311E+00	1.04	0.42	-4.331E-01	1.29	0.41	1.661E+02	1.04	0.32	AHRI21	L40
C1	3.668E+01			3.723E+01			-4.778E-03				
C2	-5.020E-01			-3.967E-01			2.149E-01				
C3	-			-3.196E-02			6.098E-02				
C4	-			-			5.692E+00				
C5	-			-			2.328E-03				
C0	2.223E+00	1.76	0.61	1.745E+00	1.75	0.61	1.697E+02	1.33	0.53	AHRI21	R32/R134a
C1	3.502E+01			3.515E+01			-8.758E-03				
C2	-8.059E-01			-7.767E-01			4.069E-01				
C3	-			-7.184E-03			6.584E-02				
C4	-			-			5.883E+00				
C5	-			-			7.470E-03				
C0	-4.472E+00	1.61	0.61	-1.032E+00	1.37	0.57	1.170E+02	1.42	0.40	AHRI11	R410A
C1	1.658E+01			1.617E+01			-6.558E-03				
C2	-6.726E-01			-8.171E-01			1.242E-01				
C3	-			1.661E-02			5.603E-02				
C4	-			-			4.082E+00				
C5	-			-			4.019E-03				
C0	-3.185E-01	2.24	0.86	-9.252E+00	1.67	0.70	7.745E+01	2.16	0.54	AHRI11	R32
C1	1.129E+01			1.227E+01			-9.097E-03				
C2	-6.301E-01			-2.390E-01			3.423E-01				
C3	-			-4.173E-02			3.534E-02				

C4	-			-			2.960E+00				
C5	-			-			9.063E-05				
C0	-2.305E+00			-2.829E-01			8.896E+01				
C1	1.346E+01			1.320E+01			-5.486E-03				
C2	-6.068E-01	1.33	0.32	-6.976E-01	1.02	0.29	9.685E-02	0.65	0.19	AHRI11	DR5
C3	-			1.121E-02			3.874E-02				
C4	-			-			3.075E+00				
C5	-			-			3.664E-03				
C0	-3.876E+00			1.350E+00			8.315E+01				
C1	1.291E+01			1.222E+01			-2.793E-03				
C2	-5.26E-01	1.87	0.41	-7.731E-01	1.22	0.27	-7.364E-02	0.99	0.25	AHRI11	L41a
C3	-			3.171E-02			3.476E-02				
C4	-			-			2.803E+00				
C5	-			-			4.679E-03				
C0	-1.155E+01			4.247E+00			1.332E+02				
C1	4.766E+01			4.575E+01			-1.610E-02				
C2	-1.706E+00	3.93	6.03	-2.297E+00	4.70	5.65	1.318E+00	2.76	4.48	Cuevas, Lebrun	R134a
C3	-			6.580E-02			1.500E-01				
C4	-			-			6.381E-01				
C5	-			-			7.263E-03				

5. CONCLUSIONS

A thorough analysis of the mass flowrate characteristics of scroll compressors has been performed. The study has included all scroll compressor results in the AHRI reports corresponding to the AHRI Low-GWP Alternative Refrigerants Evaluation Program. The following main conclusions can be drawn from the performed study.

The first conclusion is that when the compressor is measured in a wide range of operating conditions, inside its envelope, the volumetric efficiency shows a complex shape, with a main decreasing trend with the increase of the pressure ratio but with a complex influence also on the evaporation and condensation temperatures. Also, it is clearly sensitive to the suction conditions (superheat). In contrast, the compressor mass flowrate is a smooth surface when plotted versus the evaporation and condensation temperatures (or pressures). Therefore, the compressor mass flowrate is much easier to characterize by fitting a polynomial than the volumetric efficiency.

It is not necessary to employ a 10 coefficients polynomial for scroll compressors as proposed in (ANSI/AHRI, 2015) to characterize the compressor performance. A much compact expression proposed by (Shao et al., 2004) is accurate enough and requires fewer test points to be fitted to.

The authors have found that if the compressor mass flowrate is correlated versus the condensation and evaporation pressures, the correlation results are better, and it is more universal.

The mass flowrate of scroll compressors is a quite plane and smooth surface. A simple correlation with linear terms on the condensation and evaporation pressures requires only 3 coefficients and provides a very simple and robust representation. If higher accuracy is required, a 4 coefficients polynomial, including a cross-term with their product, provides a good accuracy across the compressor envelope.

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NOMENCLATURE

$\dot{m}_{ref}$	Mass flowrate (kg/h)	T_c	Condenser temperature at dew point (ºC)
n	Compressor speed (rps)	T_e	Evaporator temperature at dew point (ºC)
P_c	Condenser pressure (bar)	T_{suc}	Temperature at suction port (ºC)
P_e	Evaporator pressure (bar)	V_s	Swept volume (m3)
R_p	Pressure ratio (-)	ρ_s	Density at suction port (kg/m3)
SH	Superheat (K)	η_v	Volumetric efficiency (-)
SC	Subcooling (K)		

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