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FUNCTIONAL DEPENDENCE OF THERMODYNAMIC AND THERMOKINETIC PARAMETERS OF REFRIGERANTS USED IN MINE AIR REFRIGERATORS. PART 1 – REFRIGERANT R407C

ZALEŻNOŚCI FUNKCYJNE PARAMETRÓW TERMODYNAMICZNYCH I TERMOKINETYCZNYCH CZYNNIKÓW CHŁODNICZYCH STOSOWANYCH W GÓRNICZYCH CHŁODZIARKACH POWIETRZA. CZĘŚĆ 1 – CZYNNIK CHŁODNICZY R407C

The authors of this article dealt with the issue of modeling the thermodynamic and thermokinetic properties (parameters) of refrigerants. The knowledge of these parameters is essential to design refrigeration equipment, to perform their energy efficiency analysis, or to compare the efficiency of air refrigerators using different refrigerants. One of the refrigerants used in mine air compression refrigerators is R407C. For this refrigerant, 23 dependencies were developed, determining its thermodynamic and thermokinetic parameters in the states of saturated liquid, dry saturated vapour, superheated vapor, subcooled liquid, and in the two-phase region. The created formulas have been presented in Tables 2, 5, 8, 10 and 12, respectively. It should be noted that the scope of application of these formulas is wider than the range of changes of that refrigerant during the normal operation of mine refrigeration equipment. The article ends with the statistical verification of the developed dependencies. For this purpose, for each model correlation coefficients and coefficients of determination were calculated, as well as absolute and relative deviations between the given values from the program REFPROP 7 (Lemmon et al., 2002) and the calculated ones. The results of these calculations have been contained in Tables 14 and 15.

Keywords: refrigerants, R407C, thermodynamic and thermokinetic parameters

Autorzy niniejszego artykułu zajęli się zagadnieniem modelowania właściwości (parametrów) termodynamicznych i termokinetycznych czynników chłodniczych. Znajomość tych parametrów jest niezbędna do projektowania urządzeń chłodniczych, ich analizy energetycznej, a także do porównaniu efektywności pracy chłodziarek powietrza wykorzystujących różne czynniki chłodnicze. Jednym ze stosowanych w górniczych sprężarkowych chłodziarkach powietrza czynnikiem chłodniczym jest R407C. Dla wymienionego czynnika chłodniczego opracowano 23 zależności określające jego parametry termodynamiczne i termokinetyczne w stanie cieczy nasyconej, w stanie pary nasyconej suchej, w stanie pary przegrzanej, w stanie cieczy przechłodzonej oraz w stanie pary mokrej. Utworzone wzory podano odpowiednio w tabelach: 2, 5, 8, 10 i 12. Należy zaznaczyć, że zakresy obowiązywania tych wzorów są szersze od zakresów zmian

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tego czynnika podczas normalnej pracy górniczych urządzeń chłodniczych. Artykuł kończy weryfikacja statystyczna utworzonych zależności. W tym celu dla każdego wzoru obliczono współczynniki korelacji, determinacji oraz odchyłki bezwzględne i względne między wartościami danymi z programu REFPROP 7 (Lemmon i in., 2002) a obliczonymi. Rezultaty tych obliczeń zamieszczono w tabelach 14 i 15.

Słowa kluczowe: czynniki chłodnicze, R407C, parametry termodynamiczne i termokinetyczne

1. Introduction

In order to improve thermal working conditions in underground mine workings, air compression refrigerators are often used. Regarding the manner of heat reception, the following refrigerators can be distinguished:

- direct action refrigerators, in which the evaporator is directly used to cool the air,
- indirect action refrigerators, in which the evaporator is used to cool the water supplied to the gallery or longwall air refrigerators.

Regardless of the manner of heat reception, the refrigerators use low-boiling working fluids known as refrigerants. With respect to their composition, refrigerants are divided into single-component refrigerants (natural and synthetic, divided into the following groups: CFC – chlorofluorocarbon, HCFC – hydrochlorofluorocarbon and HFC – hydrofluorocarbon), and multi-component refrigerants (azeotropic, zeotropic, near-azeotropic) – Figure 1.

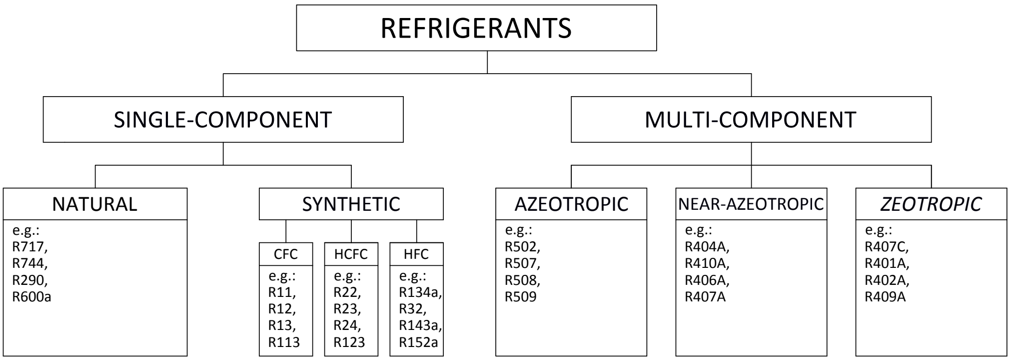

Fig. 1. Division of refrigerants due to their composition (Bonca et al., 2004)

The new group of refrigerants based on fluorines – HFO (hydrofluoroolefin) should also be mentioned. They have a lower GWP coefficient (global warming potential) than HFCs. Currently, two refrigerants belonging to this group: R1234yf and R1234ze were launched on the market. The first one is planned as a replacement for R134a in mobile air conditioning (MAC) systems.

The refrigerators in underground mining use synthetic refrigerants both single-component and multi-component. Depending on the type of the device and its nominal power, these are the following refrigerants: R407C, R404A, R507 and R134a (Elgór+ Hansen, 2014; Eurotech, 2013; IMKiUS, 2013; Gajosiński & Jankowska-Groch, 2011; Termospec, 2004; Wojciechowski, 2013). The units operating with the refrigerant R22 can still be found. Such devices may be used, provided that they are in good condition, tight and regularly serviced. It must be remembered, though, that as of 1 January 2015, it is forbidden to use R22 in any form (including recycled), so there is no possibility to fill up the installation operating on such a refrigerant (OJ L 286/1 2009). The basic properties of the refrigerants used in mine refrigerators have been illustrated in Table 1.

TABLE 1

Properties of the refrigerants used in mine refrigerators (Lemmon et al, 2002)

Parameter	Refrigerant				
	R22	R134a	R404A	R407C	R507
Group	HCFC	HFC	HFC	HFC	HFC
Chemical formula	CHF_2Cl	$C_2H_2F_4$	52% $C_2H_3F_3$ 44% C_2HF_5 4% $C_2H_2F_4$	52% $C_2H_2F_4$ 25% C_2HF_5 23% CH_2F_2	50% C_2HF_5 50% $C_2H_3F_3$
Mixture	—	—	52% R143a 44% R125 4% R134a	52% R134a 25% R125 23% R32	50% R125 50% R143a
Molar mass [kg/kmol]	86,468	102,03	97,604	86,204	98,859
Critical temperature [°C]	96,145	101,06	72,046	86,034	70,617
Critical pressure [bar]	49,9	40,593	37,289	46,298	37,05
Critical density [kg/m^3]	523,84	511,9	486,53	484,23	490,77
Normal boiling point [°C]	–40,81	–26,074	–46,5	–43,63	–46,74
Temperature of the triple point [°C]	–157,42	–103,3	–73,15	–73,15	–73,15
ODP (ozone depletion potential)	0,05	0	0	0	0
GWP (global warming potential)	1700	1300	3748	1609	3800

It is not possible to carry out the calculations of refrigeration circuits, or the working parameters of the devices in the refrigeration circuits, without the knowledge of the thermodynamic and thermokinetic properties (parameters) of the refrigerants used in these devices. This knowledge is essential in the analysis of energy efficiency, during the modeling or designing new, more efficient refrigeration equipment.

2. Thermodynamic and thermokinetic properties of refrigerants

Numerical values of various thermodynamic parameters of refrigerants, most commonly, are contained in graphs or tables. Such data can be found in numerous works dealing exclusively with the subject of refrigerants, such as (Bonca et al., 1998, 2004; Laroiya & Banwait, 2007; Grzebielec et al., 2011; Kothandaraman, 2011), in the publications of the manufacturers of refrigerants, for example (DuPont, 2004; Buchwald et al., 2008; Arkema, 2010, Mexichem, 2010), or in numerous books related to the refrigeration and air conditioning, such as (Ullrich, 1998, 1999; Bohdal et al., 2003; Radermacher & Hwang 2005; Recknagel et al., 2008; ASHRAE, 2010; Baumgarth et al., 2010; Butrymowicz et al., 2014). Detailed thermodynamic and thermokinetic parameters of refrigerants can be found using commercially available computer programs, such as Refrigerants 3.0 (Bonca et al, 1998), Thermodynamics – Heat Transfer (Domański et al., 2000), Duprex 3.2

(DuPont, 2011), released by the US National Institute of Standards and Technology, the program REFPROP 9.1 (Lemmon et al., 2013), or the program CoolProp 4.0 (Bell et al., 2014).

In engineering calculations, parameters of refrigerants read from tables or graphs may be subject to significant errors. Their reading for the measurement series is inconvenient and time-consuming. The values of these parameters can also be calculated using appropriate computer software. It involves, however, a need to purchase the license and is associated with the problem of the automation of obtaining required parameters for given input values. Numerical calculations use various kinds of equations of state, describing the relationships between the various parameters. Today, Helmholtz equation of state is the most commonly used for this purpose (Bell et al., 2014). In the literature it is possible to find dependencies describing the parameters of refrigerants in the form which does not require the use of numerical calculations but, most frequently, they only refer to the refrigerants in the state of saturated liquid or dry saturated vapour. The complex character of these dependencies makes it virtually impossible to use them in simple engineering calculations. The accuracy of the results should also be mentioned, which may differ significantly from the values obtained based on the equations of state.

In the work (Bonca et al., 1998), simple correlations can be found, describing the thermodynamic parameters and coefficients of transport of the refrigerants in the state of saturated liquid and dry saturated vapour as a function of their saturation temperature. They were obtained by approximation of the tabular data of the refrigerants with fifth degree polynomials. The author of the work (de Monte, 2002a), basing on the Martin-Hou equation of state, developed the equations describing the thermodynamic parameters of the refrigerants R407C and R410A in the superheated vapour region. The resulting equations are functions of the specific volume and temperature of the refrigerant. Continuing his research (de Monte, 2002b), F. de Monte compares calculation results obtained from the solutions to these equations compared with those obtained with the REFPROP computer program. For the various properties of R407C, the calculated relative deviations are included in the range of 0.4% to 9.7%. V. Feroiu and D. Geana in their works (Feroiu & Geana, 2003, 2011) presented the calculations results of thermodynamic parameters of the refrigerants R32, R125 and R134a and their mixtures using GEOS3C equations (General Cubic Equation of State with 3 Constants), the Soave-Redlich-Kwong equation and the Peng-Robinson equation. They compared the obtained results with the database of refrigerants available in the literature. In order to determine the relationships describing thermodynamic parameters of refrigerants (R22 and R407C), G. Ding et al. (2005) used a curve fitting method (implicit curve-fitting). The resulting formulas allow to determine the enthalpy, temperature, entropy, density and specific heat capacity for the refrigerants in the subcooled liquid state, the state of saturated liquid, two-phase region, dry saturated vapour and superheated vapour. The disadvantage of the formulas developed by the authors is their very complicated form, which makes it impossible to use them in simple engineering calculations. Using the techniques of artificial neural networks (ANN), A. Sozen et al. (2009) came up with slightly less complicated equations, but also limiting their use fast engineering calculations. The dependencies which they provide are for the two-phase region and for the superheated vapour region. For the refrigerant in the two-phase region, the knowledge of the temperature and the degree of dryness is required, while in the state of the superheated vapour – of the temperature and pressure. This allows the calculation of the specific volume, enthalpy, entropy, the dynamic coefficient of viscosity as well as thermal conductivity. E.U. Kucuksille et al. (2009, 2011), using various data mining techniques, obtained simple equations for determining the enthalpy, entropy, specific volume, specific heat capacity, the coefficient of dynamic viscosity, thermal conductivity and density of refrigerants at saturation state. The formulas were developed for R134a, R404a, R407C and R410A. A disadvantage of the developed dependencies is the need to know two parameters of the refrigerant on the saturation line: the temperature and the pressure.

In the literature, the dependencies describing the performance of refrigerants, either relate only to the region of saturated liquid and dry saturated vapour or, with its complicated form, make them impossible to be used in simple engineering calculations. Therefore, in this paper, the authors have developed the dependencies to determine the thermodynamic and thermokinetic parameters of the refrigerants in all regions, which have high accuracy and simple form.

3. Calculation formulas of thermodynamic and thermokinetic parameters of R407C

Depending on the state of a refrigerant, in order to unambiguously determine its thermodynamic and thermokinetic parameters, one independent variable is required (saturated liquid, dry saturated vapour) or two independent variables (superheated vapour, subcooled liquid, two-phase region). As previously mentioned, the literature lists quite a number of dependencies describing the parameters of a refrigerant in the state of saturated liquid and dry saturated vapour. However, calculation formulas for thermodynamic parameters for the regions of superheated vapour, subcooled liquid and two-phase region, are usually very complicated, which makes them impossible to be used in engineering practice.

Part 1 of the paper presents the functional dependencies describing the thermodynamic and thermokinetic parameters of one of the most frequently used refrigerants in mine air refrigerators – R407C.

The input and output data of the R407C parameters required for the analysis were obtained from REFPROP 7 (Lemmon et al, 2002). The sought thermodynamic and thermokinetic parameters were described using polynomials of the 4, 5, 6, 7 or 8 degree, whose coefficients were determined using STATISTICA 10 (StatSoft, 2011). For this purpose, one of the nonlinear estimation methods of least squares was used – the Levenberg-Marquardt method. Levenberg-Marquardt is a modification (extension) of the Gauss-Newton algorithm. Using the loss function of least squares, as in the case of the Gauss-Newton algorithm, to find the parameter estimates of least squares, the partial derivatives of the second order do not need to be calculated (or estimated approximately), as for each iteration, to calculate the gradient, a corresponding system of linear equations is solved (StatSoft, 2006).

The dependencies describing specific parameters of the refrigerant R407C were selected so as to obtain the largest possible values of the correlation coefficients and coefficients of determination and, at the same time, the smallest possible values of both mean and maximum deviations (absolute and relative). Thus, the obtained polynomial coefficients were given to the nearest 12 digits – in the literature, the authors typically define coefficients with greater accuracy, for example in (de Monte, 2002) to 15 digits, and in (Ding et al., 2005) to 20 digits. Depending on the parameter of the refrigerant, 3 to 6 polynomials were tested in order to obtain the most accurate calculation results possible. The rest of this article presents only these dependencies for which the statistical analysis showed the highest correlation coefficients and coefficients of determination and the lowest values of deviations.

3.1. Saturated liquid region

For the R407C refrigerant in a saturated liquid state, dependencies were determined describing the basic thermodynamic parameters as a function of pressure:

- temperature T' [K],
- specific enthalpy h' [kJ/kg],
- specific heat c_p' [kJ/(kg·K)],
- density ρ' [kg/m^3],

as well as thermodynamic and thermokinetic parameters:

- thermal conductivity λ' [W/(m·K)]·10^3,
- the coefficient of dynamic viscosity μ' [kg/(m·s)],
- Prandtl number Pr' [-],
- surface tension σ' [N/m].

Using the program REFPROP 7 for the pressures of 0.5÷40 bar with variability of 0.05 bar, the values of the corresponding parameters of saturated liquid were read. A total of 791 data was used for the calculations for each of the analyzed properties of the refrigerant. The given range of pressure changes is significantly extended when compared to the observed changes in the refrigerant pressure during a trouble-free operation of mine air compression refrigerators.

Table 2 illustrates the dependencies.

TABLE 2

Calculation formulas for the thermodynamic and thermokinetic parameters of the R407C refrigerant in a saturated liquid state

No.	Parameter	Unit	Formula	Formula No.
1	2	3	4	5
1	Temperature	[K]	$T' = \sum_{n=1}^{6} a_n \cdot \ln p^n + a_0$	(1)
2	Specific enthalpy	[kJ/kg]	$h' = \sum_{n=1}^{8} a_n \cdot \ln p^n + a_0$	(2)
3	Specific heat	[kJ/(kg·K)]	$c_p{}' = \sum_{n=0}^{8} a_n \cdot p^n$	(3)
4	Density	[kg/m^3]	$\rho' = \sum_{n=1}^{8} a_n \cdot \ln p^n + a_0$	(4)
5	Coefficient of thermal conductivity	[W/(m·K)]·10^3	$\lambda' = \sum_{n=1}^{8} a_n \cdot \ln p^n + a_0$	(5)
6	Coefficient of dynamic viscosity	[kg/(m·s)]	$\mu' = \sum_{n=1}^{8} a_n \cdot \ln p^n + a_0$	(6)

1	2	3	4	5
7	Prandtl number	[-]	$\mathrm{Pr}' = \sum_{n=1}^{8} a_n \cdot \ln p^n + a_0$	(7)
8	Surface tension	[N/m]	$\sigma' = \sum_{n=1}^{8} a_n \cdot \ln p^n + a_0$	(8)

The determined coefficients of the polynomial for the specific properties of the refrigerant have been summarized in Table 3 (thermodynamic parameters) and Table 4 (thermokinetic parameters).

TABLE 3

Coefficients of polynomials describing the thermodynamic parameters of saturated liquid of the R407C refrigerant

No.	Coefficients	Formula			
		$T' = f(p)$	$h' = f(p)$	$c_p' = f(p)$	$\rho' = f(p)$
		(1)	(2)	(3)	(4)
1	a_0	2,29250321067E+02	1,40422220472E+02	1,28528960459E+00	1,38056160758E+03
2	a_1	2,07331294777E+01	2,73191911150E+01	2,73793649218E-02	–6,42783062633E+01
3	a_2	2,16190955438E+00	1,67325019978E+00	–1,48287611661E-04	5,32615534727E+00
4	a_3	2,31771874095E-01	1,47595808451E+00	–2,62736927675E-04	–1,10497623222E+01
5	a_4	5,03999449518E-03	2,15960117966E+00	4,12910612681E-05	–1,94804030402E+01
6	a_5	9,04543420167E-03	–3,22100110688E+00	–2,80606807457E-06	2,95276767573E+01
7	a_6	–1,16532121747E-03	1,70547615957E+00	1,00327289701E-07	–1,56232932645E+01
8	a_7	—	–4,01814891894E-01	–1,83340981355E-09	3,68340824048E+00
9	a_8	—	3,59632334415E-02	1,36404350024E-11	–3,29758585664E-01

TABLE 4

Coefficients of polynomials describing the thermokinetic parameters of saturated liquid of the R407C refrigerant

No.	Coefficient	Formula			
		$\lambda' = f(p)$	$\mu' = f(p)$	$\mathrm{Pr}' = f(p)$	$\sigma' = f(p)$
		(5)	(6)	(7)	(8)
1	a_0	1,24697265723E+02	4,04381461193E-04	4,29410020046E+00	1,78731825769E-02
2	a_1	–1,19153244076E+01	–1,39649487413E-04	–9,30597587759E-01	–3,57224306557E-03
3	a_2	–1,69142973658E+00	2,08780005583E-05	–3,59549913515E-01	–3,20257399689E-04
4	a_3	3,49198418516E-01	–2,77722839213E-06	3,29394521967E-01	–4,31464355918E-06
5	a_4	9,57437765626E-01	–1,64363225291E-06	7,31145922262E-01	2,99308077241E-05
6	a_5	–1,38797551090E+00	2,67233304436E-06	–1,08258850064E+00	–4,77708267702E-05
7	a_6	7,07926072507E-01	–1,41917623695E-06	5,60723254898E-01	2,62528209510E-05
8	a_7	–1,61712602790E-01	3,34259184299E-07	–1,29855040799E-01	–6,36471593898E-06
9	a_8	1,38991606597E-02	–2,97928202377E-08	1,13564807643E-02	5,98976819606E-07

3.2. Dry saturated vapour region

For the dry saturated vapour region, analogous dependencies were determined as for the refrigerant in a saturated liquid state:

- temperature T'' [K],
- specific enthalpy h'' [kJ/kg],
- specific heat c_p'' [kJ/(kg·K)],
- density ρ'' [kg/m^3],
- thermal conductivity λ'' [W/(m·K)]·10^3,
- the coefficient of dynamic viscosity μ'' [kg/(m·s)],
- Prandtl number Pr'' [-],
- surface tension σ'' [N/m].

The dependencies have been developed as for the saturated liquid state, i.e. based on 791 data for each of the properties. Similarly as before, the given formulas are valid for the pressures of 0.5 to 40 bar. The following tables summarize:

- calculation formulas of the thermodynamic and thermokinetic parameters of the R407C refrigerant in the state of dry saturated vapour – Table 5,
- polynomial coefficients of the dependencies that describe the thermodynamic parameters of dry saturated vapour of the refrigerant – Table 6,
- polynomial coefficients of the dependencies that describe the thermokinetic parameters of dry saturated vapour of the refrigerant – Table 7.

TABLE 5

Calculation formulas of the thermodynamic and thermokinetic parameters of the R407C refrigerant in the state of dry saturated vapour

No.	Parameter	Unit	Formula	Formula No.
1	2	3	4	5
1	Temperature	[K]	$T'' = \sum_{n=1}^{6} a_n \cdot \ln p^n + a_0$	(9)
2	Specific enthalpy	[kJ/kg]	$h'' = \sum_{n=1}^{8} a_n \cdot \ln p^n + a_0$	(10)
3	Specific heat	5	$c_p'' = \sum_{n=0}^{7} a_n \cdot p^n$	(11)
4	Density	[kg/m^3]	$\rho'' = \sum_{n=0}^{7} a_n \cdot p^n$	(12)
5	Coefficient of thermal conductivity	[W/(m·K)]·10^3	$\lambda'' = \sum_{n=0}^{8} a_n \cdot p^n$	(13)
6	Coefficient of dynamic viscosity	[kg/(m·s)]	$\mu'' = \sum_{n=0}^{8} a_n \cdot p^n$	(14)

1	2	3	4	5
7	Prandtl number	[-]	$\mathrm{Pr}'' = \sum_{n=0}^{8} a_n \cdot p^n$	(15)
8	Surface tension	[N/m]	$\sigma'' = \sum_{n=1}^{8} a_n \cdot \ln p^n + a_0$	(16)

TABLE 6

Polynomial coefficients describing the thermodynamic parameters of dry saturated vapour of the R407C refrigerant

No.	**Coefficient**	**Formula**			
		$T'' = f(p)$	$h'' = f(p)$	$c_p'' = f(p)$	$\rho'' = f(p)$
		(9)	**(10)**	**(11)**	**(12)**
1	a_0	2,36260679825E+02	3,89436315999E+02	7,00107253561E-01	2,24872407118E-01
2	a_1	2,02789797499E+01	1,17564170870E+01	9,61657195713E-02	4,40789788044E+00
3	a_2	2,12995261278E+00	3,06023346166E+00	–1,43360144758E-02	–7,79698653753E-02
4	a_3	4,41905476479E-01	–1,59215078467E+00	1,62885780416E-03	1,09249091955E-02
5	a_4	–2,27324078862E-01	–3,08531870147E+00	–1,04431734622E-04	–6,50450529756E-04
6	a_5	9,19378644285E-02	4,72785556674E+00	3,81391572933E-06	2,35393536693E-05
7	a_6	–1,17214121233E-02	–2,51140699763E+00	–7,29783633399E-08	–4,47214011800E-07
8	a_7	—	5,94260442823E-01	5,75775787269E-10	3,59191208783E-09
9	a_8	—	-5,34939785696E-02	—	—

TABLE 7

Polynomial coefficients describing the thermokinetic parameters of dry saturated vapour of the R407C refrigerant

No.	**Coefficient**	**Formula**			
		$\lambda'' = f(p)$	$\mu'' = f(p)$	$\mathrm{Pr}'' = f(p)$	$\sigma'' = f(p)$
		(13)	**(14)**	**(15)**	**(16)**
1	a_0	7,87321967080E+00	9,08748865795E-06	8,15095257062E-01	1,69624683919E-02
2	a_1	1,61150931127E+00	1,11001864548E-06	3,86122364256E-02	–3,35402490636E-03
3	a_2	–2,60571168180E-01	–1,74651516494E-07	–1,80978796246E-03	–3,22486202505E-04
4	a_3	3,04905242778E-02	1,68809309104E-08	–3,06064660413E-04	–2,66148172933E-06
5	a_4	–2,11075896900E-03	–9,35325597784E-10	5,70412845411E-05	3,15456114972E-05
6	a_5	8,80898348272E-05	3,08680036095E-11	–3,76994685436E-06	–5,08962127952E-05
7	a_6	–2,15668694077E-06	–5,95296576200E-13	1,25899386562E-07	2,80424020706E-05
8	a_7	2,84864905033E-08	6,14180370300E-15	–2,12863616015E-09	–6,80265455746E-06
9	a_8	–1,55766549265E-10	–2,56315570371E-17	1,46156660187E-11	6,39281227568E-07

3.3. Superheated vapour region

In the superheated vapour region, the thermodynamic state of the refrigerant is given uniquely by two parameters of state. Therefore, determination of the dependence characterized by the highest possible value of the correlation (determination) coefficient, and possibly small deviations, is becoming more complicated. First of all, the number of data needed to conduct estimations increases significantly, and the time of calculation lengthens considerably. For further calculations, the authors developed 4 dependencies describing the parameters of the refrigerant in the superheated vapour region:

- specific enthalpy as a function of pressure and temperature: $h = f(p,t)$,
- specific enthalpy as a function of pressure and specific entropy: $h = f(p,s)$,
- specific entropy as a function of pressure and temperature: $s = f(p,t)$,
- temperature as a function of pressure and specific enthalpy: $T = f(p,h)$.

Also here, these dependencies apply to he pressures of 0.5 to 40 bar, and the temperatures – from the dry saturated vapour temperature to 100°C. Using the REFPROP program for variable pressure of 0.1 bar and a variable temperature of 1°C, the corresponding values of the specific enthalpy and the specific entropy were read. In this way, to determine individual calculation formulas, 23,033 data were used.

The resulting calculation formulas have been illustrated in Table 8, and the coefficients for the specific equations – in Table 9.

TABLE 8

Calculation formulas of the thermodynamic parameters of the R407C refrigerant in a superheated vapor state

No.	Parameter	Unit	Formula	Formula No.
1	Specific enthalpy as a function of pressure and temperature	[kJ/kg]	$h = \sum_{n=1}^{5} \left(a_n \cdot p + b_n \cdot t + c_n\right)^n$	(17)
2	Specific enthalpy as a function of pressure and specific entropy	[kJ/kg]	$h = \sum_{n=1}^{6} \left(a_n \cdot p + b_n \cdot s + c_n\right)^n$	(18)
3	Specific entropy as a function of pressure and temperature	[kJ/(kg·K)]	$s = \sum_{n=1}^{4} \left(a_n \cdot p + b_n \cdot t + c_n\right)^n$	(19)
4	Temperature as a function of pressure and specific enthalpy	[K]	$T = \sum_{n=1}^{4} \left(a_n \cdot p + b_n \cdot h + c_n\right)^n$	(20)

3.4. Subcooled liquid region

In the subcooled liquid region, the thermodynamic state of the refrigerant is also given uniquely by two state parameters. Therefore, the dependence was determined, describing the specific enthalpy of the refrigerant in the subcooled liquid region as a function of pressure and temperature, as well as the dependence describing the temperature as a function of pressure and specific enthalpy. The value of the dependent variable (specific enthalpy) was read for the

TABLE 9

Polynomial coefficients describing the thermodynamic parameters of superheated vapour of the R407C refrigerant

No.	Coefficient	Formula			
		$h = f(p,t)$	$h = f(p,s)$	$s = f(p,t)$	$T = f(p,h)$
		(17)	(18)	(19)	(20)
1	a_1	–1,65294961595E+03	–2,94158441995E+01	–1,89989364561E+00	–1,47750291327E+02
2	a_2	–1,79926636274E+00	–7,64562228377E-01	–8,53411671460E-02	–7,27209842287E-01
3	a_3	2,74658125363E-01	–1,09954201802E-01	–1,96045294858E-02	–5,23261034313E-02
4	a_4	1,02748159915E-01	–1,70815024797E-01	3,12482185641E-02	–1,82227877863E-02
5	a_5	4,16539761678E-02	9,97354877218E-02	—	—
6	a_6	—	8,55235139267E-03	—	—
7	b_1	7,28684642690E+02	–8,06701613754E+02	2,32452484605E-01	–2,64445732330E+02
8	b_2	8,30983322798E-01	–3,53779357638E+01	1,05298055396E-02	–9,40969469435E-01
9	b_3	–1,11928554081E-01	–5,34215907946E+00	2,45520632113E-03	–6,39413628736E-02
10	b_4	–3,74464624306E-02	3,40469100403E+00	4,69577711025E-04	–1,89211550901E-02
11	b_5	–1,44813353477E-02	–1,76488037523E+00	—	—
12	b_6	—	–7,34029559766E-02	—	—
13	c_1	7,27933120437E+04	1,46323609794E+03	–3,56423749994E+02	–1,42106976399E+04
14	c_2	–1,43087735806E+02	1,53111291910E+01	–2,45419536820E+01	–4,85323080283E+02
15	c_3	–5,24100047947E+01	–2,61750089115E+00	–6,25022392690E+00	–6,00695000076E+01
16	c_4	–1,79944793887E+01	–5,85766172287E-01	–7,23784202256E-01	–1,20494117267E+00
17	c_5	–8,83177713710E+00	–8,72963953015E-01	—	—
18	c_6	—	–4,20957108375E-01	—	—

pressures of 0.5 to 40.0 bar (in increments of 0.1 bar) and the temperatures of –100°C to the temperature of a saturated liquid (in increments of 1°C). In this way, 55,524 data were obtained for the analysis. The same data was also used to determine the formula for the refrigerant temperature. The forms of these two functions have been illustrated in Table 10, and the coefficients of the polynomial in Table 11.

TABLE 10

Calculation formulas of the thermodynamic parameters of the R407C refrigerant in a subcooled liquid state

No.	Parameter	Unit	Formula	Formula No.
1	Specific enthalpy as a function of pressure and temperature	[kJ/kg]	$h = \sum_{n=1}^{6} \left(a_n \cdot p + b_n \cdot t + c_n \right)^n$	(21)
2	Temperature as a function of pressure and specific enthalpy	[K]	$T = \sum_{n=1}^{4} \left(a_n \cdot p + b_n \cdot h + c_n \right)^n$	(22)

TABLE 11

Polynomial coefficients describing the thermodynamic parameters of the subcooled liquid of the R407C refrigerant

No.	Coefficient	Formula	
		$h = f(p,t)$	$T = f(p,h)$
		(21)	(22)
1	a_1	–4,98796427484E+00	4,17193968158E+00
2	a_2	–5,75014230843E-02	–4,16292119152E-03
3	a_3	1,48714891946E-02	–2,05488208514E-03
4	a_4	–6,85849431332E-03	–1,40198481292E-03
5	a_5	–3,50217321209E-03	—
6	a_6	–1,73870921417E-03	—
7	b_1	2,91384107427E+01	–1,60303977864E+01
8	b_2	3,22116370517E-01	8,78276803940E-05
9	b_3	–7,94748562287E-02	7,09498773051E-03
10	b_4	3,34877132455E-02	4,95516120731E-03
11	b_5	2,21858397674E-02	—
12	b_6	1,53791260925E-02	—
13	c_1	–4,14878066030E+01	2,34481430789E+04
14	c_2	–2,54043145782E+01	–8,28853331118E+01
15	c_3	–7,70035534228E+00	–3,16107764807E+01
16	c_4	2,70883292712E+00	–6,10733689249E+00
17	c_5	–1,03990877301E+00	—
18	c_6	–4,96833399666E-01	—

3.5. Two-phase region

For the two-phase region, the authors developed a relationship describing the heat of vaporization as a function of pressure. The dependence was based upon the data obtained in the same way as the parameters of the density line (791 data). The formula is presented in Table 12, and the polynomial coefficients are contained in Table 13.

TABLE 12

Calculation dependence describing the heat of vaporization of the R407C refrigerant

No.	Parameter	Unit	Formula	Formula No.
1	Heat of vaporization	[kJ/kg]	$r = \sum_{n=1}^{8} a_n \cdot \ln p^n + a_0$	(23)

TABLE 13

Polynomial coefficients describing the heat of vaporization of the R407C refrigerant

No.	Coefficient	Formula
		$r = f(p)$
		(23)
1	a_0	2,49014089447E+02
2	a_1	–1,55628179728E+01
3	a_2	1,38709019024E+00
4	a_3	–3,06807988658E+00
5	a_4	–5,24512520779E+00
6	a_5	7,94903970837E+00
7	a_6	–4,21695552902E+00
8	a_7	9,96089008769E-01
9	a_8	–8,94582179330E-02

4. Statistical verification of calculation formulas of the thermodynamic and thermokinetic parameters of the R407C refrigerant

In order to verify the correctness of the developed dependencies describing the thermodynamic and thermokinetic parameters, for each model, correlation coefficients, coefficients of determination, as well as absolute and relative deviations were calculated between the values given from the program REFPROP 7 (Lemmon et al, 2002) and the calculated ones. The values of the correlation coefficients and the coefficients of determination have been illustrated in Table 14.

TABLE 14

Correlation coefficients and coefficients of determination of the calculation formulas for the thermodynamic and thermokinetic parameters of the R407C refrigerant

No.	Formula		Region	Correlation coefficient R [-]	Coefficient of determination R^2 [-]
1	2	3	4	5	6
1	$T' = f(p)$	(1)	Saturated liquid	0,9999999951	0,9999999901
2	$h' = f(p)$	(2)	Saturated liquid	0,9999994348	0,9999988696
3	$c_p' = f(p)$	(3)	Saturated liquid	0,9999982169	0,9999964337
4	$\rho' = f(p)$	(4)	Saturated liquid	0,9999951614	0,9999903228
5	$\lambda' = f(p)$	(5)	Saturated liquid	0,9999982677	0,9999965355
6	$\mu' = f(p)$	(6)	Saturated liquid	0,9999998329	0,9999996658
7	$\mathrm{Pr}' = f(p)$	(7)	Saturated liquid	0,9986101992	0,9972223299
8	$\sigma' = f(p)$	(8)	Saturated liquid	0,9999999890	0,9999999781
9	$T'' = f(p)$	(9)	Dry saturated vapour	0,9999999307	0,9999998614
10	$h'' = f(p)$	(10)	Dry saturated vapour	0,9999594306	0,9999188628

1	2	3	4	5	6
11	$c_p'' = f(p)$	(11)	Dry saturated vapour	0,9999964909	0,9999929818
12	$\rho'' = f(p)$	(12)	Dry saturated vapour	0,9999999876	0,9999999753
13	$\lambda'' = f(p)$	(13)	Dry saturated vapour	0,9999962025	0,9999924050
14	$\mu'' = f(p)$	(14)	Dry saturated vapour	0,9999845443	0,9999690889
15	$\mathrm{Pr}'' = f(p)$	(15)	Dry saturated vapour	0,9999972450	0,9999944900
16	$\sigma'' = f(p)$	(16)	Dry saturated vapour	0,9999999852	0,9999999705
17	$h = f(p,t)$	(17)	Superheated vapour	0,9999221669	0,9998443400
18	$h = f(p,s)$	(18)	Superheated vapour	0,9971180270	0,9942443597
19	$s = f(p,t)$	(19)	Superheated vapour	0,9955009248	0,9910220913
20	$T = f(p,h)$	(20)	Superheated vapour	0,9999634400	0,9999268813
21	$h = f(p,t)$	(21)	Subcooled liquid	0,9999993192	0,9999986383
22	$T = f(p,h)$	(22)	Subcooled liquid	0,9999971879	0,9999943758
23	$r = f(p)$	(23)	Two-phase	0,9999958946	0,9999917892

The developed dependencies are characterized by very high values of correlation coefficients – in all cases they exceed 99%, and they are frequently close to one. Also, the coefficients of determination are characterized by the values close to one, proving that the models almost entirely explain the variability of the dependent variable. The lowest values of the correlation coefficients and the coefficients of determination exist for the dependence describing the specific entropy in superheated vapour region (formula 19) and are, respectively, 0.9955009248 and 0.9910220913. Such good fitting of the calculation results to the data means that, in most cases, the absolute and the relative deviation, listed in Table 15, between the data from the program REFPROP 7 (Lemmon et al., 2002) and the calculated ones, are very small.

TABLE 15

Absolute and relative deviations between the given and calculated values

No.	Formula		Region	Absolute deviation			Relative deviation [%]	
1	2	3	4	5	6	7	8	9
1	$T' = f(p)$	(1)	Saturated liquid	mean	[K]	0,002625	mean	0,000844
				maximum		0,009304	maximum	0,002652
2	$h' = f(p)$	(2)	Saturated liquid	mean	[kJ/kg]	0,042417	mean	0,016805
				maximum		0,246513	maximum	0,174418
3	$c_p' = f(p)$	(3)	Saturated liquid	mean	[kJ/(kg·K)]	0,000791	mean	0,041573
				maximum		0,006444	maximum	0,302075
4	$\rho' = f(p)$	(4)	Saturated liquid	mean	[kg/m^3]	0,386680	mean	0,038908
				maximum		2,204985	maximum	0,280868
5	$\lambda' = f(p)$	(5)	Saturated liquid	mean	[W/(m·K)]·10^3	0,022564	mean	0,030280
				maximum		0,164756	maximum	0,266265
6	$\mu' = f(p)$	(6)	Saturated liquid	mean	[kg/(m·s)]·10^3	0,000035	mean	0,033062
				maximum		0,000196	maximum	0,305177
7	$\mathrm{Pr}' = f(p)$	(7)	Saturated liquid	mean	[-]	0,015927	mean	0,536250
				maximum		0,107617	maximum	2,843924

1	2	3	4	5	6	7	8	9
8	$\sigma' = f(p)$	(8)	Saturated liquid	mean	[N/m]·10^3	0,000522	mean	0,025271
				maximum		0,002826	maximum	0,449592
9	$T'' = f(p)$	(9)	Dry saturated vapour	mean	[K]	0,008959	mean	0,002868
				maximum		0,057946	maximum	0,025976
10	$h'' = f(p)$	(10)	Dry saturated vapour	mean	[kJ/kg]	0,060356	mean	0,014449
				maximum		0,345470	maximum	0,083516
11	$c_p'' = f(p)$	(11)	Dry saturated vapour	mean	[kJ/(kg·K)]	0,001753	mean	0,104801
				maximum		0,014829	maximum	0,748483
12	$\rho'' = f(p)$	(12)	Dry saturated vapour	mean	[kg/m^3]	0,008607	mean	0,019952
				maximum		0,068065	maximum	1,107458
13	$\lambda'' = f(p)$	(13)	Dry saturated vapour	mean	[W/(m·K)]·10^3	0,012122	mean	0,082895
				maximum		0,203014	maximum	2,412664
14	$\mu'' = f(p)$	(14)	Dry saturated vapour	mean	[kg/(m·s)]·10^3	0,000008	mean	0,068705
				maximum		0,000130	maximum	1,368215
15	$\mathrm{Pr}'' = f(p)$	(15)	Dry saturated vapour	mean	[-]	0,000649	mean	0,057785
				maximum		0,005052	maximum	0,494715
16	$\sigma'' = f(p)$	(16)	Dry saturated vapour	mean	[N/m]·10^3	0,000577	mean	0,031054
				maximum		0,003341	maximum	0,573553
17	$h = f(p,t)$	(17)	Superheated vapour	mean	[kJ/kg]	0,177682	mean	0,039434
				maximum		3,265836	maximum	0,789498
18	$h = f(p,s)$	(18)	Superheated vapour	mean	[kJ/kg]	1,214291	mean	0,266967
				maximum		11,695349	maximum	3,062732
19	$s = f(p,t)$	(19)	Superheated vapour	mean	[kJ/(kg·K)]	0,007443	mean	0,393223
				maximum		0,062769	maximum	2,894750
20	$T = f(p,h)$	(20)	Superheated vapour	mean	[K]	0,179120	mean	0,054781
				maximum		2,584147	maximum	1,158447
21	$h = f(p,t)$	(21)	Subcooled liquid	mean	[kJ/kg]	0,041994	mean	0,026519
				maximum		1,990728	maximum	0,596669
22	$T = f(p,h)$	(22)	Subcooled liquid	mean	[K]	0,067250	mean	0,026188
				maximum		1,936642	maximum	0,551802
23	$r = f(p)$	(23)	Two-phase	mean	[kJ/kg]	0,091531	mean	0,076823
				maximum		0,591981	maximum	0,739791

The mean relative deviations are from 0.000844% to 0.536250%, but for only 4 out of 23 dependencies they exceed 0.1%. The smallest maximum deviation value is 0.002652% and concerns the dependence defining the saturated liquid temperature change as a function of pressure. The largest one is 3.062732% and concerns specific enthalpy changes of the superheated vapour as a function of pressure and specific entropy. For the 7 dependencies, the maximum deviations exceed 1% – this is due to the wide range of the applicability of the dependence (especially at low pressures). Table 16 contains the maximum relative deviations for these dependencies for different pressure ranges.

TABLE 16

Maximum relative deviations for different pressure ranges

No.	Formula		Region	Maximum relative deviation [%]				
				0,5÷40 bar	**1,0÷40 bar**	**0,5÷35 bar**	**1,0÷35 bar**	**1,0÷30 bar**
1	$Pr' = f(p)$	(7)	Saturated liquid	2,843924	2,843924	1,453629	1,053108	0,875858
2	$\rho'' = f(p)$	(12)	Dry saturated vapour	1,107458	0,218539	1,107458	0,218539	0,218539
3	$\lambda'' = f(p)$	(13)	Dry saturated vapour	2,412664	0,635281	2,412664	0,635281	0,635281
4	$\mu'' = f(p)$	(14)	Dry saturated vapour	1,368215	0,427316	1,368215	0,427316	0,427316
5	$h = f(p,s)$	(18)	Superheated vapour	3,062732	1,606049	3,062732	0,984036	0,984036
6	$s = f(p,t)$	(19)	Superheated vapour	2,894750	1,937215	2,894750	1,308641	1,308641
7	$T = f(p,h)$	(20)	Superheated vapour	1,158447	0,367569	1,158447	0,367569	0,367569

A decrease in the pressure range reduces the number of maximum relative deviations exceeding 1%. And so, for a change of pressure in the range of 1.0÷30 bar, only for the dependence describing the specific entropy of superheated vapour as a function of pressure and temperature, the aforementioned deviation is slightly higher than 1% (1.308%).

5. Summary

The knowledge of the thermodynamic and thermokinetic parameters of refrigerants is necessary for the analysis of refrigeration circuits, for the modeling and designing of refrigerators and heat exchangers. The mine air compression refrigerators currently use the following refrigerants: R407C, R404A, R507 and R134a. This work discusses the first of the above refrigerants. The thermodynamic and thermokinetic parameters of this refrigerant (R407C) were described by a total of 23 dependencies applicable in the regions of subcooled liquid, saturated liquid, two-phase region, dry saturated vapour and superheated vapour. The dependencies in the subcooled liquid region and the superheated vapour region are especially useful in analyzing the work of refrigeration equipment where, in order to unambiguously determine the state of a refrigerant, the knowledge of two of thermodynamic parameters is required. All the formulas are applicable in the wide range of pressures (0.5÷40.0 bar) and are characterized by very high values of the correlation coefficients and coefficients of determination. In addition, their simple formula should be mentioned. Given the above, it may be stated that these relationships can be widely applied in all calculations relating to the refrigeration and air conditioning systems, both in mining and in environmental engineering.

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