

# THERMODYNAMIC PROPERTIES OF REFRIGERANTS

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## INTRODUCTION

For the simulation calculations of cooling circuit the thermal and caloric status indicators of refrigerants and the relationships between them must be known. Therefore, we aimed to determine these. Here, only the fluid status change between liquid and gaseous state and these two states will be discussed. It is assumed that we know the mass of the fluid molecules ( $M$ ), the temperature ( $T_C$ ), the pressure ( $p_C$ ) and the density ( $\rho_C$ ) of the critical point, as well as the temperature of the triple point ( $T_i$ ).

## STATUS INDICATORS

To describe the thermal status indicators of the fluid we must know [1]: (*according to Gibbs phase rule in case of one phase two-, and in case of two phases only one status indicator is freely selectable*)

- the equation of state in gaseous phase in the  $p = p(\rho, T)$  form,
- the saturation vapor pressure function of temperature  $p_{sat} = p_{sat}(T_{sat})$ ,
- the saturated liquid density function of temperature  $\rho_l = \rho_l(T)$ ,
- the equation of state in liquid phase in the  $p_l = p_l(\rho, T)$  form.

In addition to the above, the ideal gas specific heat at constant pressure as a function of temperature  $c_{p0} = c_{p0}(T)$  must be known for the description of the caloric state

characteristics  $\left( e_B, h = e_B + \frac{p}{\rho}, s \right)$ . The ideal gas phase of the fluid is considered as the limit of  $\rho \rightarrow 0$ .

Equations for caloric status indicators are uncertain up to a constant  $(h_0, s_0)$ , so the value of the constants should be agreed on. According to the scientific literature the value of these constants are given in saturated liquid state at  $0^\circ\text{C}$ , namely

$$h_0 = 200 \frac{\text{kJ}}{\text{kg}} \text{ and } s_0 = 1 \frac{\text{kJ}}{\text{kgK}}.$$

After all these, let's see how the status indicators can be determined based on these data if we know the density and temperature.

The determination of the pressure is initiated by investigating whether the temperature is lower or higher than the critical temperature. If higher, the pressure value can be calculated based on function  $p(\rho, T)$  valid to the gas phase. If less, then we compute the saturated liquid and the saturated vapor density at the given temperature  $T$ ; The saturated liquid density according to the relation of  $\rho_l(T)$ , and

the saturated vapor density by solving equation  $p(\rho, T) = p_{sat}(T)$ . ( $T$  is known!) This gives the saturated vapor density, the  $\rho_v(T)$ . We investigate the relation of the given density to these values. If the current density is greater than the density of the saturated liquid  $\rho > \rho_l$ , the pressure can be calculated based on the relation  $p = p_l(\rho, T)$  which is valid in the liquid phase. If the density is lower than the density of the saturated liquid and is greater than the saturated vapor density  $\rho_l > \rho > \rho_v$ , the pressure equals to the saturation vapor pressure  $p = p_{sat}(T)$ , and if the given density is lower than the saturated vapor density, the pressure can be calculated from the state equation  $p = p(\rho, T)$  which is valid in the gas phase.

## RELATIONS BETWEEN THE STATUS INDICATORS

Thermodynamics law I and II. creates a connection between the thermal and the caloric indicators. Consequently, for the internal energy the following equation can be written:

$$de_B = \frac{p}{\rho^2} d\rho + T ds. \quad (1)$$

Expressing the entropy change from it we get

$$ds = \frac{1}{T} de_B - \frac{p}{\rho^2 T} d\rho. \quad (2)$$

Writing the entropy as the function of the temperature and density  $s = s(\rho, T)$  and its differential can be written as follows:

$$ds = \left. \frac{\partial s}{\partial T} \right|_{\rho} dT + \left. \frac{\partial s}{\partial \rho} \right|_T d\rho, \quad (3)$$

similarly in case of internal energy

$$de_B = \left. \frac{\partial e_B}{\partial T} \right|_{\rho} dT + \left. \frac{\partial e_B}{\partial \rho} \right|_T d\rho. \quad (4)$$

Substituting equation (4) into equation (2) and comparing it to expression (3) we can write that

$$ds = \underbrace{\frac{1}{T} \left. \frac{\partial e_B}{\partial T} \right|_{\rho}}_{\left. \frac{\partial s}{\partial T} \right|_{\rho}} dT + \underbrace{\left( \left. \frac{1}{T} \frac{\partial e_B}{\partial \rho} \right|_T - \frac{p}{\rho^2 T} \right)}_{\left. \frac{\partial s}{\partial \rho} \right|_T} d\rho. \quad (5)$$

Let's write the mixed second-order derivatives of entropy:

$$\frac{\partial^2 s}{\partial T \partial \rho} = \frac{1}{T} \frac{\partial^2 e_B}{\partial T \partial \rho} = -\frac{1}{T^2} \left. \frac{\partial e_B}{\partial \rho} \right|_T + \frac{1}{T} \frac{\partial^2 e_B}{\partial T \partial \rho} + \frac{p}{\rho^2 T^2} - \frac{1}{\rho^2 T} \left. \frac{\partial p}{\partial T} \right|_{\rho}, \quad (6)$$

we get

$$\left. \frac{\partial e_B}{\partial \rho} \right|_T = \frac{p}{\rho^2} - \frac{T}{\rho^2} \left. \frac{\partial p}{\partial T} \right|_{\rho}. \quad (7)$$

Introducing nomination

$$\left. \frac{\partial e_B}{\partial T} \right|_p = c_v \quad (8)$$

Using equations (7) and (8) the differential of the internal energy can be expressed as the following equation:

$$de_B = c_v dT + \left( \frac{p}{\rho^2} - \frac{T}{\rho^2} \left. \frac{\partial p}{\partial T} \right|_p \right) d\rho. \quad (9)$$

According to Thermodynamics law I and the definition of enthalpy the differential of enthalpy can be written as the following relation:

$$dh = Tds + \frac{1}{\rho} dp. \quad (10)$$

Expressing the entropy change from it we get:

$$ds = \frac{1}{T} dh - \frac{1}{\rho T} dp. \quad (11)$$

Writing the entropy as a function of the temperature and pressure  $s = s(T, p)$  and its differential we can write the following:

$$ds = \left. \frac{\partial s}{\partial T} \right|_p dT + \left. \frac{\partial s}{\partial p} \right|_T dp, \quad (12)$$

similarly in case of enthalpy

$$dh = \left. \frac{\partial h}{\partial T} \right|_p dT + \left. \frac{\partial h}{\partial p} \right|_T dp. \quad (13)$$

Substituting equation (13) into equation (11) and comparing it to expression (12) we can write that

$$ds = \underbrace{\frac{1}{T} \left. \frac{\partial h}{\partial T} \right|_p}_{\left. \frac{\partial s}{\partial T} \right|_p} dT + \underbrace{\left( \frac{1}{T} \left. \frac{\partial h}{\partial p} \right|_T - \frac{1}{\rho T} \right)}_{\left. \frac{\partial s}{\partial p} \right|_T} dp. \quad (14)$$

Let's write the mixed second-order derivatives of entropy:

$$\frac{\partial^2 s}{\partial T \partial p} = \frac{1}{T} \frac{\partial^2 h}{\partial T \partial p} = -\frac{1}{T^2} \left. \frac{\partial h}{\partial p} \right|_T + \frac{1}{T} \frac{\partial^2 h}{\partial T \partial p} + \frac{1}{\rho T^2} + \frac{1}{\rho^2 T} \left. \frac{\partial \rho}{\partial T} \right|_p, \quad (15)$$

and based on this we can write

$$\left. \frac{\partial h}{\partial p} \right|_T = \frac{1}{\rho} + \frac{T}{\rho^2} \left. \frac{\partial \rho}{\partial T} \right|_p. \quad (16)$$

Introducing nomination

$$\left. \frac{\partial h}{\partial T} \right|_p = c_p \quad (17)$$

the differential of enthalpy can be written as follows:

$$dh = c_p dT + \left( \frac{1}{\rho} + \frac{T}{\rho^2} \left. \frac{\partial \rho}{\partial T} \right|_p \right) dp. \quad (18)$$

Forming the differential of enthalpy according to its definition and using formula (9) we get

$$\begin{aligned} dh = de_B - \frac{p}{\rho^2} d\rho + \frac{1}{\rho} dp = c_v dT + \frac{p}{\rho^2} d\rho - \frac{T}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} d\rho - \\ - \frac{p}{\rho^2} d\rho + \frac{1}{\rho} dp = c_v dT - \frac{T}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} d\rho + \frac{1}{\rho} dp \end{aligned} \quad (19)$$

Writing the density as a function of the temperature and pressure, and forming its differential we can write

$$d\rho = \frac{\partial \rho}{\partial T} \Big|_p dT + \frac{\partial \rho}{\partial p} \Big|_T dp. \quad (20)$$

Substituting it into equation (19) we get

$$dh = \left( c_v - \frac{T}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} \frac{\partial \rho}{\partial T} \Big|_p \right) dT + \left( \frac{1}{\rho} - \frac{T}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} \frac{\partial \rho}{\partial p} \Big|_T \right) dp. \quad (21)$$

Writing the pressure as a function of the temperature and density, and forming its differential as well as using equation (20) we get the following relations:

$$dp = \frac{\partial p}{\partial T} \Big|_{\rho} dT + \frac{\partial p}{\partial \rho} \Big|_T d\rho = \underbrace{\left( \frac{\partial p}{\partial T} \Big|_{\rho} + \frac{\partial p}{\partial \rho} \Big|_T \frac{\partial \rho}{\partial T} \Big|_p \right)}_0 dT + \underbrace{\frac{\partial p}{\partial \rho} \Big|_T \frac{\partial \rho}{\partial p} \Big|_T}_1 dp, \quad (22)$$

$$\frac{\partial \rho}{\partial p} \Big|_T = \frac{1}{\frac{\partial p}{\partial \rho} \Big|_T}, \quad (23)$$

$$\frac{\partial \rho}{\partial T} \Big|_p = - \frac{\frac{\partial p}{\partial T} \Big|_{\rho}}{\frac{\partial p}{\partial \rho} \Big|_T}. \quad (24)$$

Based on them relation (21) can be written as follows:

$$\begin{aligned} dh = \left( c_v - \frac{T}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} \left( - \frac{\frac{\partial p}{\partial T} \Big|_{\rho}}{\frac{\partial p}{\partial \rho} \Big|_T} \right) \right) dT + \left( \frac{1}{\rho} - \frac{T}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} \frac{1}{\frac{\partial p}{\partial \rho} \Big|_T} \right) dp = \\ = \underbrace{\left( c_v + \frac{T}{\rho^2} \frac{\left( \frac{\partial p}{\partial T} \Big|_{\rho} \right)^2}{\frac{\partial p}{\partial \rho} \Big|_T} \right)}_{c_p(\rho, T)} dT + \left( \frac{1}{\rho} + \frac{T}{\rho^2} \frac{\partial p}{\partial T} \Big|_p \right) dp \end{aligned} \quad (25)$$

Substituting relation (22) into equation (19) we get the following expression to the differential of enthalpy:

$$\begin{aligned}
dh &= c_v dT - \frac{T}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} d\rho + \frac{1}{\rho} dp = c_v dT - \frac{T}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} d\rho + \\
&+ \frac{1}{\rho} \left( \frac{\partial p}{\partial T} \Big|_{\rho} dT + \frac{\partial p}{\partial \rho} \Big|_T d\rho \right) = \underbrace{\left( c_v + \frac{1}{\rho} \frac{\partial p}{\partial T} \Big|_{\rho} \right)}_{\frac{\partial h}{\partial T} \Big|_{\rho}} dT + \underbrace{\left( \frac{1}{\rho} \frac{\partial p}{\partial \rho} \Big|_T - \frac{T}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} \right)}_{\frac{\partial h}{\partial \rho} \Big|_T} d\rho. \quad (26)
\end{aligned}$$

Based on relation (25) the specific heat at constant pressure can be calculated according to the following formula at known density and temperature:

$$c_p(\rho, T) = c_v(\rho, T) + \frac{T}{\rho^2} \frac{\left( \frac{\partial p}{\partial T} \Big|_{\rho} \right)^2}{\frac{\partial p}{\partial \rho} \Big|_T}. \quad (27)$$

The specific heat at constant volume can be calculated according the following equation:

$$c_v(\rho, T) = \underbrace{\int_0^T \frac{\partial c_v}{\partial T} \Big|_{\rho} dT}_{c_{v0}(T)} + \int_0^{\rho} \frac{\partial c_v}{\partial \rho} \Big|_T d\rho = c_{v0} + \int_0^{\rho} \frac{\partial c_v}{\partial \rho} \Big|_T d\rho, \quad (28)$$

where the function in the second integral can be determined according to the following equation:

$$\begin{aligned}
\frac{\partial c_v}{\partial \rho} \Big|_T &= \frac{\partial^2 e_B}{\partial \rho \partial T} = \frac{\partial^2 e_B}{\partial T \partial \rho} = \frac{\partial \left( \frac{p}{\rho^2} - \frac{T}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} \right)}{\partial T} = \\
&= \frac{1}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} - \frac{1}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} - \frac{T}{\rho^2} \frac{\partial^2 p}{\partial T^2} \Big|_{\rho} = - \frac{T}{\rho^2} \frac{\partial^2 p}{\partial T^2} \Big|_{\rho}
\end{aligned} \quad (29)$$

According to the relation for ideal gases

$$c_{v0}(T) = c_{p0}(T) - R, \quad (30)$$

equation (28) can be written as follows:

$$c_v(\rho, T) = c_{p0}(T) - R - \int_0^{\rho} \frac{T}{\rho^2} \frac{\partial^2 p}{\partial T^2} \Big|_{\rho} d\rho. \quad (31)$$

In case of a two-phase (liquid-vapor) fluid let's use the Clausius-Clapeyron equation, which provides a link between the thermal and the caloric status indicators of wet steam, namely as follows:

$$\frac{dp_{sat}}{dT} = \frac{h_v(T) - h_l(T)}{T \left( \frac{1}{\rho_v(T)} - \frac{1}{\rho_l(T)} \right)}, \quad (32)$$

based on it we can write the following relation:

$$h_{vl}(T) = h_v(T) - h_l(T) = T \left( \frac{1}{\rho_v(T)} - \frac{1}{\rho_l(T)} \right) \frac{dp_{sat}}{dT} = T \frac{\rho_l - \rho_v}{\rho_v \rho_l} \frac{dp_{sat}}{dT} \quad (33)$$

Thereafter, enthalpy is calculated as follows in case that density and temperature  $(\rho, T)$  are given. Starting point of  $0^\circ C$  saturated liquid whose enthalpy is  $h_0$ . If the temperature is higher than the critical temperature, or the temperature is lower than the critical temperature, and the density is lower than the corresponding saturated vapor density at a given temperature, enthalpy can be calculated as follows:

The  $0^\circ C$  saturated vapor enthalpy is obtained using equation (33):

$$h = h_0 + h_{vl}(0^\circ C). \quad (34)$$

Then we get the enthalpy at given  $(\rho, T)$  if we add the result of the following relation to result of equation (34)

$$\Delta h = \int_{(\rho_0, T_0)}^{(\rho, T)} dh = \int_{T_0}^T \left( c_v(\rho, T) + \frac{1}{\rho} \frac{\partial p}{\partial T} \Big|_{\rho} \right) dT + \int_{\rho_0}^{\rho} \left( \frac{1}{\rho} \frac{\partial p}{\partial \rho} \Big|_T - \frac{T_0}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} \right) d\rho. \quad (35)$$

In relation (35) the values are  $T_0 = 0^\circ C$ , and  $\rho_0 = \rho_v(0^\circ C)$ . Thus, enthalpy can be calculated as follows:

$$h = h_0 + h_{vl}(0^\circ C) + \int_{T_0}^T \left( c_v(\rho, T) + \frac{1}{\rho} \frac{\partial p}{\partial T} \Big|_{\rho} \right) dT + \int_{\rho_0}^{\rho} \left( \frac{1}{\rho} \frac{\partial p}{\partial \rho} \Big|_T - \frac{T_0}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} \right) d\rho. \quad (36)$$

If the temperature is lower than the critical temperature and the density is greater than that of the corresponding saturated steam at the given temperature, and the density is less than the density of the saturated liquid corresponding to the given temperature, the enthalpy can be calculated as follows: In wet vapor state the enthalpy can be calculated based on formula

$$h = h_l + x_v h_{vl} = h_v - h_{vl} + x_v h_{vl} = h_v - (1 - x_v) h_{vl} \quad (37)$$

where

$h_l = h_l(T)$  is the saturated liquid enthalpy at the given  $T$  temperature,

$h_v = h_v(T)$  is the saturated vapor enthalpy at the given  $T$  temperature,

$h_{vl} = h_{vl}(T) = h_v - h_l$  is the latent heat of vaporization at the given  $T$  temperature,

$$x_v = x_v(\rho, T) = \frac{\frac{1}{\rho} - \frac{1}{\rho_l}}{\frac{1}{\rho_v} - \frac{1}{\rho_l}} \text{ is the specific steam content.}$$

Equation (36) is integrated to  $\rho = \rho_v(T)$ , thereby we get the  $h_v(T)$ , and based on equation (33) the value of  $h_{vl}(T)$  can be calculated.

If the temperature is lower than the critical temperature and the density is greater than the corresponding saturated liquid density at the given temperature, we can first compute the enthalpy of saturated liquid during the calculation of the enthalpy according to relation

$$h = h_0 + h_{vl}(0^\circ C) + \int_{T_0}^T \left( c_v(\rho, T) + \frac{1}{\rho} \frac{\partial p}{\partial T} \Big|_{\rho} \right) dT + \int_{\rho_0}^{\rho_v(T)} \left( \frac{1}{\rho} \frac{\partial p}{\partial \rho} \Big|_T - \frac{T_0}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} \right) d\rho - h_{vl}(T) \quad (38)$$

and then we calculate the enthalpy of the fluid along the isotherm using the second integral of expression (35), and thus the enthalpy can be calculated as follows:

$$h = h_0 + h_{vl}(0^\circ C) + \int_{T_0}^T \left( c_v(\rho, T) + \frac{1}{\rho} \frac{\partial p}{\partial T} \Big|_{\rho} \right) dT + \int_{\rho_0}^{\rho_v(T)} \left( \frac{1}{\rho} \frac{\partial p}{\partial \rho} \Big|_T - \frac{T_0}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} \right) d\rho - h_{vl}(T) + \int_{\rho_l(T)}^{\rho} \left( \frac{1}{\rho} \frac{\partial p}{\partial \rho} \Big|_T - \frac{T_0}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} \right) d\rho \quad (39)$$

For the specific entropy calculation let's start with the comparison of expressions (5), (7) and (8), i.e.

$$ds = \underbrace{\frac{1}{T} \frac{\partial e_B}{\partial T} \Big|_{\rho}}_{\frac{\partial s}{\partial T} \Big|_{\rho}} dT + \underbrace{\left( \frac{1}{T} \frac{\partial e_B}{\partial \rho} \Big|_T - \frac{p}{\rho^2 T} \right)}_{\frac{\partial s}{\partial \rho} \Big|_T} d\rho = \frac{1}{T} c_v dT + \left( \frac{p}{\rho^2 T} - \frac{1}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} - \frac{p}{\rho^2 T} \right) d\rho = \underbrace{\frac{1}{T} c_v dT}_{\frac{\partial s}{\partial T} \Big|_{\rho}} - \underbrace{\frac{1}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} d\rho}_{\frac{\partial s}{\partial \rho} \Big|_T} \quad (40)$$

Based on equation (11) we can write

$$s_{vl} = \frac{h_{vl}}{T} \quad (41)$$

For these reasons, the entropy can be calculated similarly to the enthalpy. The  $0^\circ C$  saturated steam entropy can be calculated based on formula

$$s = s_0 + s_{vl}(0^\circ C) \quad (42)$$

then the entropy at the given  $(\rho, T)$  can be calculated according to relation

$$s = s_0 + s_{vl}(0^\circ C) + \int_{T_0}^T \frac{1}{T} c_v dT - \int_{\rho_0}^{\rho} \frac{1}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} d\rho \quad (43)$$

In the range of the two-phase the following formula can be used

$$s = s_v - (1 - x_v) s_{vl} \quad (44)$$

In the liquid phase the entropy can be calculated according to equation

$$s = s_0 + s_{vl}(0^\circ C) + \int_{T_0}^T \frac{1}{T} c_v dT - \int_{\rho_0}^{\rho_v(T)} \frac{1}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} d\rho - s_{vl}(T) - \int_{\rho_l(T)}^{\rho} \frac{1}{\rho^2} \frac{\partial p}{\partial T} \Big|_{\rho} d\rho \quad (45)$$

## ISOBUTANE STATE EQUATIONS

In household refrigerators the most frequently used refrigerant is isobutane (R600a). The data and relations of this refrigerant based on [2] are the following:

Molecular mass:  $M = 58,123 \frac{g}{mol}$ , critical temperature:  $T_C = 407,85 K$  ( $134,7 ^\circ C$ ), critical pressure:  $p_C = 3,64 MPa$ , critical density:  $\rho_C = 224,35478 \frac{kg}{m^3}$ , triple point temperature:  $T_t = 113,55 K$ , triple point pressure:  $p_t = 0,019481 Pa$ , liquid density in the triple point:  $\rho_{tl} = 12,755 \frac{mol}{dm^3}$ .

In vapor phase function  $p = p(\rho, T)$  is given by the following modified Benedict-Webb-Rubin equation:

$$\begin{aligned}
 p = & \rho RT + \rho^2 \left( G_1 T + G_2 T^{1/2} + G_3 + \frac{G_4}{T} + \frac{G_5}{T^2} \right) + \rho^3 \left( G_6 T + G_7 + \frac{G_8}{T} + \frac{G_9}{T^2} \right) + \\
 & + \rho^4 \left( G_{10} T + G_{11} + \frac{G_{12}}{T} \right) + \rho^5 G_{13} + \rho^6 \left( \frac{G_{14}}{T} + \frac{G_{15}}{T^2} \right) + \rho^7 \frac{G_{16}}{T} + \\
 & + \rho^8 \left( \frac{G_{17}}{T} + \frac{G_{18}}{T^2} \right) + \rho^9 \frac{G_{19}}{T^2} + \rho^3 \left( \frac{G_{20}}{T^2} + \frac{G_{21}}{T^3} \right) \exp \left( -\frac{\rho^2}{\rho_C^2} \right) + \\
 & + \rho^5 \left( \frac{G_{22}}{T^2} + \frac{G_{23}}{T^4} \right) \exp \left( -\frac{\rho^2}{\rho_C^2} \right) + \rho^7 \left( \frac{G_{24}}{T^2} + \frac{G_{25}}{T^3} \right) \exp \left( -\frac{\rho^2}{\rho_C^2} \right) + \\
 & + \rho^9 \left( \frac{G_{26}}{T^2} + \frac{G_{27}}{T^4} \right) \exp \left( -\frac{\rho^2}{\rho_C^2} \right) + \rho^{11} \left( \frac{G_{28}}{T^2} + \frac{G_{29}}{T^3} \right) \exp \left( -\frac{\rho^2}{\rho_C^2} \right) + \\
 & + \rho^{13} \left( \frac{G_{30}}{T^2} + \frac{G_{31}}{T^3} + \frac{G_{32}}{T^4} \right) \exp \left( -\frac{\rho^2}{\rho_C^2} \right)
 \end{aligned} \tag{46}$$

The saturation vapor pressure as a function of temperature is the following:

$$p_{sat} = p_C e^{[V_{p1}x + V_{p2}x^2 + V_{p3}x^3 + V_{p4}x^4 + V_{p5}x(1-x)^{p6}]}, \tag{47}$$

where  $x = \frac{1 - \frac{T}{T_t}}{1 - \frac{T}{T_C}}$ .

The saturated liquid density can be calculated based on the following:

$$\rho_l = \rho_C + (\rho_{tl} - \rho_C) e^{h(T)}, \tag{48}$$

where

$$h(T) = A_7 \ln x + \sum_{n=8}^{10} A_n \left( 1 - x^{\frac{n-11}{3}} \right) + \sum_{n=11}^{13} A_n \left( 1 - x^{\frac{n-10}{3}} \right) \tag{49}$$

and  $x = \frac{T_C - T}{T_C - T_t}$ .

The specific heat at constant pressure of ideal gas is



$$c_{p0}(T) = R \left[ \sum_{n=1}^7 G_{in} T^{n-4} + \frac{G_{i8} u^2 e^u}{(e^u - 1)^2} \right], \quad (50)$$

where  $u = \frac{G_{i9}}{T}$ .

The equation of state in liquid phase [3] is

$$p = (B + p_{sat}) e^{\frac{1 - \frac{V}{V_s}}{C}} - B, \quad (51)$$

where

$$B = p_c \left[ -1 + a(1 - T_r)^{1/3} + b(1 - T_r)^{2/3} + d(1 - T_r) + e(1 - T_r)^{4/3} \right] \quad (52)$$

$$e = e^{f + g\omega + h\omega^2} \quad (53)$$

$$C = j + k\omega \quad (54)$$

and  $T_r = \frac{T}{T_c}$ ,  $V_s = \frac{1}{\rho_l(T)}$ ,  $V = \frac{1}{\rho}$ .

Based on the above relations the log p-h graph can be drawn which is used in refrigeration technology (Figure 1).

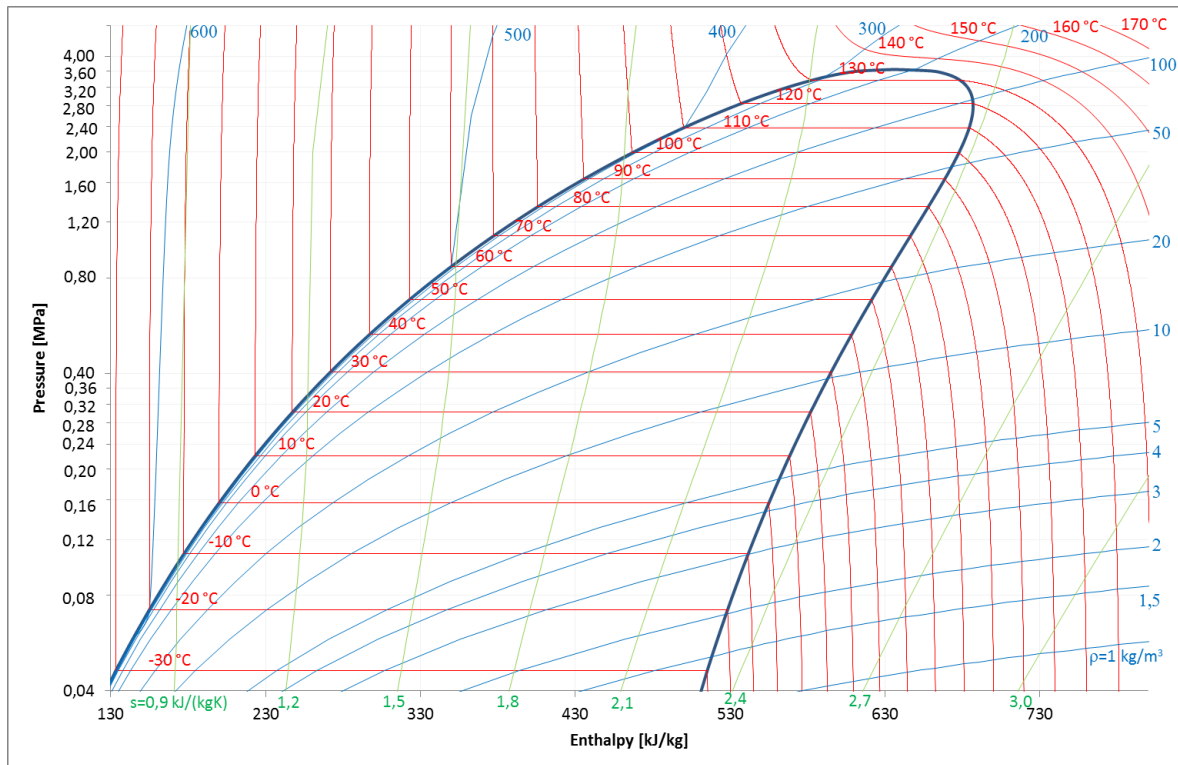


Figure 1  
Log(p)-h Graph of Isobutane

## CONCLUSION

Based on the correlations shown above the status indicators of refrigerants and their derivatives can be computed. The necessary material properties for the simulation of refrigeration circuit can be produced. We have shown the relations for the calculation of the status indicators of isobutane, (which is) nowadays the most widely used refrigerant in household refrigeration appliances, moreover, the necessary constant values can be found in the literature cited.

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## REFERENCES

- [1] W. C. Reynolds, Thermodynamic properties in SI graphs, tables and computation equations for 40 substances, Stanford University: Department of Mechanical Engineering, 1979.
- [2] B. A. Younglove and J. F. Ely, Thermophysical Properties of Fluids II. Methane, Ethane, Propane, Isobutane and Normal Butane, 1987.
- [3] G. H. Thomson, K. R. Brobst and R. W. Hankinson, "An Improved Correlation for Densities of Compressed Liquids and Liquids Mixtures," *AIChE Journal*, vol. 28, no. 4, July 1982.