The psychrometric problem for the evaporation of NH₃ in NH₃/H₂ atmosphere in neutral gas absorption refrigeration units for pressures 17.5 to 27.5 bar

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Abstract. The present work considers the thermodynamic and transport properties of the real NH₃/H₂ gas mixture as a function of the state variables temperature, mass fraction and pressure. The relevant properties are presented in the form of analytical expressions, valid in the pressure range of 17.5 to 27.5 bar. The psychrometric problem is used to determine the mass fraction of the NH₃/H₂ gas mixture with the “dry” and “wet bulb” temperatures as input variables.

Das Psychrometrische Problem der Verdampfung von NH₃ in NH₃/H₂ Atmosphäre bei Neutralgasabsorptionskälteanlagen für Drücke von 17,5 bis 27,5 bar


Nomenclature

- $A_{1}, ..., A_{3}/A_{4}', ..., A_{4}'$: Enthalpy coefficients [Eq. (2)]
- $a_{ij}, a_{ij}', a_{ij}': i = 1, 4, j = 1, 4$
- $B_{1}, B_{2}, ..., B_{5}, B_{6}$
- $h_{ij}': i = 1, 6, j = 1, 4$
- $b_{1}$, $b_{12}$, $b_{12}$: cm³/mole
- $C_{1}, ..., C_{3}/C_{1}', ..., C_{3}'$,
- $c_{ij}, c_{ij}', c_{ij}': i = 1, 4, j = 1, 4$
- $c_{p}$: kJ/kg grd
- $D_{12}$: cm³/sec
- $D_{1}, ..., D_{4}/D_{4}', ..., D_{4}'$, $D_{1}^{'}$: coefficients [Eq. (7)] concerning the thermal conductivity of the NH₃/H₂ gas mixture
- $f_{d}, f_{g}$
- $f_{sat}, f_{s}$
- $h$: kJ/kg
- $H$: kJ/kmole
- $H_{11}$: kJ/kmole
- $H_{22}$: kJ/kmole
- $h_{0}$: kJ/kg
- $h_{5}$: kJ/kg
- $n$: moles of the mixture
- $N_{p}$, $N_{sc}$, $N_{pr}$, $N_{cycle}$, $N_{le}$, $N_{le}$
- $p$: bar
- $T$: °C, K
- $v$: m³/kg
- $x$: mole fraction
- $x_{1}$, $x_{2}$: moles mixture
- $\dot{q}$: kJ/m h grd
- $\lambda$: thermal conductivity of the real NH₃/H₂ gas mixture
- $\lambda_{1}$, $\lambda_{2}$: kJ/m h grd
- $\eta$: μP
- $\varrho$: kg/m³

Greek letters

- $\lambda_{M}$: kJ/m h grd
- $\lambda_{1}$, $\lambda_{2}$: kJ/m h grd
- $\eta$: μP
- $\varrho$: kg/m³

1 Introduction

The main thermodynamic quantities used, i.e. the enthalpy and the specific volume of the real NH₃/H₂ gas mixture, are
given in the form of virial equations [1, 2], whereas the obtained results are presented with equations having the temperature, the mass fraction of the mixture and the total pressure as variables. The boundary values of the enthalpy and of the specific volume, across the saturation line, are deduced by a corresponding analytical relationship giving the saturation mass fraction of the real NH$_3$/H$_2$ gas mixture as a function of temperature and total pressure.

The transport properties, calculated by using the second virial coefficient approximation, include the diffusion coefficient, the thermal conductivity, the dynamic viscosity, the specific heat capacity and the numbers of Prandtl, Schmidt and Lewis [3].

The analytical expressions obtained, concerning the thermodynamic and transport properties of the real NH$_3$/H$_2$ gas mixture, are necessary to calculate the heat and mass transfer operations taking place along the evaporator and the gas heat exchanger of the heat driven neutral gas absorption refrigeration units. In the following there are presented briefly the main functions required for the solution of the NH$_3$/H$_2$ "psychrometric problem". By using a "dry" and a "wet bulb" thermocouple, inside the evaporator, it is possible to determine the mass fraction of the gas mixtures. The obtained results are presented briefly in diagrams plotted for the pressures of 20 bar, 25 bar, 27.5 bar. It is to be noticed that the pressure can take any value in the range of 17.5 bar to 27.5 bar in the corresponding analytical expression.

2 Thermodynamic properties of the real NH$_3$/H$_2$ gas mixture

2.1 Enthalpy

The molar enthalpy of the real NH$_3$/H$_2$ gas mixture can be deduced by using the Eq. [2]:

$$ h = (1 - x) h_{11} + x h_{22} \quad (1 \text{a}) $$

where

$$ h_{11} = H_{11} + \left(2 B_{12} - B_{11} - B_{22}\right) $$
$$ - T \frac{d}{dT} \left(2 B_{12} - B_{11} - B_{22}\right) x^2 p \quad (1 \text{b}) $$

$$ h_{22} = H_{22} + \left(2 B_{12} - B_{11} - B_{22}\right) $$
$$ - T \frac{d}{dT} \left(2 B_{12} - B_{11} - B_{22}\right) \left(1 - x\right)^2 p \quad (1 \text{c}) $$

The specific enthalpy is derived by division of the molar enthalpy with the mixture's molecular weight. For a given temperature, mass fraction and pressure the enthalpy values are calculated knowing the second virial coefficients ($B_{11}, B_{22}, B_{12}$) and the enthalpies $H_{11}$ (enthalpy of the H$_2$), $H_{22}$ (enthalpy of the NH$_3$). In previous works [4–6], the second virial coefficients and the enthalpies have been given as a function of temperature and of partial pressure [7, 8]. The partial pressures of the two components have been calculated by using an iterative method, estimating the specific volume of the NH$_3$/H$_2$ gas mixture [4].

The obtained enthalpy values of the real NH$_3$/H$_2$ gas mixture can be correlated by the following equation:

$$ h = (A_1 + A_2 T + A_3 T^2) $$
$$ + (A_4 + A_5 T + A_6 T^2 + A_7 T^3) f $$
$$ + (A_8 + A_9 T + A_{10} T^2 + A_{11} T^3) f^2 \quad (2) $$

where

$$ A_1 = a_{11} + a_{12} p + a_{13} p^2 \quad (2 \text{a}) $$
$$ A_2 = a_{21} + a_{22} p \quad (2 \text{b}) $$
$$ A_3 = a_{31} + a_{32} p + a_{33} p^2 + a_{34} p^3 \quad (2 \text{c}) $$
$$ A_4 = a_{41} + a_{42} p + a_{43} p^2 a_{44} p^3 \quad (2 \text{d}) $$
$$ A_5 = a_{51} + a_{52} p + a_{53} p^2 + a_{54} p^3 \quad (2 \text{e}) $$
$$ A_6 = a_{61} + a_{62} p + a_{63} p^2 \quad (2 \text{f}) $$

and $h$ in kJ/kg, $p$ in bar and $T$ in °C. For the values of the coefficients $a_{ij}, a'_{ij}, a''_{ij}$ see Appendix 1. The above enthalpy equation is valid for pressures between 17.5 bar to 27.5 bar and temperatures –40 °C to +50 °C. The enthalpy boundary values as a function of the saturation mass fraction $f_{SAT}$ of the NH$_3$/H$_2$ gas mixture and the temperature and pressure, can be found by using the following relationship:

$$ f_{SAT} = B_1 + B_2 T + B_3 T^2 + B_4 T^3 + B_5 T^4 + B_6 T^5 \quad (3) $$

where

$$ B_1 = b_{11} + b_{12} p + b_{13} p^2 + b_{14} p^3 \quad (3 \text{a}) $$
$$ B_2 = b_{21} + b_{22} p + b_{23} p^2 + b_{24} p^3 \quad (3 \text{b}) $$
$$ B_3 = b_{31} + b_{32} p + b_{33} p^2 + b_{34} p^3 \quad (3 \text{c}) $$
$$ B_4 = b_{41} + b_{42} p + b_{43} p^2 + b_{44} p^3 \quad (3 \text{d}) $$
$$ B_5 = b_{51} + b_{52} p + b_{53} p^2 + b_{54} p^3 \quad (3 \text{e}) $$
$$ B_6 = b_{61} + b_{62} p + b_{63} p^2 + b_{64} p^3 \quad (3 \text{f}) $$

and $p$ in bar and $T$ in °C. For the values of the coefficients $b_{ij}$ see Appendix 1.

2.2 Specific volume

The procedure to deduce the enthalpy values of the NH$_3$/H$_2$ gas mixture includes the calculation of the partial pressures of the H$_2$ and of the NH$_3$ and the calculation of the specific volume.

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