

Properties of Humid Air for Power-Cycle Calculations

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EU Project AA-CAES

AA-CAES Cycle

Working Fluid: Humid Air

- at pressures from ambient to 150 bar,
- at temperatures from ambient to 550 °C,
- at water content up to 10 ... 20% (mass).

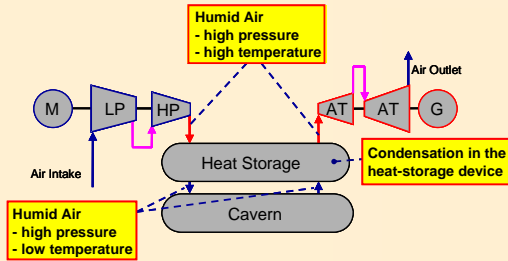


Figure 1: The basic AA-CAES process using compressed humid air as working fluid. The important components of this cycle are the compressor (Motor (M) driven LP – compressor under low pressure and HP – compressor under high pressure), the heat storage, the cavern, and the air turbines (AT) which drive a Generator (G).

Investigated Models

Table 1: Models for calculating thermodynamic properties of humid air used for comparisons.

| Abbreviation | Model | Author(s) |
|--------------|--|-------------------------|
| IdGas | Ideal mixture of ideal gases | VDI-Guideline 4670 [1] |
| HuAir | Ideal mixture of the real fluids dry air and water | Hellriegel [2] |
| HuGas | Ideal mixture of the real fluids N ₂ , O ₂ , Ar, and water | Kleemann, Seibt [3] |
| KTH | Modified Redlich-Kwong equation of state for the mixture | Ji, Yan [4] |
| RB | Virial equation for the mixture | Rabinovich, Beketov [5] |
| NEL | Virial equation for the mixture | Nelson, Sauer [6] |
| HyW | Virial equation for the mixture | Hyland, Wexler [7] |

Add-In FluidEXL Graphics for Excel®

The developed property library LibAirWa [8] contains the calculation procedures for the thermodynamic properties of humid air from the proposed model as well as the calculation algorithms for the transport properties of humid air which were prepared by the Department of Physical Chemistry at the University of Rostock.

Abstract

To model compressed air energy storage power cycles and to design their components, accurate algorithms for thermodynamic properties of humid air are required. In the past, the evaluation of thermodynamic-property models and the verification of their accuracy were hampered due to the lack of experimental data for humid air at higher temperatures and pressures. New experimental data generated within the AA-CAES project of the European Commission Sixth Framework Programme [9] have become the basis for comparisons between different models described in this paper. Here, a model for calculating thermodynamic properties for humid air in power-cycle design and operation, developed out of these investigations, is recommended. This model consists of an ideal mixture of the real fluids dry air and steam, water, or ice [10]. Dry air is calculated from the fundamental equation provided by Lemmon *et al.* [11], steam and water from IAPWS-95, and ice from IAPWS-06. Saturation of humid air is calculated using a modified virial equation [12]. At high temperatures, dissociation is considered. The resulting model has been implemented in a property library which can be applied to modelling power cycles with the working fluid humid air. In addition, algorithms for transport properties are included. Properties can be calculated based on various sets of independent variables including (p, h) , (p, s) , and (h, s) . Application of the software is possible up to temperatures of 2000 K and pressures of up to 100 MPa. Add-Ins have been prepared for using the property library in Excel®, MATLAB®, and Mathcad®.

Comparison of the Models

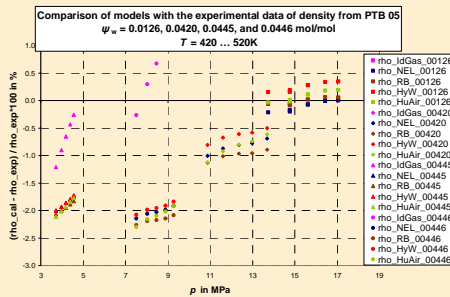


Figure 2: Relative deviations for the density of humid air calculated for models listed in Table 1 from the experimental data of Klingenberg & Ulbig [13] as a function of pressure.

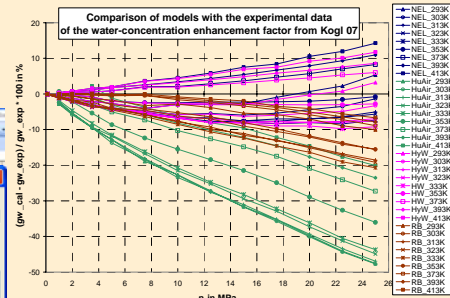


Figure 3: Relative deviations of the water concentration enhancement factor g_w for the saturated composition of humid air calculated for the models listed in Table 1 from the experimental data of Koglbauer & Wendland [14] as a function of pressure.

The comparison calculations show a similar behaviour of all investigated models for density values excepted the ideal-gas model (e.g. Fig. 2). The experimental data with a mole fraction of water of 1% were described within $\pm 0.3\%$. The other three data sets for mole fractions of about 4% water are represented differently by the models. This seems to be due to the uncertainty of the experimental data, since the deviations of values calculated for different models from the experimental data are nearly identical.

In the case of the saturated composition, significant differences occurred between the different models (e.g. Fig. 3). The poynting correction of the ideal-mixing model HuAir is too low. The relatively small difference between the NEL model and the HyW model results from the fact the first is a further development of the second.

The comparison calculations were restricted by the lack of experimental data for the thermodynamic properties of humid air available in the literature.

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Proposed Calculation Model

The following mixing rules, e.g. for density and enthalpy, are implemented in the proposed calculation model for the thermodynamic properties of humid air.

Mass Density

The mass density of humid air $\rho = \rho M$ is calculated from the molar density ρ , which has to be iteratively calculated from the following expression for the mixture pressure

$$p = \psi_a p_a(\rho, T) + \psi_w (p_w, T),$$

where the partial pressure of dry air is calculated from the very accurate fundamental equation for dry air given by Lemmon *et al.* [11] at molar mixture density and temperature

$$p_a = \rho R T^{a_{a,1}} [1 + \delta_a \alpha_{a,2}^* (\delta_a, \tau_a)]$$

and the partial pressure of steam is calculated from a reduced Helmholtz free-energy equation of the scientific formulation for water IAPWS-95 [15]

$$p_w = \rho_w T R^{a_{w,1}} [1 + \delta_w \alpha_{w,2}^* (\delta_w, \tau_w)] \text{ with } \rho_w = \psi_w \rho.$$

Molar Enthalpy

$$h = \psi_a h_a(\rho, T) + \psi_w h_w(\rho_w, T) + \Delta h_{\text{mix}}(p, T, \psi)$$

where the dry air contribution is calculated from Lemmon *et al.* [11]

$$h_a(\rho, T) = R^{a_{a,2}} T [1 + \tau_a (\alpha_{a,2}^* + \alpha_{a,3}^* + \alpha_{a,4}^*)]$$

the steam contribution is calculated from IAPWS-95 [15]

$$h_w(\rho_w, T) = R^{a_{w,2}} T [1 + \tau_w (\alpha_{w,2}^* + \alpha_{w,3}^* + \alpha_{w,4}^*)],$$

Δh_{mix} consider the influence of the dissociation at temperatures greater than 1200 K.

Saturated Composition

The mole fraction of water in saturated humid air is

$$\psi_{s,w} = \frac{f p_{s,w}}{p}$$

where f is the enhancement factor, $p_{s,w}$ is the saturation pressure of pure water, and p is the ambient pressure. The enhancement factor f considering the non-ideal behaviour of the mixture at the saturated state is given as a function of p and T and can be derived iteratively from the isothermal compressibility of liquid water, from Henry's constant, and from the virial coefficients of air, of water, and of the mixture air-water using the following relationship. The calculation of f is obtained from the model of Nelson and Sauer [6] with modifications from this work.

$$\ln(f) = \left[\frac{(1 + k_T p_{s,w})(p - p_{s,w}) - k_T \left(\frac{p^2 - p_{s,w}^2}{2} \right)}{RT} \right] v_{w,\text{liq}} + \ln(1 - \beta_H \psi_{s,a} p) +$$

$$\left[\frac{\psi_{s,a}^2 p}{RT} \right] B_{aa} - \left[\frac{2\psi_{s,a} p}{RT} \right] B_{aw} - \left[\frac{p - p_{s,w} - \psi_{s,a} p}{RT} \right] B_{ww} +$$

$$\left[\frac{\psi_{s,a}^2 p^2}{(RT)^2} \right] C_{aaa} + \left[\frac{3\psi_{s,a}^2 (1 - 2\psi_{s,a}) p^2}{2(RT)^2} \right] C_{aaw} -$$

$$\left[\frac{3\psi_{s,a}^2 (1 - \psi_{s,a}) p^2}{(RT)^2} \right] C_{aww} - \left[\frac{(1 + 2\psi_{s,a})(1 - \psi_{s,a})^2 p^2 - p_{s,w}^2}{2(RT)^2} \right] C_{www} -$$

$$\left[\frac{\psi_{s,a}^2 (1 - 3\psi_{s,a})(1 - \psi_{s,a}) p^2}{(RT)^2} \right] B_{aa} B_{aw} - \left[\frac{2\psi_{s,a}^2 (2 - 3\psi_{s,a}) p^2}{(RT)^2} \right] B_{aa} B_{ww} +$$

$$\left[\frac{6\psi_{s,a}^2 (1 - \psi_{s,a})^2 p^2}{(RT)^2} \right] B_{ww} B_{aw} - \left[\frac{3\psi_{s,a}^2 p^2}{2(RT)^2} \right] B_{aa}^2 -$$

$$\left[\frac{2\psi_{s,a}^2 (1 - \psi_{s,a})(1 - 3\psi_{s,a}) p^2}{(RT)^2} \right] B_{aw}^2 - \left[\frac{p_{s,w}^2 - (1 + 3\psi_{s,a})(1 - \psi_{s,a})^3 p^2}{2(RT)^2} \right] B_{ww}^2$$

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