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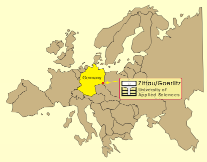
R. Span
University of Paderborn

E. Vogel
University of Rostock



Properties of Humid Air

Progress Report of the EU Project
Advanced Adiabatic Compressed Air Energy Storage
AA-CAES

Situation

► **EU Project AA-CAES**
Work Package 4: Thermophysical Properties
Chairman: Peter Ulbig, National Metrology Institute of Germany

► **IAPWS Certified Research Need:**
Thermophysical Properties of Humid Air and Combustion-Gas Mixtures

► **IAPWS Task Group:**

Properties of combustion gases and humid air

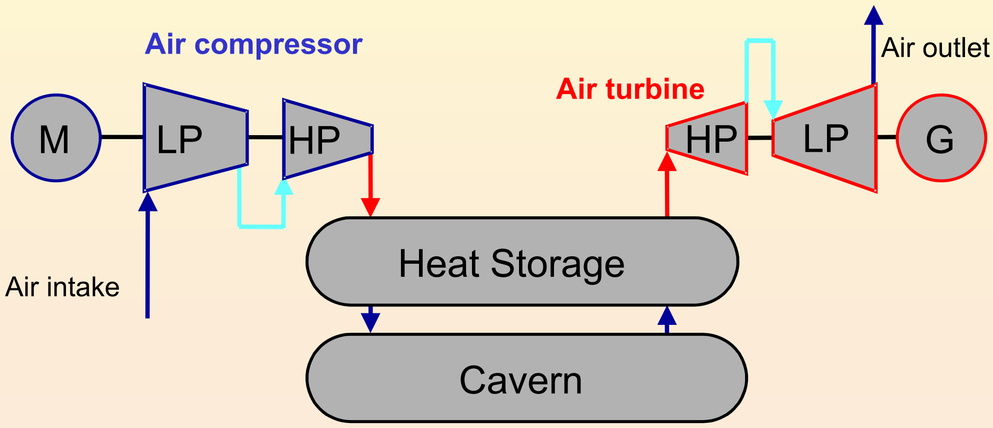
Members: **R. Span (Chair)**
J. R. Cooper
A. H. Harvey
H.-J. Kretzschmar

Objective of the EU Project AA-CAES

Development of an economically viable pure storage technology based on compressed air

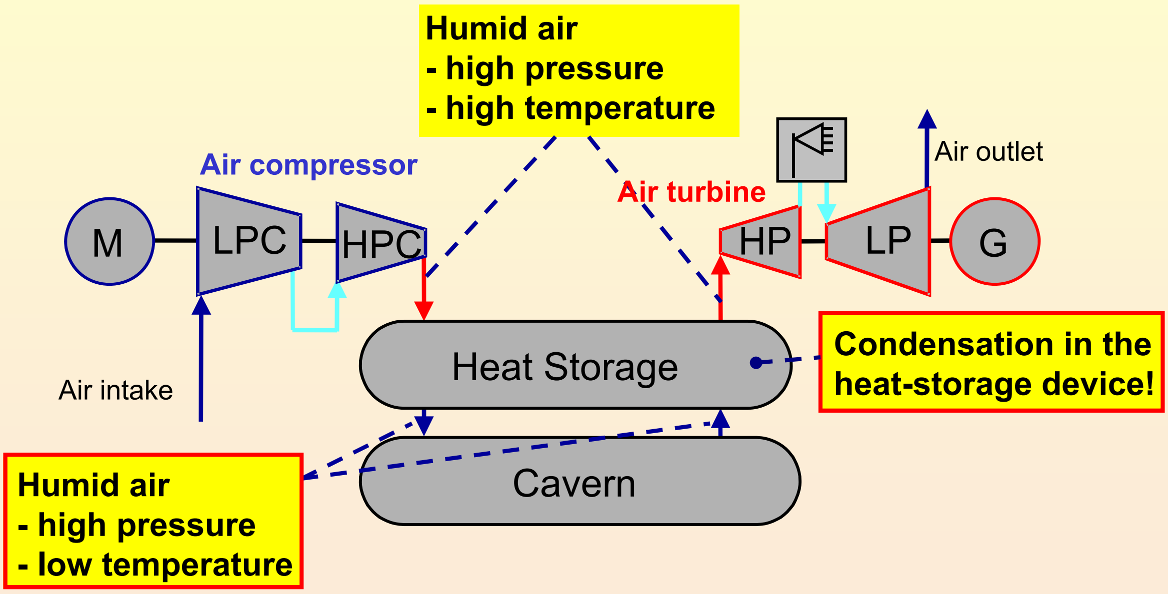
- **Storage efficiency of electrical energy > 70 %**
- **Investment cost < 1200 € / kW at 30 MW**

Technical Concept



Work Package 4: Thermophysical Properties

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 (40) % (mass)



Tasks of WP 4: Thermophysical Properties

Task 4.1	Task 4.2	Task 4.3
Generation of experimental reference data	**Development of a data base**	**Identification/development of suitable models, exploitation of results**
Imperial College of London (UK) Univ. for Agriculture of Wien (A) Univ. of Lisboa (P) PTB Braunschweig (D) Ruhr-Univ. of Bochum (D)	Zittau Univ. Appl. Sc. (D) Univ. of Rostock (D)	Univ. of Stockholm (S) Zittau Univ. Appl. Sc. (D) Univ. of Rostock (D)
(December 2005)	(June 2005)	(December 2005)

Task 4.2: Development of a Data Base

► **The property data base was completed**

The data base is organized by a MS-Excel table including all information of the sources, and hyperlinks to:

- **Prepared data files**
- **Prepared MS-Excel files**
- **Plots with data points**
- **PDF files of the sources**

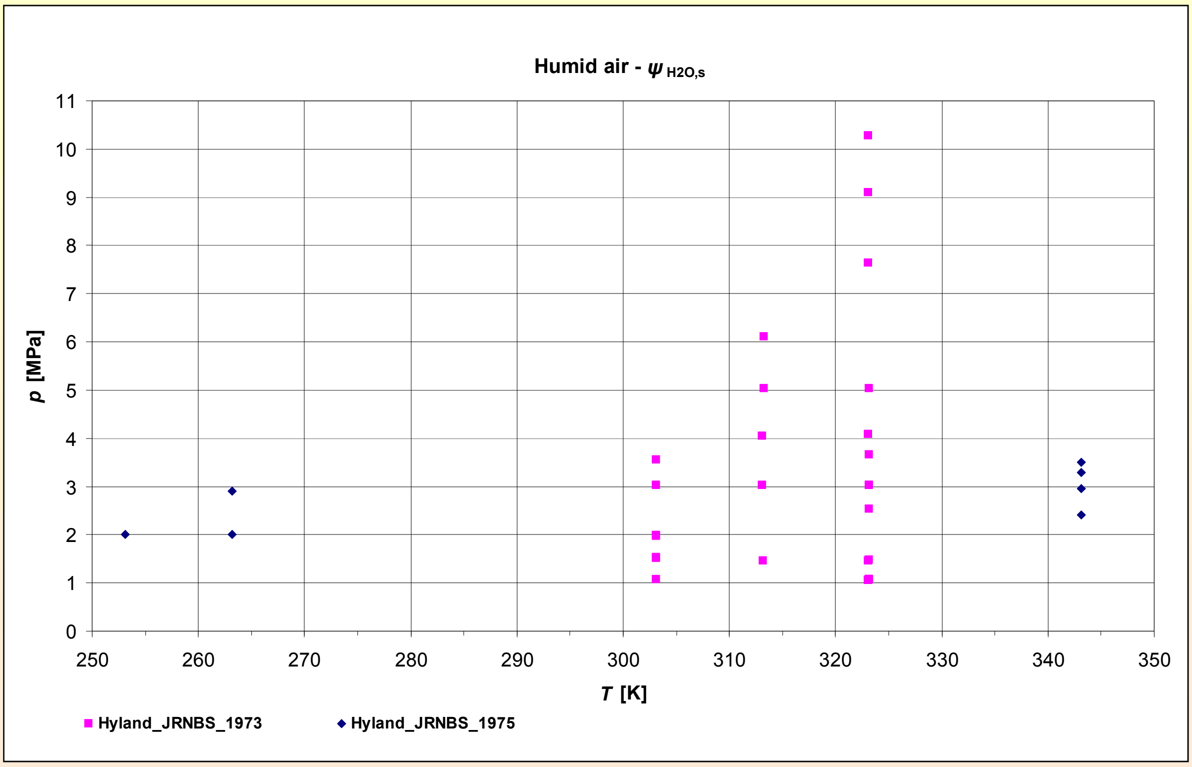
⇨ **190 sources including thermodynamic and transport properties**

⇩

Only 7 sources include experimental data for humid air

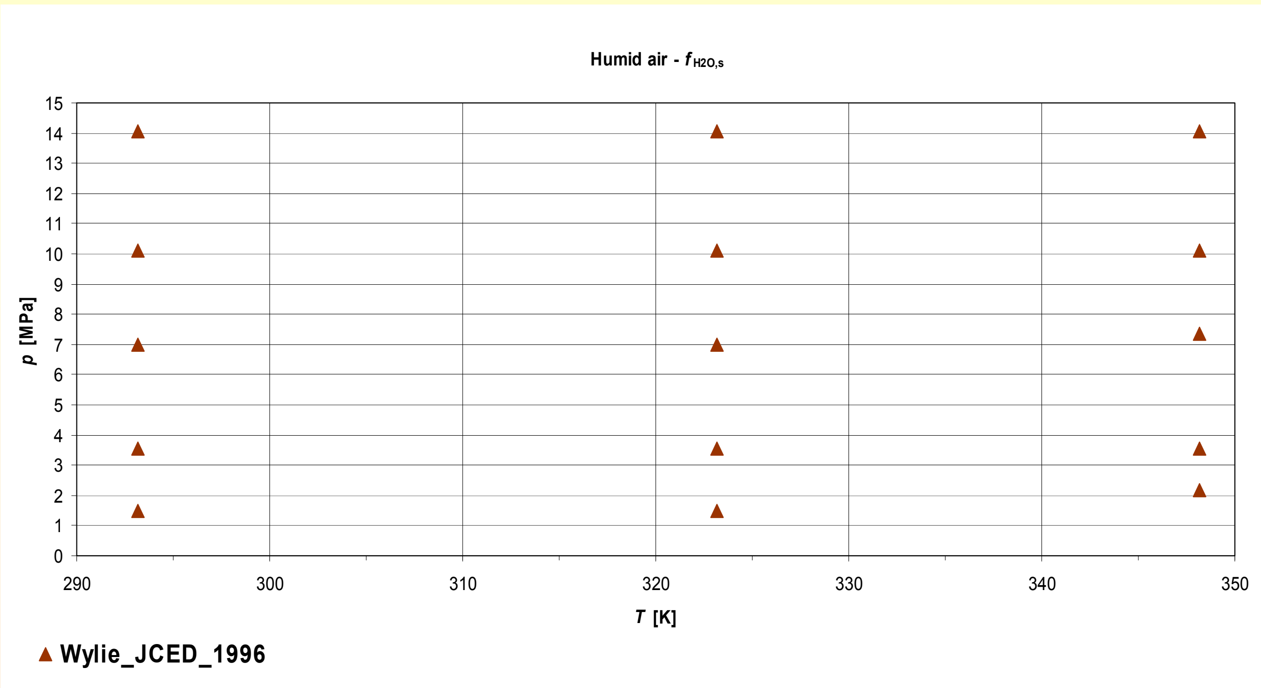
Molefraction of saturated steam	- $\Psi_{H2O,s}$	**Hyland 1973, 1975**
Enhancement factor for saturation pressure of steam	- $f_{H2O,s}$	**Wylie 1996**
Density	- p-ρ-T	**Japas 1985**
Thermal conductivity	- λ	**Gruess 1928**
Dynamic viscosity	- η	**Kestin 1964, Hochrainer 1966**

Mole fraction of saturated steam $\psi_{H2O,\,s}$

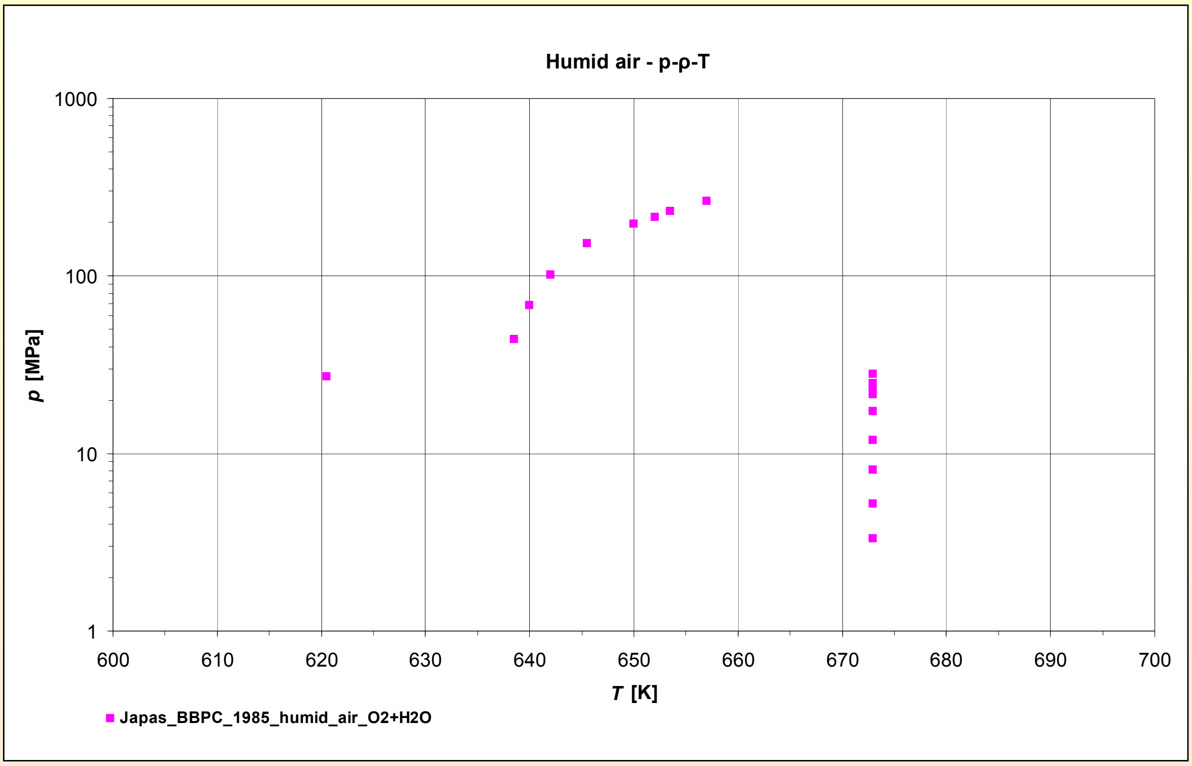


Enhancement factor $f_{H2O,\,s}$

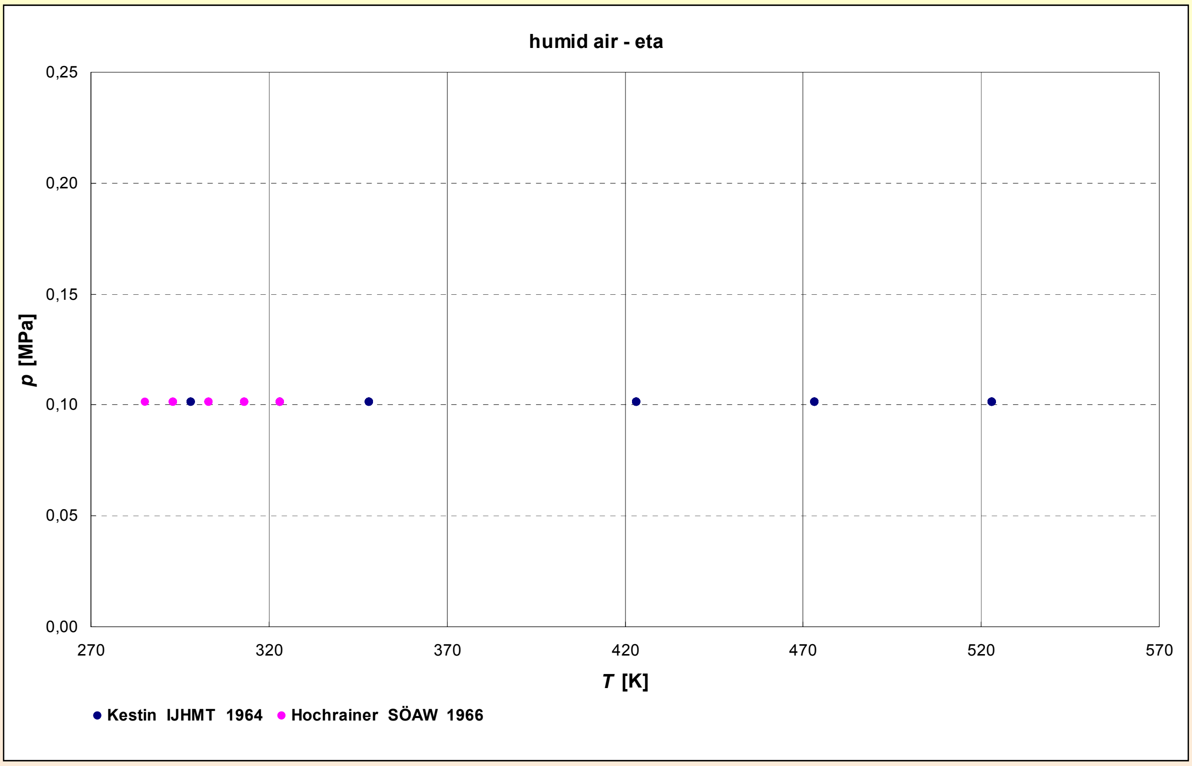
$$f_{H_2O,s} = \frac{p^{mix}_{H_2O,s}}{p_{H_2O,s}} = \frac{\psi_{H_2O,s} \cdot p}{p_{H_2O,s}}$$



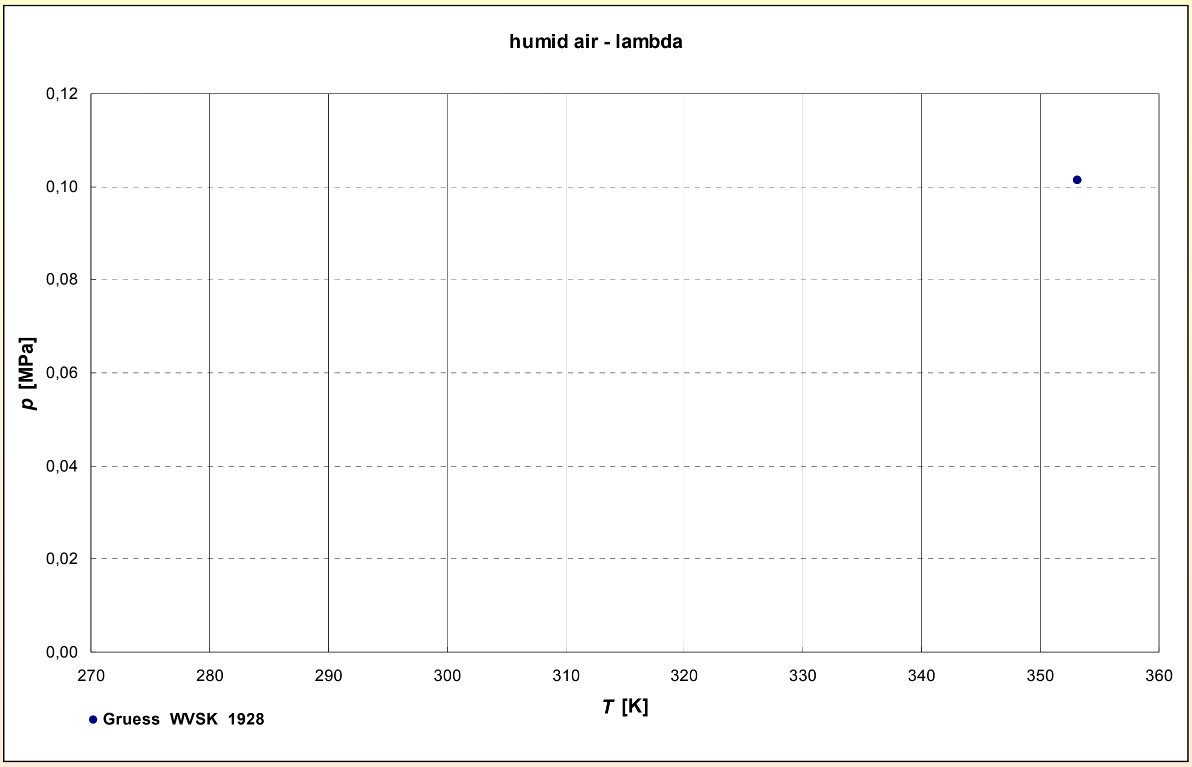
p-ρ-T



Viscosity η



Thermal conductivity λ



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- $\Psi_{H2O,s}$ **Hyland 1973, 1975**
- $f_{H2O,s}$ **Wylie 1996**
- p-ρ-T **Japas 1985**
- λ **Gruess 1928**
- η **Kestin 1964, Hochrainer 1966**

⇩

There is a lack in experimental data for humid air

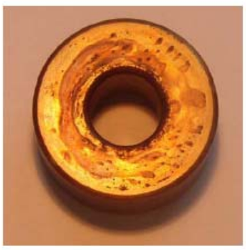
Task 4.1: Generation of Experimental Reference Data

Property	Institution	Temp. Range [K]	Pressure Range [MPa]	Comments
Density	PTB - National Metrology Institute of Germany	298 ... 520	0,1 ... 15	T_{max} may be extended to 670 K
	Ruhr-Univ. of Bochum (D)	240 ... 520	0,1 ... 30	
Speed of sound	Imperial College of London (UK)	100 ... 450	0,1 ... 20	T_{max} may be extended to 475 K
	Univ. for Agriculture of Wienna (A)	230 ... 470	0,1 ... 15	
Dew point	Imperial College of London (UK)	298 ... 700	0,1 ... > 20	
	Univ. for Agriculture of Wienna (A)	278 ... 420	0,1 ... 15	Two methods tested
Viscosity	Ruhr-Univ. of Bochum (D)	240 ... 520	0,1 ... 30	
Thermal conductivity	Univ. of Lisbon (P)	298 ... 620	0,5 ... > 30	T_{max} may be extended to 720 K
Mole fractions of steam: 0 %, 1 %, 3 %, 5 %, 10 %, 25 %				

Call for measurements of heat capacity !

Problems in Measuring Humid Air

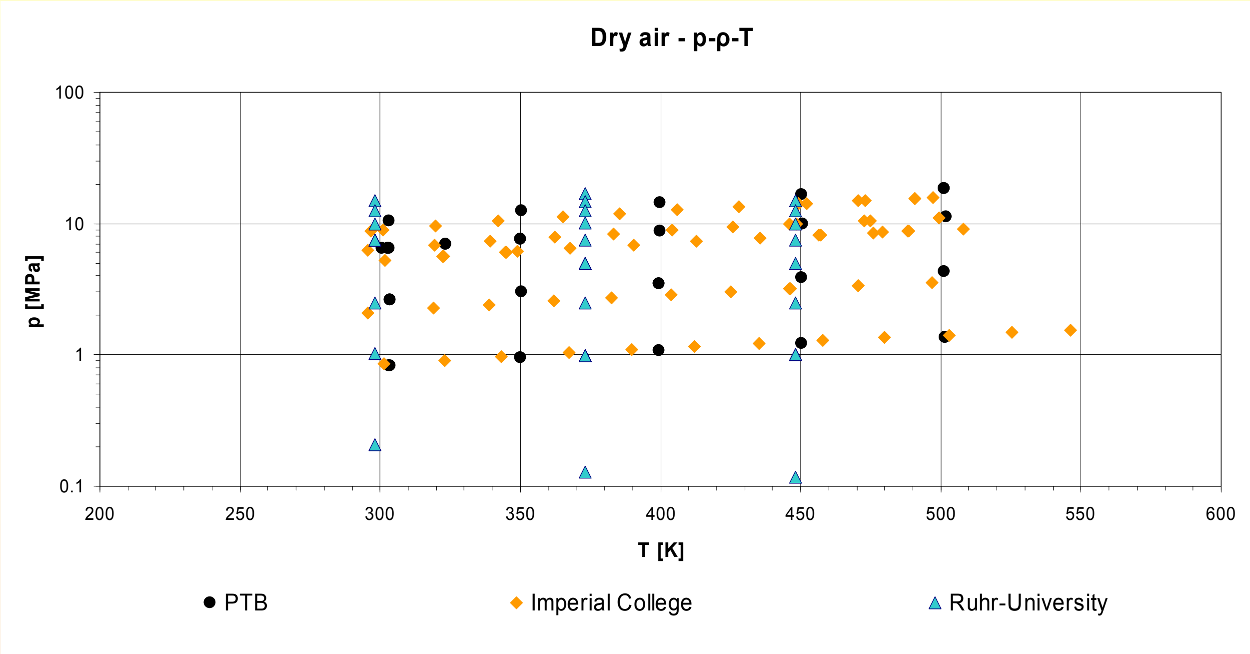
- **Uncertainty of the measured humidity**
- **Condensation in measurement cells and in tubes**
- **Corrosion of measurement cells**



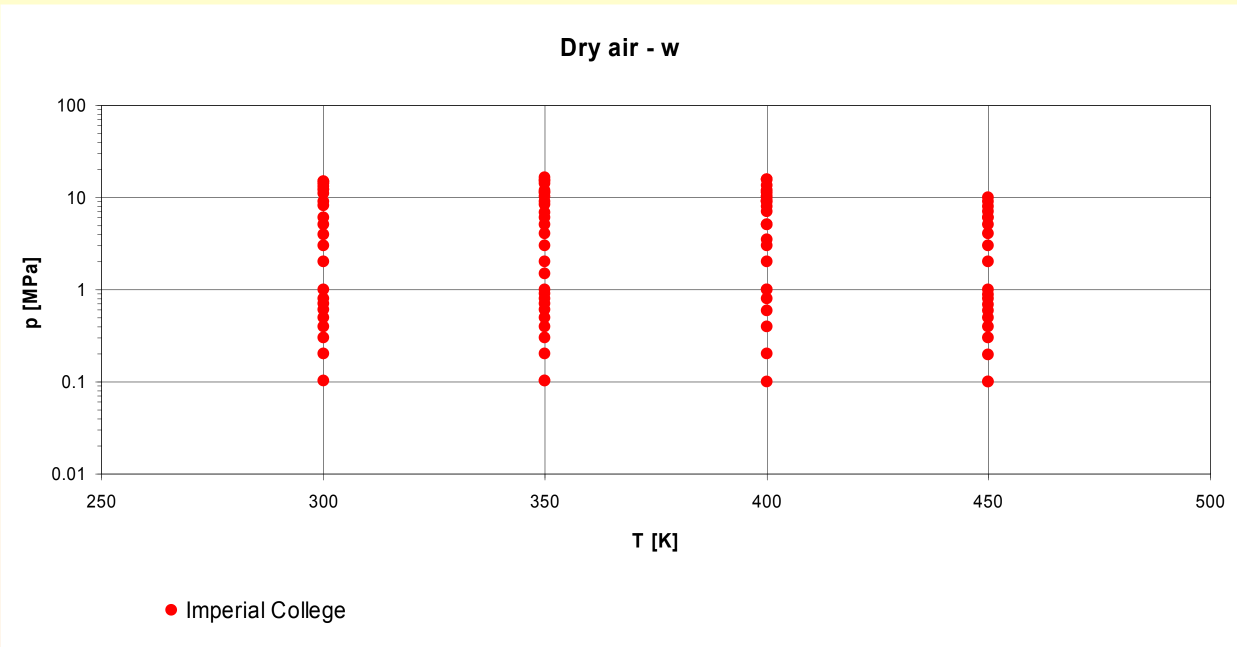
Imperial College London UK

x(steam)	*T*/°C	*p*/bar	status
25%	220	65	corrosion
10%	220	55	corrosion
5%	220	50	Traces?
1%	220	40	no-corrosion

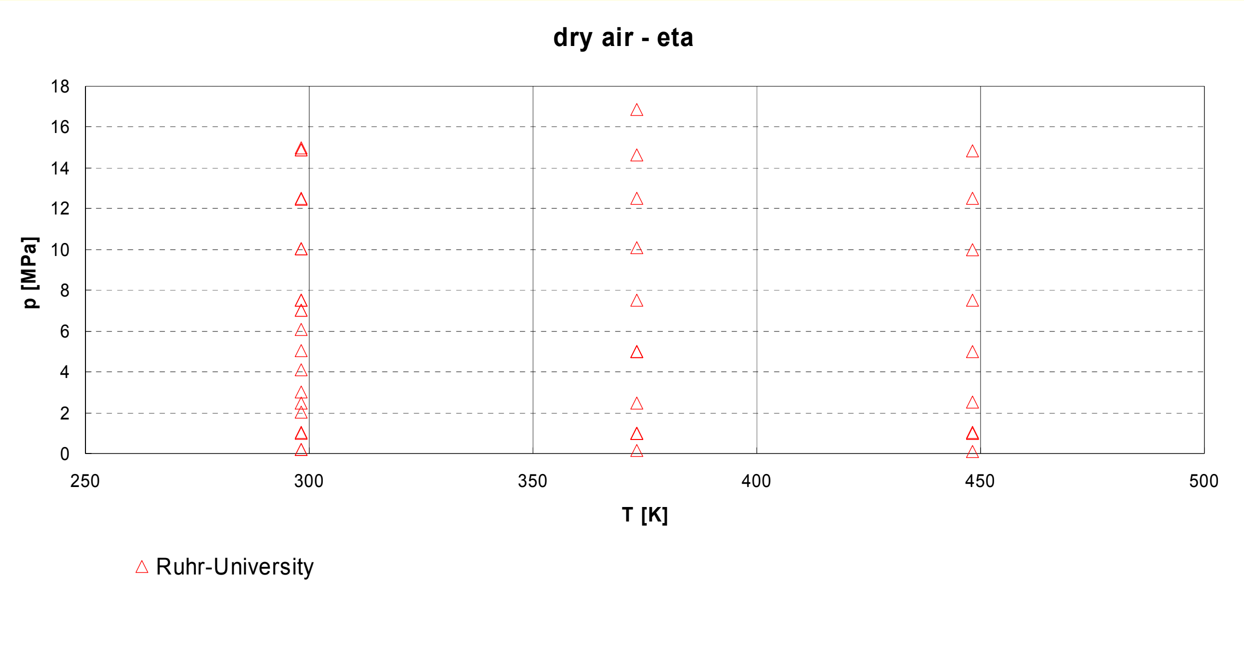
Dry Air – p – ρ – T



Dry Air – Speed of Sound



Dry Air – Dynamic Viscosity



Task 4.3: Identification/Development of Suitable Models, Exploitation of the Results

Thermodynamic Properties

⇩

Comparing existing property models with data from literature and new experimental data

⇩

Evaluating different property models

⇩

Recommendation for the calculation of thermodynamic properties

⇩

Assumption for the development of a new standard for calculating thermodynamic properties of humid air

Transport Properties

⇩

Comparing existing property models with data from literature and new experimental data

⇩

Evaluating different property models

⇩

Development of a new standard for calculating transport properties of humid air

Thermodynamic Property Models for Humid Air

► Ideal mixture of real fluids

Kretzschmar, Kleemann, Seibt (Property Library LibHuGas, 2002-2005)
Ideal mixture of the real fluids N2, O2, Ar, and steam

Kretzschmar, Hellriegel, Seibt, Weidner (Property Library LibHuAir 2001-2005)
Ideal mixture of the real fluids dry air and steam

► Real mixture of real fluids

Hyland and Wexler (1973, 1975, 1983)
Virial equations of state for mixtures
Carotenuto (1996)
Algorithms of Hyland 1983
Nelson (2001)
Improved virial equation of state of Hyland 1983
Rabinovich and Beketov (1995)
Virial equation of state for mixtures
Wylie (1996)
Enhancement factor from poynting
Yan and Ji (2003)
Modified Redlich-Kwong equation of state for mixture

► Multi fluid model

Wagner (2004)
Fundamental equation for natural gas

Transport Property Models for Humid Air

E. Vogel, University of Rostock

► Model of Vesovic and Wakeham

Mixture of the real fluids dry air (Lemmon) and water (IAPWS) as hard spheres adjusted on the contact value of the radial distribution function

Conclusions

- Almost no experimental data are available for humid air.
- There are corrosion and condensation problems in measuring properties for humid air.
- New experimental data were generated for dry air first.
- Measurements of humid air will be completed by the end of 2005.
- The most accurate algorithms for the thermodynamic properties of humid air are being compared.
  - → A recommendation will be given.
- New correlations for viscosity and thermal conductivity of humid air are being developed.
  - → A new standard can be expected next year.

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The ICRN "Thermophysical Properties of Humid Air and Combustions-Gas Mixtures" should be extended.