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Akademische Ausbildung

Mag. rer. nat.	1961	Universität Graz
Dr. sc. techn.	1963	TU Graz
Dr.-Ing. habil.	1974	TU Berlin

Berufserfahrung

1963 - 1971	Wiss. Ass. RWTH Aachen
1972 - 1973	Ass. Prof. TU Berlin
1974	Vis. Assoc. Prof. U of Michigan, Ann Arbor
1975 - 1978	Privatdozent Inst. Thermodynamik u. Anlagentechnik TU Berlin
1979	Gastprofessor U Erlangen – Nürnberg
1979 - 1981	Forschungsingenieur Daimler-Benz AG, Berlin
1981 - 1984	Professor für Thermodynamik TU Berlin
1984 -	Professor für Thermodynamik U Siegen
1988, 1992	Gastprofessor U British Columbia, Vancouver, Kanada
1995 -	Ständiger Gastprofessor an der Universität Leipzig, Fak. Chemie - Mineralogie
1996, 1998	Gastprofessor U Queensland, Brisbane, Australien
1998	Gastprofessor Instituto Pheridisciplinar, Madrid, Spain
1999	Inst. High Pressure Adsorption, Tianjin University, VR China
2000	Gastprofessor Penn State University, PE USA
1988 - 2004	Vorsitzender Haushaltskommission FB Maschinentechnik Div. Ämter in weiteren universitären und fachbereichsbezogenen Gremien.

Fachgebiet: Thermodynamik

Forschungsschwerpunkte: Adsorption von Gasen und Porösstoffen
Absorptionsarbeitsstoffsysteme
Thermodynamik irreversibler Prozesse
Wirbelrohrtechnik
Biothermodynamik

Wissenschaftliche Bücher

- Keller J. U.** Über den Zweiten Hauptsatz der Thermodynamik Irreversibler Prozesse, W. de Gruyter, Berlin – New York, 1976, ISBN 311 005 9991.
- Keller J. U.** Thermodynamik der irreversiblen Prozesse Teil 1, Thermostatik und Grundbegriffe, p. 570, W. de Gruyter, Berlin – New York, 1977.
- Keller J. U.** Technische Thermodynamik in Beispielen, Teil 1, Grundlagen, p. 307 W. de Gruyter, Berlin – New York, 1979.
- Keller J. U. Staudt R.** Gas Adsorption Equilibria, Experimental Methods and Adsorption Isotherms, ca. p. 420, Kluwer Academic Publishers, Norwell, USA, 2004.

Fachartikel

112 Publikationen (begutachtet) in deutschen und internationalen Zeitschriften
6 Fortschrittsberichte VDI, Verfahrenstechnik

Patente

6 Int. und Nat. Patente zu Absorptionsstoffen

Editor – in – Chief

Journal of Non-Equilibrium Thermodynamics
W. de Gruyter, Berlin – New York, 1976-

Gründer

und stellv. Vorsitzender der DECHEMA Arbeitsausschüsse Adsorptions- (1995) und Biothermodynamik (2000)

Board of Directors

International Adsorption Society (1998-2004)

Mitgliedschaften wiss. Gesellschaften

DECHEMA, Deutsche Gesellschaft für Chemische Technik und Biotechnologie e. V.
Deutscher Kälte- und Klimatechnischer Verein e. V.
Gesellschaft für Angewandte Mathematik und Mechanik (GAMM)
Gesellschaft deutscher Naturforscher und Ärzte (GdNÄ)
Deutsche Physikalische Gesellschaft
Arbeitskreis Energie (AKE)
Member Editorial Board
„Adsorption“ (K. Knaebel, Ed.)
„Adsorption, Science & Technology“ (F. G. R. Gimblett, Ed.)

Hobby:

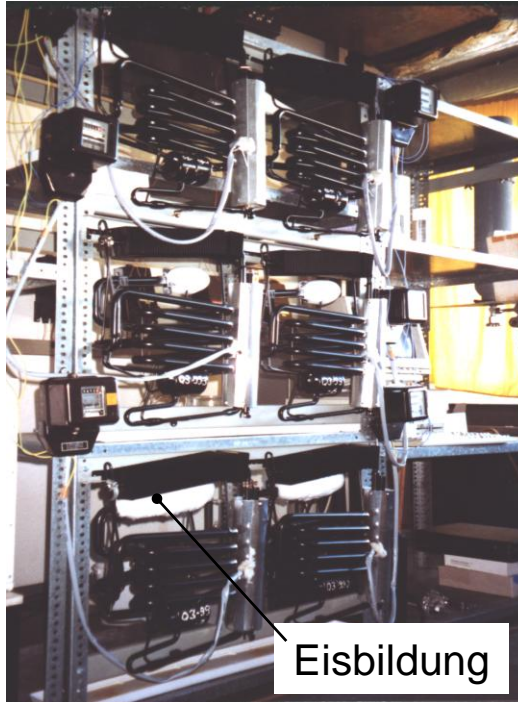
Bergsteigen, Kammermusik (Flöte, Klavier)



Thermodynamik

Kälteerzeugung

Luftreinigung



Eisbildung



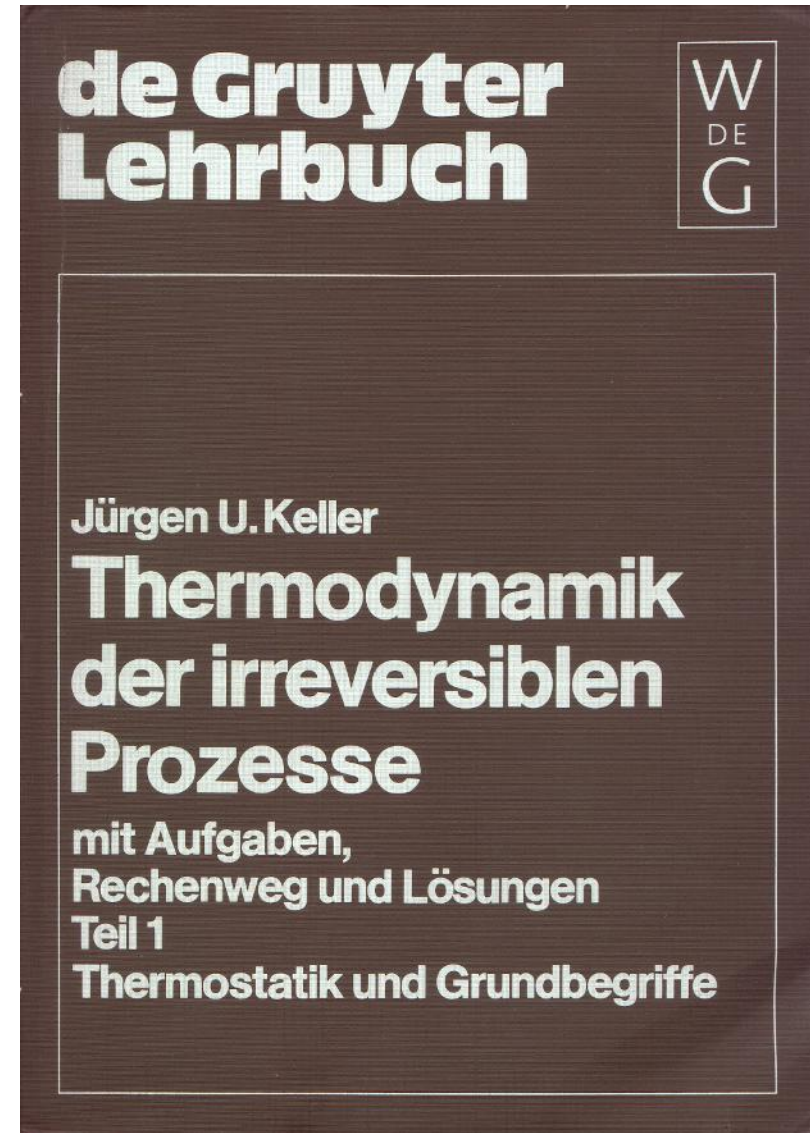
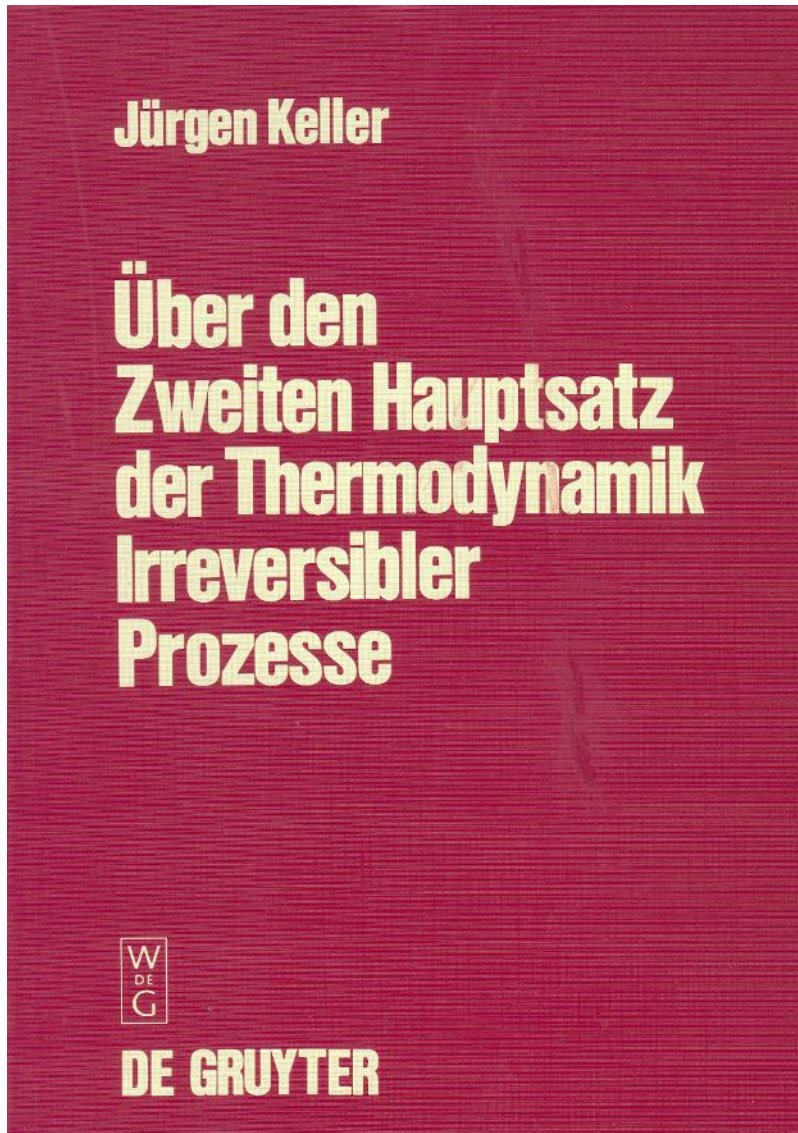
Smog bei Sonnenuntergang
(11/2003)

Aktivkohlefilter
Gasadsorption



Apparatur für
Adsorptionsmessungen

Absorberkühlschränke (Electrolux)
mit einem neuen Arbeitsstoff
im Langzeitversuch



**de Gruyter
Lehrbuch**



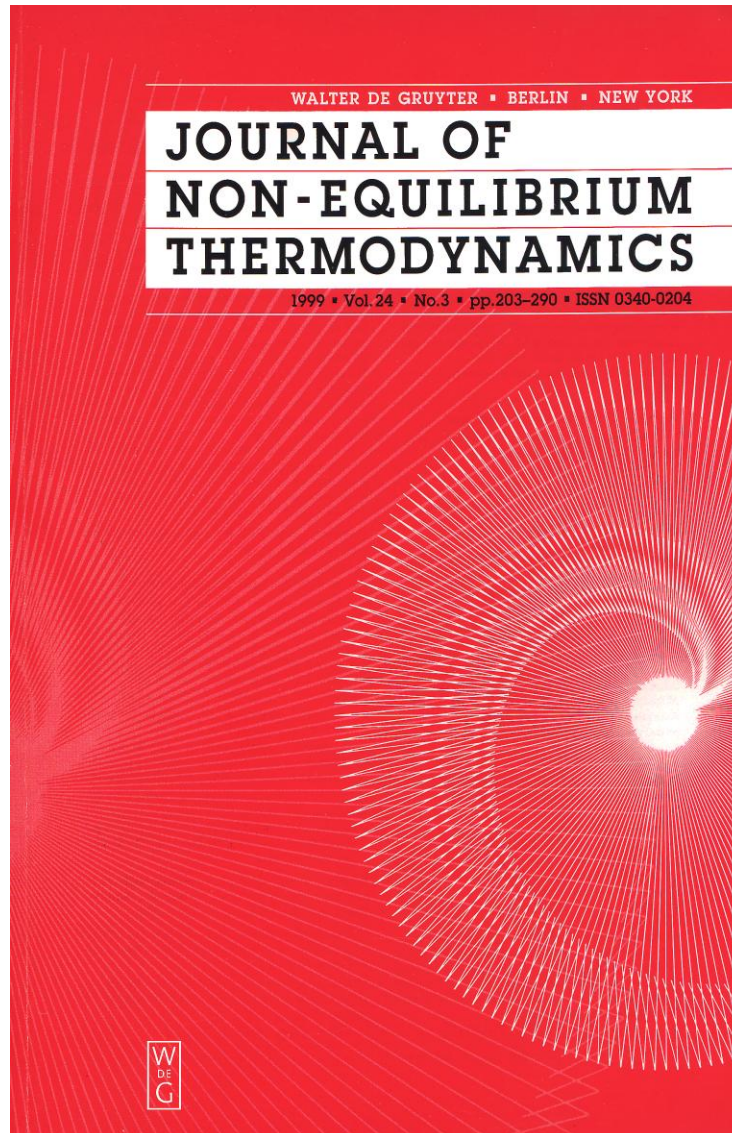
Jürgen U. Keller

**Technische
Thermodynamik
in Beispielen**

**Aufgaben · Rechenweg ·
Lösungen**

Begriffssammlung

Teil 1 Grundlagen



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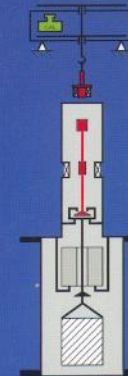
Forthcoming Papers

See inside back cover

GAS ADSORPTION EQUILIBRIA

Experimental Methods and
Adsorption Isotherms

Jürgen Keller
Reiner Staudt



Gas Adsorption Equilibria

Experimental Methods and Adsorption Isotherms
By Jürgen Keller and Reiner Staudt

This book is intended to present for the first time experimental methods to measure equilibria states of pure and mixed gases being adsorbed on the surface of solid materials. It has been written for engineers and scientists from industry and academia who are interested in adsorption-based gas separation processes and/or in using gas adsorption for characterization of the porosity of solid materials.

Traditional and new measurement methods for gas adsorption equilibria are presented in Chapters 2-6 and elucidated by quite a number of experimental data sets, most of them having been measured in the authors' laboratories. Special emphasis is given to uncertainties of data, and pros and cons of all measurement methods are offered. Also, the basic concepts underlying interpretation of measurements and calculations of adsorbed masses from measurement signals are discussed in Chapter 1.

The authors state that in publishing this book they hope to contribute to:

- *"The development of effective and reliable methods to measure pure gas and gas mixture adsorption equilibria.*
- *Preventing young (and old) experimenters from doing all the mistakes we have done during our laboratory work.*
- *Making experimental gas adsorption data measured today in many laboratories all over the world more easily comparable to each other, as methods and procedures should become more and more similar and possibly also will be standardized (IUPAC) in the years to come."*

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Informationsblatt für angehende Studierende

Überall auf der Welt sind Menschen hungrig und durstig. Sie frieren im Winter in gemäßigten Breiten und schwitzen in den tropischen Zonen der Erde. Daher besteht ständiger Bedarf an Nahrungsmitteln, sauberem Trinkwasser, Raumwärme und Klimakälte für Wohnräume, Arbeitsplätze etc. Zur Bereitstellung dieser Stoffe und Energien ist es notwendig, entsprechende Rohstoffe und Primärenergien wie z. B. Rohöl, Kohle, Erdgas etc. aufzubereiten, umzuwandeln, zu speichern und zu verteilen.

Die **Thermodynamik** stellt die naturwissenschaftlichen Gesetzmäßigkeiten bereit, nach denen dies grundsätzlich möglich ist. Sie liefert auch die stoffspezifischen Daten, die z. B. angeben, wie viel Benzin unbedingt notwendig ist, um einen LKW von Paris nach Berlin zu bringen oder wie ein Blockheizkraftwerk dimensioniert werden muss, um eine Wohnsiedlung vorgegebener Größe mit Strom und Fernwärme zu versorgen.



Abwärme nutzende Kälteanlage zur Kühlung eines Zwischenproduktes einer Kunststoffproduktion in einem Chemiekomplex der BASF in Schwarzeide

Die weltweit zu beobachtenden Rückwirkungen menschlicher Gesellschaften auf die Umwelt wie z. B. die wachsende Umweltverschmutzung, insbesondere der Gewässer!, die Klimaveränderungen u. a. erfordern eine verstärkte Analyse technischer und natürlicher Prozesse mit dem Ziel,

Rohstoffe und Energieressourcen möglichst schonend und umweltneutral, d. h. „nachhaltig“ einzusetzen.



Wirbelrohranlage zur Erdgastrocknung der Thyssengas GmbH in Gronau – Epe, NW.

Die **Technische Thermodynamik** ist für viele Teilgebiete der Technik ein unverzichtbares Grundlagenfach. So z. B. beruhen die wichtigsten Berechnungsverfahren der Wärmetechnik, Heiz- und Klimatechnik, Trocknungs- und Kältetechnik, des Industrieofenbaus, des Motorenbaus und vieler anderer mehr auf den grundlegenden Hauptsätzen und Beziehungen der Thermodynamik, die natürlich immer wieder an die besonderen Bedingungen eines Fachgebietes angepasst werden müssen.

In Zukunft wird die **Thermodynamik** sicher auch bei verschiedenen Schlüsseltechnologien wie z. B. der **Biotechnologie**, d. h. der Entwicklung neuer Verfahren zur Herstellung biochemischer, pharmazeutischer und medizinischer Substanzen mit z. B. selbstorganisierenden bzw. funktionalen Molekülen eine wichtige Rolle spielen. Dasselbe gilt für die **Nanotechnologie**, bei der das Verhalten von Flüssigkeiten und Gasen in engen Poren und Kanälen von entscheidender Bedeutung ist.

In wissenschaftsmethodischer Hinsicht werden für die **Thermodynamik** neben den klassischen Ansätzen des wissenschaftlichen Experiments und der Theorie auch EDV-gestützte **Simulationen**, insbesondere von molekularen Modellen von Mehrstoffsystemen mit komplexen Molekülen immer wichtiger werden.

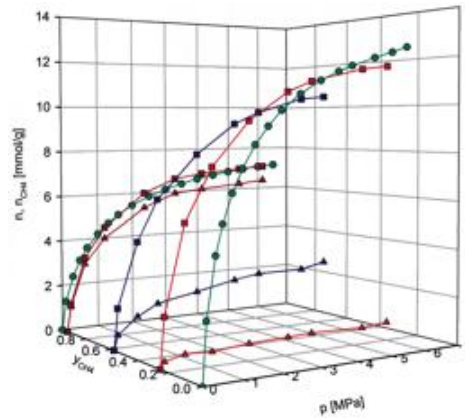
Gas Adsorption

Measurement of Adsorption Equilibria and Break Through Curves of Gas Mixtures for Design and Calculation of Gas Purification Installations

Apparatus for volumetric-gravimetric measurements including a magnetic suspension balance



Adsorption equilibria of methane and carbon dioxide and their mixtures on activated carbon Norit R1 Extra



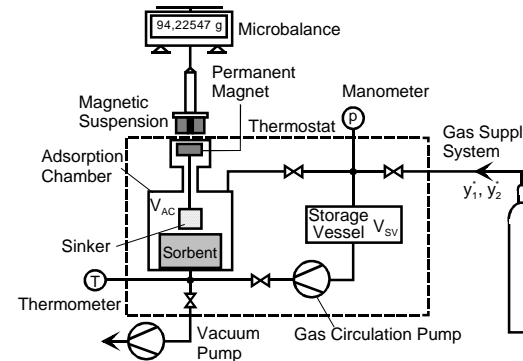
- Pure gases
- Total load of the mixture ($n_{CH_4} + n_{CO_2}$)
- ▲ Partial load of CH_4 (n_{CH_4}) $T = 298\text{ K}$

Measurement methods:

- Gravimetry / Volumetry
- Chromatography (Break Through Curves)
- Impedance Spectroscopy
- Oscillometry (Rotational Pendulum)

Binary Gas Mixture Adsorption

Densimetric-volumetric measurements (DVM)* of binary coadsorption equilibria without using a gas chromatograph



Instrument for densimetric-volumetric measurements of binary coadsorption equilibria of gas mixtures on porous solids without using a gas chromatograph. The sorptive gas supplied to the system is assumed to be a binary mixture with known initial molar concentrations (y^*_1, y^*_2). © IFT University of Siegen, 2002.



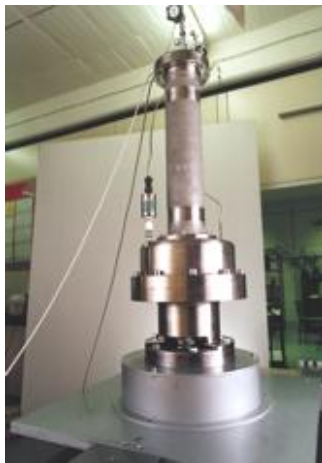
- Equipment needed: Spring balance or Microbalance or Magnetic suspension balance
- Operation: Fairly Simple
- Automation: Fairly simple
- Kinetics of Adsorption: Hardly observable
- Activation of sorbent: Outside the instrument
- Amount of sorbent needed: Large (5g – 100g)
- Thermostatization: Easily achievable

*) German patent pending.

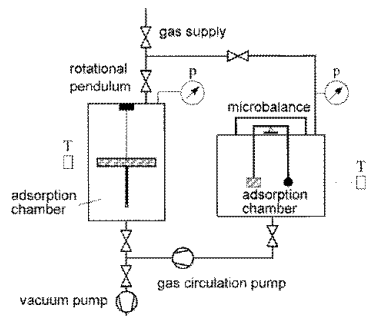
Oscillometric Measurements

Measurement of Gas-Adsorption Equilibria and Swelling Isotherms of Polymers during Sorption Processes

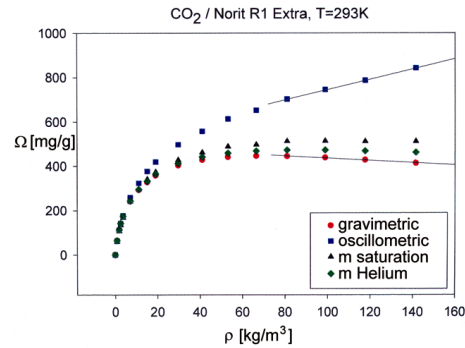
Oscillometric experimental setup for measurements of gas-adsorption equilibria



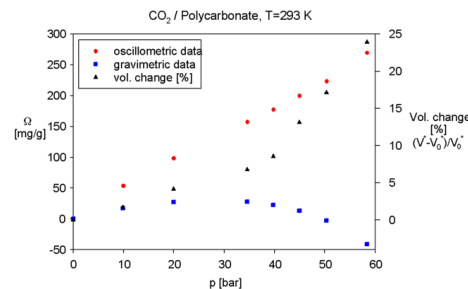
Combination of oscillometric and gravimetric measurements for the investigation of swelling processes



Adsorption isotherm of CO₂ on AC Norit R1 Extra at T = 293 K



Swelling behavior of polycarbonate in carbon dioxide at T = 293 K

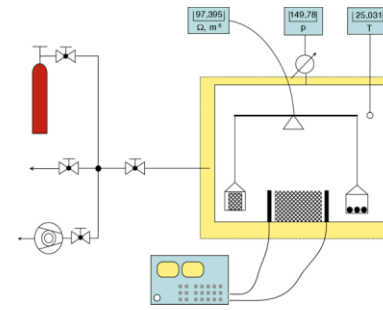


Impedance spectroscopy

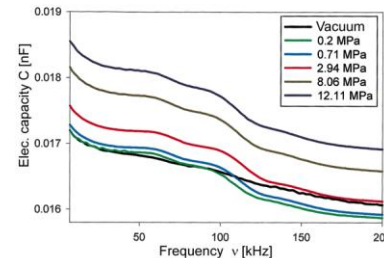
Measurements of adsorption equilibria, diffusion coefficients and breakthrough curves of pure gases and gas mixtures on porous solids

Physical adsorption processes of gases on the surface of porous solids are becoming more and more important in both chemical engineering and science. Examples for this are the air separation process at ambient temperature by microporous zeolites and/or activated carbons, the separation process of light paraffines, the regain of volatile organic compounds (VOCs), the cleaning of air, storage of natural gas or hydrogen in solid matrices and the characterization of newly developed porous materials by gas adsorption (N₂, 77K).

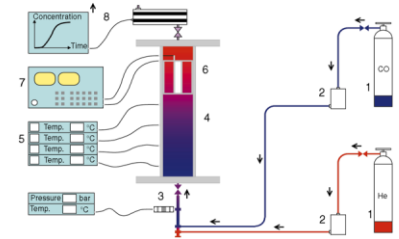
A new way to detect adsorption processes is to put the sorbent material between the plates of an electric capacitor, to exert it to a sorptive gas and to observe the change of the electric capacity of the capacitor. The aim of this work is to establish a relationship between the electric capacity of the sorbent/sorbate system and the amount of gas adsorbed. On principle, this offers the possibility to check the quality and state of a technical adsorber online! This allows to improve and possibly to optimize the technical adsorption and regeneration cycle considered.



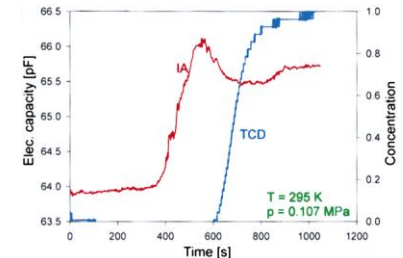
Experiment for gravimetric and dielectric measurements of adsorption equilibria



Impedance spectra of CO on molecular sieve MS 13X, T = 298 K.



Experiment for measurements of breakthrough curves by TCD and impedance analyser

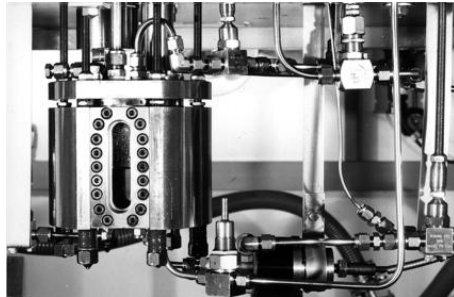


Breakthrough curve of CO on Envisorb b+. Carrier gas: N₂ measured by TCD and impedance analyser at (IA) $\nu = 250$ kHz.

Phase Equilibria

Measurement and Correlation of Vapor-Liquid-Equilibria (VLE) of Ammonia - Water- X Systems
(X = Sodiumhydroxide, Potassiumhydroxide, Lithiumbromide)

Measurements: Static VLE-cell with closed liquid circuit



VLE-apparatus

Analyses: Liquid: ionselective electrodes
Gas: gaschromatograph

Solid-Liquid-Vapor-Equilibria (SLVE)



SLVE of ammonia-water-sodium hydroxide

Industrial applications: SLVE of ammonia-water-sodium hydroxide

Company liaisons: Electrolux, Siegen
Hans Güntner GmbH Absorptionskälte KG, Berlin
Buderus, Wetzlar
Robur, Italy, USA

Absorption Heat Pump Chemical Heat Pump and Storage System

Industrial waste heat at low temperature (323K - 353 K) partially can be transformed to higher temperatures (373K - 453K) by using absorption processes. Also the waste heat can be stored at ambient temperature as chemical energy in either concentrated water-sulphuric acid or water-phosphoric acid mixtures.



Chemical Heat Pump and Storage System

Method:

Storage of waste heat:

diluted acid + waste heat concentrated acid + water

Production of useful heat:

water + waste heat → water vapor
concentrated acid + water vapor → diluted acid + useful heat

Chromatefree Working Fluid for Absorption Refrigeration Machines (NH₃ - H₂O, X) ^{*)}



Industrial absorption machinery (1.6 MW cooling capacity at -30°C) as part of a chemical plant, Germany.

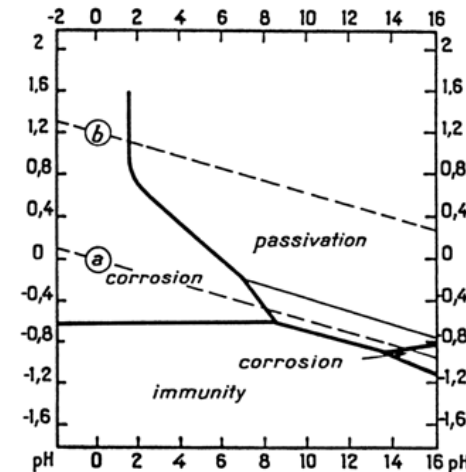


^{*)} Int. Patents pending

Absorption-refrigeration aggregates (Dometic, Tadiran, Sibir, Sanyo) in a lab of the IFT, University of Siegen
 icy bulbs around evaporators clearly can be recognized.

Advantages

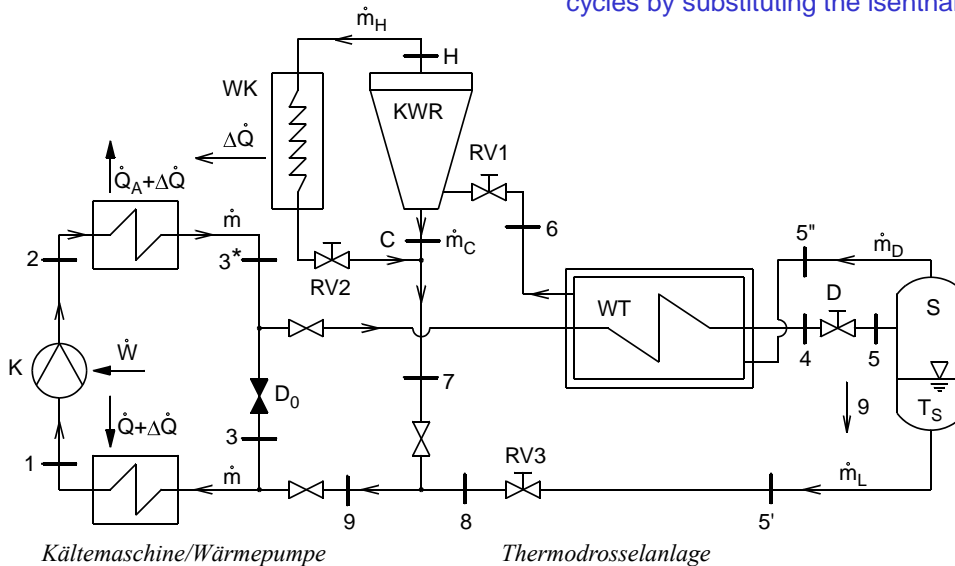
- corrosion inhibitor (X) is not poisonous to the environment, like sodium chromate or bichromate,
- simple treatment of waste fluid without environmental problems,
- vapor of refrigerant (NH₃) is nearly free of water, therefore
 - ▶ low temperatures of evaporation are attainable near -65°C / -85°F,
 - ▶ no dephlegmation of ammonia vapor is necessary and
 - ▶ the heat for generation of ammonia vapor is reduced considerably.



Pourbaix-Diagramm of iron after passivation by Fe₂O₃ / Fe₃O₄ Layer

Increasing the Coefficient of Performance by Use of Thermovalves

Increasing the Coefficient of Performance (COP) of heat pump and refrigeration cycles by substituting the isenthalpic throttle by a thermovalve*).



In the thermovalve working fluid in a liquid boiling state is partially depressurized in valve (D). Liquid and vapor phases are separated in the separator (S). Then the gas phase is superheated in the heat exchanger (HE) by subsequent liquid fluid. The preheated vapor is sent to a vortex tube (VT) to be expanded to evaporator's pressure level. The hot end flow leaving the vortex tube is cooled in a second heat exchanger and after this recombined with the cold end flow. This flow is merged with the liquid flow leaving the separator, both flows then being sent to the evaporator of the compression cycle.

Advantages of the thermovalve process:

- the vapor fraction of the working fluid in the expanded state is smaller than it would be after isenthalpic expansion
- the cooling power of the evaporator is increased by the heat released by the heat exchanger (WK) combined with the thermovalve;
- this leads to an increase of the coefficient of performance (COP) of heat pumps and refrigerator cycles,
- which can be about 5% for R22 or R134 or as working fluid, but may be about 15% if CO₂ is used.



Vortex Tube and hot end heat exchanger

Publications:

Ahlborn, B.; Keller, J.U.; Staudt, R.; Treitz, G.; Rebhahn, E.: Limits of temperature separation in a vortex tube. *J. Phys.: Appl. Phys.* 27 (1994), 480-488.

Keller, J.U.; Göbel, M.U.:

Die Thermodrossel: Eine Anlage zur Entspannung komprimierter Flüssigkeiten unter Wärmeabgabe. *Ki, Klima, Kälte, Heizung*, 25 (1997), 57.

Keller, J.U.:

Das Injektor-Wirbelrohr. Artikel in "Turbulenz in der Strömungstechnik", M.S. Kim Hsg., p. 103-116, Shaker, Aachen 1997, ISBN 3-8265-2968-5.

Ahlborn, B.; Keller, J.U.; Rebhahn, E.:

The Heat Pump in a Vortex Tube. *Journal of Non-Equilib. Thermodyn.* Vol. 23 (1998), p. 159-165.

THERMODYNAMIC PUMP

Hermetically sealed oscillating displacer

Joint development of the Institute Fluid- and Thermodynamics University Siegen and KAMAT-Pumps Witten / Germany

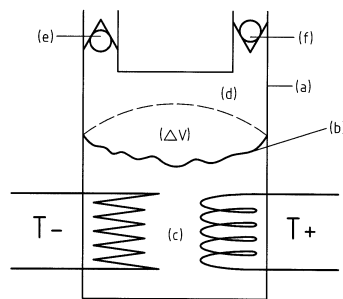


Advantages

- Hermetically sealed fluidic pumping against high differential pressures
- Mutual contamination between pumping fluid and environment excluded by 100 %
- Prime moving by electrical heater or by surplus process heat (steam, gas, fluids)
- High primary energy efficiency in case of process-integration
- Basically no limitation of unit-size or hydraulic power
- No noises nor any vibrations
- Full CIP and SIP capability
- Suitable to discharge all pumpable media and mixtures
- Variable selection of discharge characteristics
- Careful pressurized transport of sensitive media

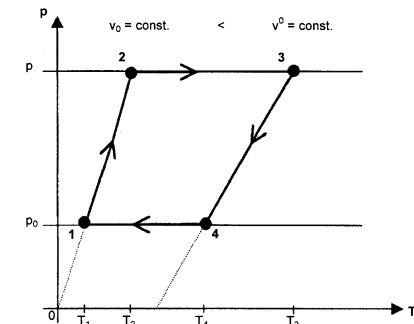
Applications

- Petrochemical, chemical and pharmaceutical industries
- Conversion of batch processes into continuous flow operations
- Pumping of supercritical fluids
- Biotechnology (Research labs, Pilot-Engineering, Production)
- Use of surplus process heat for fluidic transport
- Use of geothermal and solar heat



Working Scheme

- (a) = hermetically sealed pumping chamber
- (b) = diaphragm
- (c) = Working fluid
- (d) = pumping fluid
- (e+f) = inlet and discharge valves
- (+T) = induced heat
- (-T) = heat carried away
- (ΔV) = displaced volume = discharge volume per stroke



Thermodynamic Cycle-Process