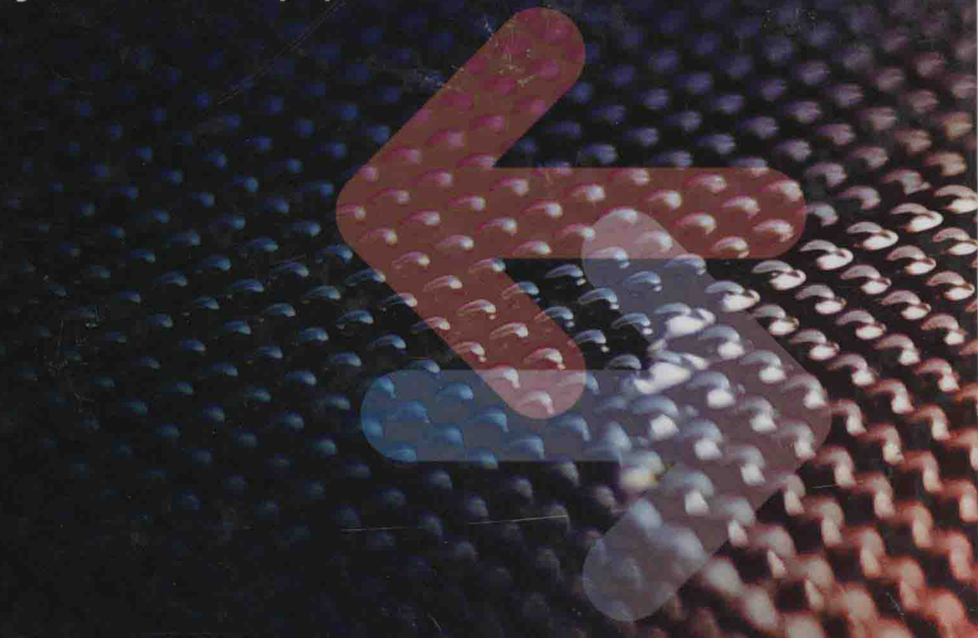
Adsorption Refrigeration Technology

Theory and Application



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THEORY AND APPLICATION

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Shanghai Jiao Tong University, China

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ADSORPTION REFRIGERATION TECHNOLOGY

About the Authors

Ruzhu Wang (R.Z. Wang) is a Professor of Institute of Refrigeration and Cryogenics at Shanghai Jiao Tong University. His major contributions are adsorption refrigeration, heat transfer of superfluid helium, heat pumps, CCHPs (cogeneration systems for cooling, heat, and power), and solar energy systems. He has published about 300 journal papers; about 200 of them are in international journals. He has written five books regarding Refrigeration Technologies. He was elected as CheungKong Chaired Professor in 2000 by the Ministry of Education (MOE) of China. Currently he is the vice president of the Chinese Association of Refrigeration, the vice chairman of the Chinese Society of Heat Transfer. Professor Wang was elected as one of the top 100 outstanding professors in Chinese universities in 2007. He was awarded as the model teacher of China in 2009. Professor Wang won second prize for the National Invention Award in 2010 on "Solar air conditioning and efficient heating units and their application," and also received the second prize for the National Award for Education in 2009 for his ideas and successful practices on "Innovative, Globalization, and Research Learning" for talents education in the field of refrigeration.

Liwei Wang (L.W. Wang) is Professor of the Institute of Refrigeration and Cryogenics at Shanghai Jiao Tong University. Her research experience focuses on the conversion of low grade waste heat using the technology of adsorption, such as the adsorption refrigeration cycle, intensification of the heat and mass transfer performance of adsorbents, and adsorption cogeneration cycle for refrigeration and power generation. For her research work she received awards such as the National 100 Outstanding PhD Theses, IIR Young Researchers Award, Royal Society International Incoming Fellowship in the UK, and the EU Marie Curie International Incoming Fellowship.

Jingyi Wu (J.Y. Wu) is a Professor of the Institute of Refrigeration and Cryogenics at Shanghai Jiao Tong University. Her achievements are mainly in the utilization of low grade heat and cryogenics for aerospace. She has published over 130 papers and has led various research projects funded by National Natural Science Foundation of China (NSFC), Hi-Tech Research and Development Program, Aerospace Research Funding, and so on. As a main member, she won second prize at the National Invention Award (second prizes) in 2010 and the second prize in the National Award for Education in 2009.

Preface

The supply and demand of energy determine the course of global development in every sphere of human activity. Finding sufficient supplies of energy to satisfy the world's growing demand is one of society's foremost challenges. Sorption refrigeration, which is driven by the low grade heat and provides the air conditioning and refrigeration effect, is paid more and more attention as one of the energy conversion technologies.

Sorption technology includes absorption and adsorption technology. The main differences between two types of technologies are the sorbents. The absorbents generally are liquid such as LiBr and NH_3, and the adsorbents are granular or compact solids, such as silica gel, zeolite, and chlorides. Compared with the absorption technology, the adsorption technology has the advantages of the wide choices of adsorbents for the wide scopes of driven temperatures for different heat sources, which generally ranges from 50 to 400 °C. The feature of solid adsorbents also makes it more feasible under the conditions with serious vibration. It doesn't need the rectifying equipments, nor does it have the problems of crystallization that can easily occur in absorption systems.

Adsorption refrigeration has two working processes. The first process is adsorption and refrigeration. In this process the adsorption heat releases cooling water or air to the heat sink and the pressure inside the adsorber decreases to a level lower than the evaporating pressure. The refrigerant evaporates and is adsorbed by the adsorbent under the function of pressure difference, and the evaporation process provides the refrigeration output. The second process is desorption and condensation. In this process the endothermic process of desorption is driven by the low grade heat. The desorbed refrigerant vapor is cooled by the heat sink and condensed in the condenser.

The earliest record of the phenomena of adsorption refrigeration was that AgCl adsorbed NH_3, which was discovered by Faraday in 1848. After that several refrigerators were developed for storing food and air conditioning. In the 1930s, the compression refrigeration technology was accelerated by technology innovations such as the discovery of Freon, the manufacture of a fully closed compressor, the application of compound refrigerants, and so on, and adsorption refrigeration could not compete with the CFCs (chlorofluorocarbons) system because of its low efficiency.

Since the late twentieth century, more and more research concentrated on sustainable development and the technology of adsorption refrigeration began to develop. There were two reasons for the fast development of sorption technologies: one is the need to solve the problems of energy shortage, which became more and more important since the worldwide energy crisis after the Middle East War during 1973. It takes about 7 million years to form petroleum and current supplies have almost been used up after more than 200 years' of exploitation. The stock of coal is greater than petroleum, but it is also consumed quickly especially with increasing demand as people all over the world desire comfortable living standards. The recovery of the low grade heat is one of the main technologies that may overcome the increasing constraints related to energy utilization. Another reason is related to climate change caused by ozonosphere depletion. There is a common recognition by international academics that depletion of the ozonosphere is caused by CFCs, which are found in refrigerators, air conditioners, and heat pumps. The green refrigerants, which are common in sorption technologies, are now being focused on as a replacement for traditional compression refrigeration technology.

The main technologies on adsorption refrigeration which are being researched by academics are mainly advanced adsorbents, advanced cycles, and advanced design for refrigeration systems. For example, Professor Critoph in the UK has worked on adsorption refrigeration for over 20 years. He and his research team have developed the consolidated activated carbon needed for the refrigeration and thermal wave cycle for the high coefficient of performance. The research team in France, such as Spinner, Meunier, and Mauran have worked on chemisorption thermodynamics and developed IMPEX for refrigeration. The research team of Kashiwagi and Saha developed the silica gel–water adsorption chiller and proposed the multi-stage cycle; Lebrun studied the heat and mass transfer of adsorbers; Vasiliev developed the heat pipe type adsorbers; Aristov studied the composite adsorbents of silica gel and the thermodynamics of composite adsorbents; and the academics in Korea studied the heat and mass transfer performances of solidified adsorbent, and so on. But there are no books which have systematically summarized the technology of adsorption refrigeration although it has now been developed for over 150 years.

As researchers in Shanghai Jiao Tong University, P.R. China, we have researched adsorption refrigeration for over 20 years. The research aspects include adsorbents, adsorption working pairs, adsorption refrigeration cycles, and adsorption applications. In order to share our research experience with international academics we have summarized our achievements as well as other researchers' outcomes. In this book the history of the development of adsorption refrigeration, development of adsorbents, thermodynamic theories, design of adsorption systems, adsorption refrigeration cycles have been discussed step by step. The main objective of the book is to give the readers a comprehensive guide to the research on adsorption refrigeration.

Ruzhu Wang, Liwei Wang, Jingyi Wu
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Nomenclature

a	Coefficient for the equilibrium reaction, coefficient in the van der Waals equation
a_p	The surface area per unit mass of adsorbent, m^2/kg
a_v	The surface area per unit volume of the adsorbent m^2/m^3
A	Coefficient in Clausius-Clapeyron equation
A_0	Dynamic coefficient
A_{0b}	The area of two back plates, m^2
A_a	Adsorbent cross-sectional area in the unit, m^2
A_{adb}	The heat transfer area of adsorber, m^2
A_c	The heat transfer area at the cooling side of the heat exchanger, m^2
A_{eff}, $A_{a,eff}$	Heat transfer area of heat exchanger at the solid adsorbent side, m^2
A_{evf}	The area at the fluid side of the heat pipe type evaporator, m^2
A_f	Heat transfer area of heat exchanger at the fluid side, m^2
A_{fa}	Internal surface area of the fin tube, m^2
A_{fe}	Anterior factor
A_{fin}	The area for the cross section of the fin, m^2
A_{fm}	The surface area of condensation pipe, m^2
A_g	Gas flow cross-sectional area in the unit, m^2
A_m	Heat transfer area of the metal wall at the adsorbent side, m^2
A_{mr}	Cross-sectional area of mass recovery channel, m^2
A_{rx},A_{ry}	Constants in Mazet reaction models
A_s	The area of solar collector, m^2
A_{seff}	Effective collector area, m^2
b	Coefficient in the van der Waals equation
B	Parameter for the pore structure of the adsorbent
c	Concentration of adsorbate, kg/m^3
c^*	Equilibrium concentration corresponding to the adsorption capacity x, kg/m^3
c_i	Concentration of the adsorbate on the surface of the adsorbent, kg/m^3
C	Constant in the Clausius-Clapeyron equation, specific heat, (J/(kg °C))
$C_{0\sim3}$	Coefficients in Tykodi models
C_a, C_{pa}	Specific heat of adsorbent, J/(mol K), J/(kg °C)
C_{ca}	Specific heat of composite adsorbent, J/(mol K), J/(kg °C)
C_{Ha}	Adsorbent heat capacity in the high-temperature adsorbent bed, J/(mol K), J/(kg °C)
C_{hb}	Specific heat of the liquid in the boiler, J/(mol K), J/(kg °C)

C_{Lc}	Specific heat of liquid refrigerant, J/(mol K), J/(kg °C)
C_{Lv}, C_{vg}	Specific heat of refrigerant vapor, J/(mol K), J/(kg °C)
C_m, C_{pm}	Specific heat of metal materials, J/(mol K), J/(kg °C)
C_{mal}	Specific heat of the aluminum, J/(mol K), J/(kg °C)
C_{mcu}	Specific heat of the copper, J/(mol K), J/(kg °C)
C_{mh}	Metal heat capacity of the heating boiler, J/(kg °C)
C_p	Isobaric specific heat, J/(mol K), J/(kg °C)
C_{pb}	The total thermal capacity, J/(mol K) or J/(kg °C)
C_{pc}, C_{pg}	Isobaric specific heat of refrigerant vapor, J/(mol K), J/(kg °C)
C_{pf}	The thermal capacity of the fluid, J/(mol K), J/(kg °C)
C_{pr}, C_{pl}	Isobaric specific heat of liquid refrigerant, J/(mol K) or J/(kg °C)
C_{ps}	The isobaric specific heat of solid material, J/(mol K), J/(kg °C)
C_{pw}	Thermal capacity of the metal walls, J/(mol K) or J/(kg °C)
C_{ra}	Proportional coefficient determined by evaporator type
C_{vf}	Specific heat at constant volume of the liquid refrigerant, J/(kg K)
COP	Coefficient of performance for refrigeration
COP_{AC}	COP for activated carbon adsorber
COP_{carnot}	COP for Carnot cycle
COP_{hp}	COP of heat pump
COP_i	Ideal COP
COP_{int}	COP for intermittent cycle
COP_Z	COP for zeolite adsorber
d	Distance, distance between molecules, diameter, m
d_a	The diameter of the adsorbent particles, m
d_{ave}	Average pore diameter, m
d_e	Equivalent diameter, m
d_p	Equivalent diameter of the solid particles, m
d_{pi}	Inlet diameter of the tube, Inner diameter of the pipe, m
d_{po}	Outer diameter of the pipe, m
d_v	Equivalent diameter for the flowing process of the vapor, m
d_w	The channel width, m
D'	The coefficient in D-A equation
D_e	Diffusion coefficient in the micropore, effective diffusion coefficient
D_{go}	Diameter of the outer glass tube, m
D_i	Effective diffusion coefficient, m^2/s
D_k	Knudsen diffusion coefficient
D_{ms}	Mass diffusion coefficient of the fluid, m^2/s
D_s, D_{so}	Surface diffusion coefficient, m^2/s
e_{eff}	Effective thickness of adsorbent, m
e_{so}	The internal energy for the solid adsorbent skeleton, kJ/kg
E	Specific adsorption power, J/mol
E_a	Activated energy for adsorption, J/mol
E_d	Activated energy for desorption, J/mol
E_{ij}	Thermal dispersion coefficient
E_p	Pseudo-activated energy, J/mol
f	The fugacity under the pressure of p, Pa

f_0	The fugacity under the pressure of p_s, Pa
f_S	The ratio between the area of airflow area and area of the cross-section area of wheel, m^2/m^2
f_V	Surface area of unit volume of adsorbent, m^2/m^3
g	Acceleration of gravity, m/s^2
G	Free enthalpy, J
h	Specific enthalpy, J/kg
h_a,h_d	Adsorption heat, desorption heat, kJ/kg
h_{ev}	The height for the evaporating section of the heat pipe, m
h_f	Specific enthalpy of the refrigerant liquid, J/kg
h_r	Specific enthalpy of the ammonia liquid at the condensation temperature, J/kg
h_w	The depth of the channels, m
H	Enthalpy, J
H_a,H_d	Adsorption heat, desorption heat, kJ
H_{adb}	The thickness (i.e., height) of the adsorbent bed, m
$\overline{H}_2$	Partial molar enthalpy, J/mol
$\overline{H}_g$	Molar enthalpy, J/mol
$H_{\max}$	Maximum capillary height, m
H_r	Chemical reaction heat, J
H_{st}	Isobaric adsorption/desorption heat, kJ/kg
I	The solar radiation intensity, W/m^2
I_0	Direct sunlight intensity, W/m^2
I_{ref}	Reflected sunlight intensity from back plate, W/m^2
J	Heat flux, W/m^2
k	Coefficient in D-R equation
k_1,k_2,k_3	Stability constants
k_F	Mass transfer coefficient, $kg/(m^2\ s)$
k_{ij}	The component of permeability tensor, m^2
k_p	Permeability of porous medium, m^2
k_s	Mass transfer coefficient inside the solid phase film, $kg/(m^2\ s)$
k_y	Convection mass transfer coefficient, $kg/(m^2\ s)$
K	The coefficient for D-R equation, equilibrium constant of the reaction, permeability (m^2)
K_a	Coefficient for the reaction rate in adsorption process, $1/(m^2\ s)$
K_d	Coefficient for the reaction rate in desorption process, $1/(m^2\ s)$
K_F	Mass transfer coefficient of the fluid side, m/s
K_i	The dynamic coefficient
K_{ms}	Coefficient of the mass transfer
K_{md}	Coefficient for the influence of chemical kinetics on the reaction
K_n	Knudsen diffusion rate
K_r	Reaction kinetic constant
K_s	The total mass transfer coefficient ($kg/(m^2\ s)$), permeability (m^2/s)
$K_s a_p$	Surface diffusion rate coefficient 1/s
K_v	Net adsorption rate, (kg/kg)/s
K_x	Reaction coefficient in Iloeje's equation, °C/s
l	Length, mass transfer scale, m

l_{ah}	Heat pipe height in the adsorbent bed, m
l_{fin}	The perimeter of the cross section, m
L	Latent heat of vaporization of refrigerant, kJ/kg
L_a	Adsorbent thickness along the direction of L_y, m
L_{ad}	The length of adsorbent bed, m
L_b	The width of the adsorbent bed along the direction of L_y, m
L_{bw}	Thickness of the wall, m
L_B	Unit lateral equivalent width, m
L_c	The condensation heat of the refrigerant in the condenser, kJ/kg
L_e	The evaporating heat of the refrigerant in the evaporator, kJ/kg
L_{ev}	The length of the evaporation section of the heat pipe type evaporator (m); the latent evaporation heat of the refrigerant (kJ/kg)
L_{fin}	The half distance between fins in the adsorption bed, m
L_{hp}	Evaporation latent heat of the fluid inside the heat pipe, kJ
L_m	Height of the heat medium along the direction of L_z, m
L_{pi}	The length of the pipe, m
L_{sat}	Evaporation latent heat of the refrigerant at the temperature of T_s, J/kg
L_x,L_y,L_z	Three coordinates, m
L_{xt}	The total length along the direction of L_x, m
$\dot{\mathrm{m}}$	Gas flow rate from a unit to the next unit, kg/s
m	Flow rate (kg/s, g/s)
m_{am}	Mass flow rate of ammonia, kg/s
m_{air}	The airflow rate, kg/s
m_C	The molar mass of $CaCl_2$, 110.99
m_e	The mass flow rate of the vapor, kg/s
m_f	Volume flow rate of the fluid, m^3/s
m_i	Air flow through the unit cross-sectional area of wheel, kg/(m^2s)
m_{mr}	The mass flow rate for the vapor in mass recovery phase, kg/s
m_N	Molar mass of NH_3, 17
m_{oil}	Fuel quantity, kg/h
m_{uA}	Mass flow rate per unit area, kg/(m^2 s)
m_w	Mass flow rate of heating/cooling fluid, kg/s
m_{water}	Flow rate of the water, kg/s
m_x,m_y	Reaction order
m_y	Flow rate of the exhaust gas, kg/s
M	Mass, kg
M_a	The mass of adsorbent, kg
M_{av}	The adsorbent mass in unit volume, kg/m^3
M_C	The mass of $CaCl_2$, kg
M_{ca}	The mass of composite adsorbent, kg
M_{e0}	Mass of the refrigerant in the evaporator under equilibrium conditions, kg
M_{eqh}	The mass of the working fluid in the liquid pumping boiler, kg
M_{ev}	The mass of the refrigerant in the evaporator, kg
M_{ew}	Mass of the refrigerant liquid inside the evaporator, kg
M_g	The mass of graphite, kg

M_{ha}	The mass of the working fluid in the fin tube of the adsorbent bed and in the liquid chamber, kg
M_{hb}	Total mass of the working fluid in the boiler, kg
M_{hp}	The initial mass of the working fluid in the liquid pumping boiler, kg
M_{Ha}	Adsorbent mass in the high temperature adsorbent bed, kg
M_m	The mass of support body in the unit volume, kg/m^3
M_{madb}	Metal mass of the adsorbent bed, kg
M_{mal}	The mass of aluminum inside the adsorber, kg
M_{mcu}	The mass of the copper material inside the adsorber, kg
$M_{m,con}$	The metal mass of the condenser, kg
$M_{m,eva}$	The metal mass of the evaporator, kg
M_{me}	Mass of methanol desorbed from adsorber, kg
$M_{meva,cond}$	The metal mass of evaporator and condenser, kg
M_{mh}	Metal mass of the heating boiler, kg
M_{pbf}	Mass of the liquid in the liquid pumping boiler that cannot be pumped into the adsorbent bed, kg
M_r	Reaction kinetic constant
M_{Re}	The function of the Reynolds number
M_z	Total mass of the working fluid filled into the heat pipe system, kg
Ma	Reaction dynamic coefficient for adsorption
Md	Reaction dynamic coefficient for desorption
$\dot{n}$	The total molar flow rate, mol/s
n	Coefficient in D-A equation, coefficient for reaction equilibrium, reaction order
n_2^s	Molar adsorption quantity on the surface of solid adsorbent, mol/mol
n_s	Number of flow channels
N	Molar mass (mol), layer numbers of the glass cover
N_g	Molar adsorption quantity, mol/mol
p	Pressure, Pa
p'	Pressure on the metal chloride's surface, Pa
p_{ae}, p_{ads}	The pressure inside the adsorber at the end of the adsorption phase, Pa
p_c	Constrained pressure, Pa
p_{de}, p_{des}	The pressure of the adsorber at the end of the desorption phase, Pa
p_{ea}	Equilibrium pressure of adsorption state, Pa
p_{ed}	Equilibrium pressure of desorption state, Pa
p_h	Pressure of reaction interface, Pa
p_i	Pressure of the vapor reactant interface, Pa
p_m	The pressure of the system after the mass recovery, Pa
P_{el}	The electricity generation of the cogeneration system, W
p_i	Pressure inside pore, Pa
PER	Primary energy ratio
Pr	Prandtl number
Pr_s	Prandtl number of the media under the saturated temperature
Pr_w	Prandtl number of the media under the plate surface temperature of the heat exchanger
q	Heat flux density, W/m^2

q_{ads}	Average differential adsorption heat, J/kg
q_c	Heat adsorbed by the adsorbent, J/kg
$q_{c,st}$	The cold storage quantity per unit mass of adsorbent, kJ/kg
$q_{h,st}$	The heat storage quantity per unit mass of adsorbent, kJ/kg
q_{in}	Endothermic heat, J/kg
q_r	The sum of the radiation, W/m^2
q_{reg}	Required heat of the adsorbent bed without heat recovery process, J
q_{reg}^*	Heat recovered in a heat recovery process of the adsorbent bed, J
q_{st}	Isosteric heat, J/mol, J/kg
Q	Heat, J or kJ
Q_{bind}	The difference between the heat required for desorption Q_{des} and the condensation heat Q_{cond}, J or kJ
Q_{cc}	The sensible heat of the liquid refrigerant, J or kJ
Q_{char}	Charging heat, J or kJ
Q_{chill}	The heat at the refrigeration section of the heat pipe type evaporator, J or kJ
Q_{eref}	Cooling power generated by the evaporation of the refrigerant in evaporator, J or kJ
Q_{evas}	The sensible heat of liquid refrigerant in evaporator, J or kJ
Q_{ew}	The heat at the condensation section of the heat pipe type evaporator, J or kJ
Q_{hg}	Heat from the heat source, kJ
Q_{hs}	Heat quantity for convective heat transfer process, J or kJ
$Q_{h,st}$	The heat stored, J or kJ
Q_{reg}	Regenerative heat, J or kJ
Q_{sens}	Prerequisite energy to heat up the reactor to a required desorption temperature, J or kJ
Q_{Hd}	The desorption heat of the high temperature adsorber, J or kJ
Q_{Hs}	The synthetization heat of high temperature adsorber, J or kJ
Q_{seff}	Heat transformed from the actual solar radiation, J or kJ
Q_{st}	Isobaric adsorption heat, J or kJ
Q_{sen}	Sensible heat of the adsorber, J or kJ
Q_{solar}	Solar radiation, J or kJ
r	Radius, m
r_{as}	Ratio between expansion space and volume of adsorbent
r_c	Diameter of reaction surface, m
r_g	Radius of grain, m
r_{hc}	Heat recovery coefficient
r_{sh}	Shape factor of isothermal adsorption process of ideal adsorbent material
R	The universal gas constant, J/(mol K)
R_0	Thermal resistance of tube, (m^2 °C)/W
R_f	The thermal resistance of the fouling between the fluid and the metal wall, °C/W
R_{go}	The radius of the outer glass tube, m
R_H	Relative humidity, %
R_i	Thermal resistance of dirt, (m^2 °C)/W
R_m	The radius of metal tube, m
R_p	Average diameter of the adsorbent granules, m