能源与环境出版工程

总主编 翁史烈

经典中国国际出版工程
China Classics International

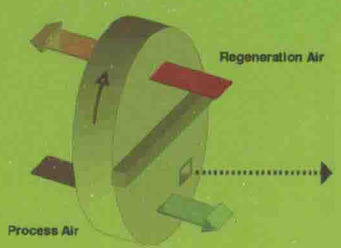
上海交通大学学术出版基金资助

Ultrasonic Technology for Desiccant Regeneration

除湿剂超声波再生技术（英文版）

Ye Yao Shi-Qing Liu

姚 晔 刘世清 著



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内容提要

本书详细论述了不同类型除湿剂(包括除湿硅胶、蜂窝式除湿材料以及 $LiCl\backslash CaCl_2$ 除湿溶液)超声波强化再生的基本原理、实验研究方法、理论建模过程及模型计算分析结果,并重点介绍了不同类型超声波换能装置的工作原理、设计计算方法及其在固、液除湿剂再生系统中的作用。本书可供大专院校师生、建筑空调系统科研、设计院以及空调开发企业的工程技术研发、设计和管理人员学习参考之用。

图书在版编目(CIP)数据

除湿剂超声波再生技术:英文/姚晔,刘世清著. —上海:上海交通大学出版社,2014

ISBN 978-7-313-10867-8

Ⅰ.①除… Ⅱ.①姚…②刘… Ⅲ.①防潮剂—超声波处理—英文 Ⅳ.①TQ047.3

中国版本图书馆 CIP 数据核字(2014)第 024858 号

除湿剂超声波再生技术(英文版)

著　　者:姚　晔　刘世清
出版发行:上海交通大学出版社
地　　址:上海市番禺路 951 号
邮政编码:200030
电　　话:021-64071208
出 版 人:韩建民
印　　制:上海万卷印刷有限公司
经　　销:全国新华书店
开　　本:787mm×1092mm　1/16
印　　张:21.25
字　　数:710 千字
版　　次:2014 年 9 月第 1 版
印　　次:2014 年 9 月第 1 次印刷
书　　号:ISBN 978-7-313-10867-8/TQ
定　　价:98.00 元

能源与环境出版工程
丛书学术指导委员会

能源与环境出版工程
丛书编委会

总　序

能源是经济社会发展的基础，同时也是影响经济社会发展的主要因素。为了满足经济社会发展的需要，进入21世纪以来，短短十年间（2002—2012年），全世界一次能源总消费从96亿吨油当量增加到125亿吨油当量，能源资源供需矛盾和生态环境恶化问题日益突显。

在此期间，改革开放政策的实施极大地解放了我国的社会生产力，我国国民生产总值从10万亿元人民币猛增到52万亿元人民币，一跃成为仅次于美国的世界第二大经济体，经济社会发展取得了举世瞩目的成绩！

为了支持经济社会的高速发展，我国能源生产和消费也有惊人的进步和变化，此期间全世界一次能源的消费增量28.8亿吨油当量竟有57.7%发生在中国！经济发展面临着能源供应和环境保护的双重巨大压力。

目前，为了人类社会的可持续发展，世界能源发展已进入新一轮战略调整期，发达国家和新兴国家纷纷制定能源发展战略。战略重点在于：提高化石能源开采和利用率；大力开发可再生能源；最大限度地减少有害物质和温室气体排放，从而实现能源生产和消费的高效、低碳、清洁发展。对高速发展中的我国而言，能源问题的求解直接关系到现代化建设进程，能源已成为中国可持续发展的关键！因此，我们更有必要以加快转变能源发展方式为主线，以增强自主创新能力为着力点，规划能源新技术的研发和应用。

在国家重视和政策激励之下，我国能源领域的新概念、新技术、新成果不断涌现；上海交通大学出版社出版的江泽民学长著作《中国能源问题研究》（2008年）更是从战略的高度为我国指出了能源可持续的健康发展之路。为了“对接国家能源可持续发展战略，构建适应世界能源科学技术发展趋势的能源科研交流平台”，我们策划、组织编写了这套“能源与环境出版工

程”丛书,其目的在于:

一是系统总结几十年来机械动力中能源利用和环境保护的新技术新成果;

二是引进、翻译一些关于“能源与环境”研究领域前沿的书籍,为我国能源与环境领域的技术攻关提供智力参考;

三是优化能源与环境专业教材,为高水平技术人员的培养提供一套系统、全面的教科书或教学参考书,满足人才培养对教材的迫切需求;

四是构建一个适应世界能源科学技术发展趋势的能源科研交流平台。

该学术丛书以能源和环境的关系为主线,重点围绕机械过程中的能源转换和利用过程以及这些过程中产生的环境污染治理问题,主要涵盖能源与动力、生物质能、燃料电池、太阳能、风能、智能电网、能源材料、大气污染与气候变化等专业方向,汇集能源与环境领域的关键性技术和成果,注重理论与实践的结合,注重经典性与前瞻性的结合。图书分为译著、专著、教材和工具书等几个模块,其内容包括能源与环境领域内专家们最先进的理论方法和技术成果,也包括能源与环境工程一线的理论和实践。如钟芳源等撰写的《燃气轮机设计》是经典性与前瞻性相统一的工程力作;黄震等撰写的《机动车可吸入颗粒物排放与城市大气污染》和王如竹等撰写的《绿色建筑能源系统》是依托国家重大科研项目的新成果新技术。

为确保这套“能源与环境”丛书具有高品质和重大的社会价值,出版社邀请了杜祥琬院士、黄震教授、王如竹教授等专家,组建了学术指导委员会和编委会,并召开了多次编撰研讨会,商谈丛书框架,精选书目,落实作者。

该学术丛书在策划之初,就受到了国际科技出版集团 Springer 和国际学术出版集团 John Wiley & Sons 的关注,与我们签订了合作出版框架协议。经过严格的同行评审,Springer 首批购买了《低铂燃料电池技术》(*Low Platinum Fuel Cell Technologies*),《生物质水热氧化法生产高附加值化工产品》(*Hydrothermal Conversion of Biomass into Chemicals*)和《燃煤烟气汞排放控制》(*Coal Fired Flue Gas Mercury Emission Controls*)三本书的英文版权,John Wiley & Sons 购买了《除湿剂超声波再生技术》(*Ultrasonic Technology for Desiccant Regeneration*)的英文版权。这些著作的成功输出

体现了图书较高的学术水平和良好的品质。

希望这套书的出版能够有益于能源与环境领域里人才的培养，有益于能源与环境领域的技术创新，为我国能源与环境的科研成果提供一个展示的平台，引领国内外前沿学术交流和创新并推动平台的国际化发展！

翁史烈

2013 年 8 月

About the Authors

Dr Ye Yao is an Associate Professor at the School of Mechanical Engineering, Shanghai Jiao Tong University, China. He received his PhD from Shanghai Jiao Tong University (SJTU), China. He was promoted as Associate Professor of SJTU in December 2008. From September 1, 2009 to September 1, 2010, he performed his research work in the Ray W. Herrick Laboratory at Purdue University (PU), USA. He was awarded as Excellent Reserve Youth Talent (First Class) and SMC Excellent Young Faculty by SJTU, respectively, in the year 2009 and 2010, and got the Shanghai Pujiang Scholars Talent Program in the year 2012. His current interests of research mainly include: (1) heat and mass transfer enhancement assisted by ultrasound; and (2) HVAC modeling and optimal control for energy conservation. He has successfully published about 100 academic publications and 30 patents and one academic monograph (sole author). He is now the peer reviewer of many international academic journals, such as the *International Journal of Heat and Mass Transfer*, *International Journal of Thermal Sciences*, *International Journal of Refrigeration*, *Energy*, *Building and Environment*, *Energy and Buildings*, and *Applied Energy*.

Dr Shiqing Liu is a Professor at the School of Mathematical and Information Engineering, Zhejiang Normal University, China. He received his PhD from Shanxi Normal University, China. His current interests of research are mainly applied acoustic and ultrasound transducers. He has published about 40 academic publications and over 10 patents in his research domains.

Preface

With global warming and the rapid improvement of people's living standards, energy consumption by air conditioning (AC) systems in buildings is on the rise. It has been noted that the dehumidification process accounts for a large proportion of energy consumption by an AC system. In southern areas of China where the climate is very hot and humid, the percentage of energy to be consumed by the dehumidification process in an AC system will be more than 40%. By using adsorption/absorption dehumidifying technology, the heat and moisture load of air can be processed separately, and a higher energy efficiency will be achieved compared with the conventional cooling dehumidification method. In addition, no condensation of water happens during the air dehumidification process with the adsorption/absorption method, which effectively prevents virus and mold from breeding, and hence improves indoor air quality (IAQ). Therefore, people are paying more attention to the adsorption/absorption dehumidifying method as the key technology for developing high-performance of AC systems.

Regeneration of desiccant is a crucial process during the air dehumidification cycle with the adsorption/absorption method. It will produce great influence on the energy efficiency of desiccant AC systems. The conventional regeneration method by heating is found to be energy-wasting due to the relatively higher regeneration temperature of some desiccant materials. So, we have put forward the ultrasound-assisted regeneration method in this book. The fundamental theory of the novel regeneration method is summarized as follows: ① The mechanical effect of ultrasound causes a series of rapid and successive compressions. This can reduce the thickness of boundary layer near the surface of solid desiccants and bring about the enhancement of mass transfer during regeneration. Meanwhile, the ultrasonic heating effect causes a temperature rise in solid desiccants and enhances internal moisture diffusivity known as "rectified diffusion." ② For liquid desiccants, the cavitation effect induced by power ultrasound sprays the solution into numerous tiny droplets with a size range of 40–80 μm, which improves the regeneration rate of liquid desiccants through enlarging the contact area between the air and the desiccant solute instead of increasing the solution temperature.

The study in this book demonstrates that ultrasound-assisted regeneration can significantly increase energy efficiency of regeneration, shorten regeneration time and hence improve performance of the desiccant AC system. In addition, the temperature for regeneration can be reduced by introducing power ultrasound, which provides favorable conditions for the utilization of low-grade thermal energy (e.g., solar energy and waste heat) in the desiccant regeneration.

This book is edited based on recent studies on ultrasound-assisted regeneration. It consists of six chapters as below:

Chapter 1 introduces the background of the topic to be illustrated in this book; it includes a literature review on up-to-date technologies related to desiccant materials, desiccant dryer systems and regeneration methods, and gives basic knowledge about ultrasound and methods for producing ultrasound.
Chapter 2 deals with models for ultrasound-assisted regeneration for silica gel, presenting experimental and theoretical results and including a parametric study of the new regeneration method.
Chapter 3 investigates the effect of ultrasound on the regeneration of a new honeycomb-type desiccant and includes a parametric study on ultrasound-assisted regeneration.
Chapter 4 introduces the mechanism of the ultrasound-assisted regeneration for the liquid desiccants, and studies the effects of the ultrasonic atomization on the liquid desiccant regeneration.
Chapter 5 deals with the working principle and design calculation method for longitudinal and radial vibration ultrasonic transducers that have potential applications in ultrasound-assisted regeneration.
Chapter 6 presents several desiccant air-conditioning systems in which ultrasound-assisted regeneration is employed.

The book is written by Dr Ye Yao (Associate Professor at the Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, China) and Dr Shiqing Liu (Professor at the Institute of Mathematics and Physics, Zhejiang Normal University, China). Chapters 1, 2, 3, 4 and 6 as well as the appendix have been written by Dr Ye Yao, and Chapter 5 has been written by Dr Shiqing Liu and Dr Ye Yao.

Acknowledgements

The study work related to the book has been financially supported by Shanghai Pujiang Program (2012) and several National Nature Science Foundations (No.50708057; No.11274279; No.11074222) as well as Shanghai Jiaotong University Academic Publishing Fund (2013). Meanwhile, this book has been successfully chosen as China Classics International Academic Publishing Project (2014). The publication of the book will be an important reference for related research fields.

I would like to express my appreciation to those who have educated, aided and supported me: my mentors Prof. Ruzhu Wang (Shanghai Jiao Tong University), Prof. Guoliang Ding (Shanghai Jiao Tong University), Prof. Xiaosong Zhang (Southeast University, China); my collaborators Mr Beixing He (senior engineer at the Institute of Acoustics, Chinese Academy of Sciences) and Prof. Houqing Zhu (Institute of Acoustics, Chinese Academy of Sciences); and my students, including my PhD Candidate Yang Kun (who designed most of the computer programs), Dr Weijiang Zhang (who carried a large number of experimental studies related to this book), my Master Candidate Godwin Okotch (who revised the language errors), Weiwei Wang and Zhengyuan Zhu (who participated in some experimental tests and measurements).

Finally, I offer my heartfelt gratitude to the editorial director Dr Fangzhen Qian and Mrs Yingchun Yang at Shanghai Jiao Tong University Press for their help, cooperation, advice and guidance in preparing this edition of the book.

Ye Yao
Shanghai Jiao Tong University
December 30, 2013

Nomenclature

a_u	Ultrasonic absorptivity by medium
A_o	Pre-exponential factor of Arrhenius equation, m^2/s
A_w	Activity of water
A_ϕ	Debye-Huckel constant for the osmotic coefficient
AEE	Average energy efficiency, %
AMR	Additional moisture removal brought about by ultrasound, kg
AMRC	Additional moisture removal capacity brought about by ultrasound, kg/s
ASEC	Adiabatic specific energy consumption, J/(kg moisture desorption)
B	Standard atmosphere pressure, Pa
c	Specific heat, J/(kg.°C)
c_Y	Specific heat ratio
cos	Cosine function
C_m	Mechanical quality factor of transducer
C_w	Moisture concentration in the mainstream air, kg/m^3
C_w*	Concentration on the surface of liquid droplet, kg/m^3
COP	coefficient of performance
CR	Contribution ratio of ultrasonic effect to the total enhancement of regeneration
CRT	Conditioned regeneration time, s
d	Diameter, m
D	Diffusion coefficient, m^2/s
DCOP	Dehumidification coefficient of performance
E	Energy consumption, J; or NRTL binary interaction energy parameter; or Young's modulus of the material, Pa; or electric field
E_a	Activation energy, kJ/mol
EP	Enhancement percentage of regeneration, %

cosh	Hyperbolic cosine function
cot	Cotangent
c_o	Adiabatic sound velocity in the air, m/s
$c_{e,cp}$	Equivalent vibration velocity, m/s
C	Heat capacity rate, W/°C
C_o	One-dimensional cutoff capacitance of the piezoelectric ceramic, F
C_f	Drag coefficient
f_c	Activity coefficient
F	Force, N
g	Gibbs energy of molecules; or acceleration of gravity, m/s^2
g'	Derivative of equilibrium isotherm
g_{33}	Voltage constant of piezoelectric ceramic
G	Mass flow rate, kg/(m^2.s)
h	Enthalpy, J/kg; or height, m
H	Adsorption (desorption) heat of desiccant, kJ/(kg water)
H_m	Coefficient of heat transfer, W/(m^2.C)
i	Unit of the imaginary number
I	Sound intensity, W/m^2; or electric current, A
I_x	Ionic strength in mole fraction scale
$J_0(x)$	The zero-order Bessel function of the first kind
$J_1(x)$	The first-order Bessel function of the first kind
k	Wave number, 1/m
k'	Modified complex wave number
K_m	Coefficient of mass transfer or mass transfer flux, kg/(m^2.s)
l	Length, m
ER	Enhanced ratio of regeneration brought by ultrasound
ERE	Experimental relative error
ERARR	Enhancement ratio of average regeneration rate
ERERR	Experimental relative error of regeneration rate, %
ESR	Energy-saving ratio
ESEC	Excess specific energy consumption, J/(kg moisture desorption)
f	Acoustic frequency, Hz
MAMR	Maximum additional moisture removal, kg
MEEU	maximum energy efficiency of ultrasound, %
MMD	Mass mean diameter, m
MR	Dimensionless moisture ratio
MRC	Moisture removal capacity, kg/s
MRS	Mean regeneration speed, kg/s
MRE	Mean Relative Error, %
n	Electromechanical conversion factor of piezoelectric ceramic
N	Molar flux, mol/(m^2.s); or number of droplets or piezoelectric ceramic wafers
*N*u	Nusselt number
NRTL	Nonrandom two-liquid theory
p	Pressure or tensile stress, Pa
P	Power, W
PE	Prediction error, %
q	Moisture ratio in medium, kg water/(kg dry medium)
Q	Heat trtansfer rate, W
r	Radius, m
r_0	Latent heat of vaporization of water at 0°C, J/kg

L	Height of the packed bed or thickness of particle surface layer or mean free path, m	R	Dynamic flow resistance, kg/(m^2.s); or gas constant, kJ/(mol.K)
m	Mass, kg	RD	Regeneration degree
M	M-type honeycomb desiccant; or molecular weight, kg/kmol	R_m	Mass transfer resistance, $m^2 \cdot s/kg$
R_V	Vibration speed ratio of the front surface to the rear surface of the transducer	SPL	Sound pressure level
RR	Regeneration rate, kg/s	t	Temperature
Re	Reynolds number	tan	Tangent function
RE	Regeneration enhancement, kg/s; or regeneration effectiveness	tanh	Hyperbolic tangent function
s	Strain, m/m	T[t]	Temperature, K [°C]
sc	Strain constant	TSEC	Total specific energy consumption, J/(kg moisture desorption)
ss_r	Elastic flexibility coefficient, m^2/N	u	Velocity or sound wave propagation speed, m/s
sin	Sine function	u_s	Induced velocity of air due to ultrasonic oscillation, m/s
s_{33}^D	Elastic flexibility coefficient under constant axial electric displacement, m^2/N	U	Overall heat transfer coefficient of heat exchanger, W/(m^2.°C)
s_{33}^E	Elastic flexibility coefficient under constant axial electric field, m^2/N	UF	Ultrasonic frequency, Hz
		UP	Ultrasonic power, W
sinh	Hyperbolic sine function	V	Volume, m^3; or voltage, V
S	Area, m^2	w^*	Humidity of air on the surface of solid or liquid, kg/(kg dryair)
SEC	Specific energy consumption, J/(kg moisture desorption)	w	Humidity of air in the main stream, kg/(kg dryair)
SMD	Sauter mean diameter	x	Distance or spatial space, m; or mole fraction in the mixture; or concentration by mass
Sh	Sherwood number	$Y_0(x)$	The zero-order Bessel function of the second kind
Sc	Schmidt number	$Y_1(x)$	The first-order Bessel function of the second kind
S_V	Volumetric surface area of solid desiccant, m^2/ m^3	z (or Z)	Acoustic impedance in medium, Pa.s/m^3
SS	ss-type honeycomb desiccant		

Greek Letters

δ	Thickness, m	φ	Relative humidity, %
λ	Coefficient of thermal conductivity, W/m·°C; or wave length, m	ρ	Density, kg/m^3
ν	Kinematic viscosity, m^2/s; or Poisson's ratio	η	Working efficiency
α	Sound attenuation coefficient in medium; or NRTL non-randomness factor	ϕ	Electric displacement
β_{33}^{T}	Voltage constant of the piezoelectric ceramic	τ	Time, s
ε	Void fraction of desiccant bed; or porosity of particle; or effectiveness of a heat exchanger	Υ	Shear modulus of material
$\varepsilon_{33}^{\mathrm{T}}$	Dielectric constant	ψ	Structure factor of the packed bed
ε_{m-e}	Transverse electro-mechanical coupling coefficient	κ	Slope of the straight line
ε_{e}	Effective electro-mechanical coupling coefficient	μ	Dynamic viscosity, Pa.s
ω	Acoustic angular frequency or resonance angular frequency of transducer, rad/s	γ	Mass flow rate ratio of liquid desiccant to air; or the ratio of the outer radius to the inner radius of the metal cylindrical shell
σ	Surface tension, N/m; or stress, Pa	ς	Tortuosity factor
χ	Closest approach parameter of the Pitzer-Debye-Huckel equation	ϑ	Extension factor of the conical rod
ξ	Vibration displacement, m	Δ	Increment or absolute error
$\dot{\xi}$	Vibration velocity, m/s		

Subscripts

a	Air	e	Equivalent size of pore in the packed bed; or equilibrium state; or effective
ads	Adsorption	env	Environmental or ambient
ave	Average	f	Falling
c	Cool fluid	fc	Front cover of the transducer
dry	Dry sample	g	gas
des	Desorption	h	Hot fluid

deh	Air dehumidifier
in	Inlet
i	Inner surface
ini	Initial state
K	Knudsen
LRC	Long-range contribution to the activity of molecules
m	Mechanical; or mean value
mcs	Metal thin-walled cylindrical shell
mole	Molar
min	Minimum
max	Maximum
mcs	Metal cylindrical shell
NU	Without ultrasonic radiation
o	On the radiation surface of ultrasonic transducer; or outer surface
ord	Ordinary
out	Outlet
p	At constant pressure
pc	Piezoelectric ceramic
hx	Heat exchanger
qb	Saturated sate
SRC	Short-range contribution to the activity of molecules
reg	Regenerator or regeneration
rc	Rear cover of the transducer
s	Solid desiccant or liquid droplet
syn	Synergistic effect
ta	At the regeneration air temperature
tar	Target (or terminal) value
teff	Ultrasonic heating effect
ts	At the solution temperature
T	Ultrasonic transducer
U	In the presence of an ultrasonic field
v	At constant volume
veff	Ultrasonic mechanical effect
vap	Vapor or vaporization
w	Moisture or water