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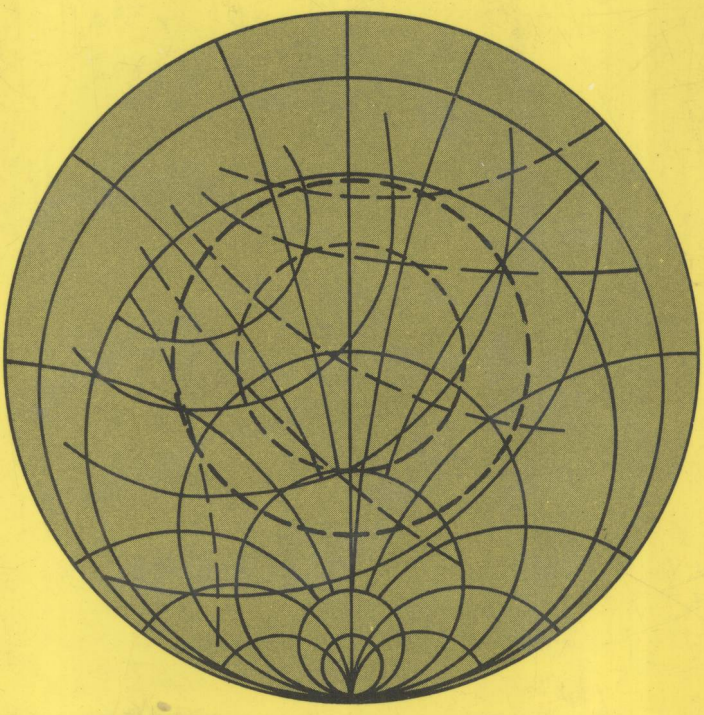
INDUSTRIAL MICROWAVE HEATING

A.C. Metaxas & R.J. Meredith



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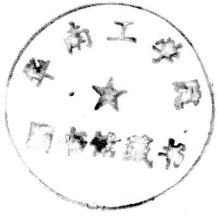

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INDUSTRIAL MICROWAVE HEATING

Principal list of symbols

a, a', a_0	dimension (of waveguide broad, dielectric specimen broad or semi-major axis of ellipse or aperture broad, off-centre position of dielectrics in TM_{11n} cavity)
$a_1 - a_4$	input voltages to directional coupler
α	attenuation constant
$\alpha_T, \alpha_p, \alpha_m$	diffusivities (thermal, pressure, mass)
α_{mv}	diffusion coefficient of vapour flow
$\alpha_t, \alpha_a, \alpha_e, \alpha_d, \alpha_{MW}$	polarisabilities (total, atomic, electronic, dipolar, Maxwell–Wagner)
α_r	number of revolutions/sec
A_c, A_s	area (cross-sectional, surface)
A	general constant, energy fraction
b, b'	dimension (of waveguide narrow, semi-minor axis, aperture narrow or dielectric specimen)
$b_1 - b_4$	output voltages from directional coupler
b_i	normalised iris susceptance, i.e., (B/Y_0)
β	phase constant
β'	coupling factor
$\boldsymbol{B}$	flux density
B, B_a	susceptance (general, aperture)
$\gamma, \gamma_2, \gamma', \gamma_c$	propagation constant (general, specimen filled line, in periodic waveguides, in conductor)
c	velocity of light
c_a	specific moisture capacity of vapour phase
c_v, c_p	specific heat (constant volume, constant pressure)
C_0	constant
C_{14}	voltage coupling coefficient in loop resonator

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C, C_p, C_c	capacitance (general, between parallel plates, cavity)
Γ	coupling factor in dielectric loaded applicator
$d, d_i, d_s, d_0, d_0', d_c$	distance (general, iris width, meander interpass length, meander pass length, load/waveguide distance in horn applicators, TE_{10n} cavity length
D_p	penetration depth
$\boldsymbol{D}$	charge density vector
D_e	electron diffusion coefficient
e	eccentricity
ϵ_0	permittivity of free space
ϵ^*	relative complex permittivity, $\epsilon' - j\epsilon''$
ϵ_a	absolute permittivity ($= \epsilon_0 \epsilon^*$)
$\epsilon', \epsilon_s, \epsilon_\infty$	(relative dielectric constants)
$\epsilon_{eff}'', \epsilon_d'', \epsilon_c''$	relative loss factors (effective, dipolar, conductive)
ϵ_i	emissivity
ϵ_v	ratio of vapour flow to total moisture flow
$E, E_{rms}, E_{av}, \hat{E}, E_i, E_{max}, E_{res}, E^*, E_z, E_b$ and E_m, $E_s, E_+, E_-, E_e, E_{zm}, E_{ext}$	electric field strength (general, r.m.s., average, peak, in dielectric, maximum, resultant, conjugate, axial in cylindrical cavity, breakdown and maintenance of a gas, in metal, forward, reflected, effective, maximum longitudinal in elliptical cavity, external)
δ	loss angle
δ_T, δ_p	gradient coefficient (thermal, pressure)
δn	number of modes at a given frequency
δ_s	skin depth
δv	incremental volume
δP	localised power density
Δf	bandwidth ($\Delta\omega/2\pi$)
f, f_0, f_a	frequency (general, resonant, operating in waveguide)
f_c, f_{c2} and $f_{c1}, f_{cc}, f_{cc\epsilon}$	cutoff frequencies (general, upper and lower of pass band, in cutoff waveguide, in cutoff waveguide carrying dielectric)
F	frequency independent constant
$g(t)$	fraction of orientation polarisations
$g(M), g'(M), g(U_a)$	functions of moisture and energy barrier
g_1, g_0	capital costs of microwave equipment in £/kW, unit cost of electricity in p/kWh
g_{con}, g_{mw}	energy running costs per hour (conventional equipment, of microwave equipment)

G	conductance
h	height (general, cylindrical or elliptical cavity, slab in waveguide or oven)
$h_T, \bar{h}_T$	heat transfer coefficient (general, mean)
H_h	enthalpy
$H, H_t, H_{rms}, H_+, H_-, H_{max}, H_n, H_\phi, H_{res}$	magnetic field strengths (general, tangential, r.m.s., forward, reflected, maximum, nornal, circumferencial, resultant)
θ_0	angle between E and I vectors (power factor $\cos\theta_0$)
θ	phase angle
η	refractive index
η_v	viscosity
i, i_e, i_c	currents (general, resistive, capacitive)
J, J_c	current density (general, conductive)
J_n	Bessel function of the first kind and of order of n
k, k_0	general constant, frequency exponent in ϵ''_{dc} equation
k_b	Boltzmann's constant
K, K_0	constant in Bessel function and $K_0 = Kr$
l, l_e	distance (general, effective cylindrical cavity length), integer
L_j	electron loss process
L, L_c	inductance (general, cavity)
L_h	latent heat of vaporisation
Λ	characteristic diffusion length
$\lambda, \lambda'_0, \lambda_g, \lambda_c, \lambda_0$	wavelengths (general, free, waveguide, cutoff, resonant)
$M, M', M'', M''', M_0, M_c, M_l$ and M_v, M_i, and M_f, M_∞	moisture content (dry basis, wet basis, pick-up basis, solids basis, equilibrium, critical, liquid and vapour, initial and final, constant)
M_a, M_{ad}	mass (general, dry)
M'_p	magnetic polarisability
$\mu_0, \mu^*, \mu_a, \mu_c, \mu', \mu''_{eff}$	permeability (free space, complex, absolute ($= \mu_0\mu^*$), wall, real, effective magnetic loss factor)
μ	dipole moment
$n_0, n_g, n_t, n_c, n_a, n_u$	efficiencies (overall, generation, transfer, coupling, applicator, utilisation)
n	integer
n_e, n_{e0}	electron concentration (general, initial)
N	turns ratio

N_0	number of stirrer blades
ν, ν_c	frequency (dipole oscillation $(1/\tau)$, collision)
p	pressure, integer
p_r^2	ratio of dielectric constants in cylindrical cavity heater
P_i	electron production process
$P, P_w, P_s, P_{av}, P_m, P_{in}, P_0, P_{ex}, P_{sc}, P_{th}$	power dissipated (general, dielectric, surface, average, mains, input into cavity, incident on cavity's aperture, in external circuit, microwave source power, theoretical)
$\boldsymbol{P}, \boldsymbol{P}_{max}$	polarisation field vector (instantaneous, maximum)
$\boldsymbol{\rho}$	Poynting's vector
q	charge
$Q, Q_0', Q_0, Q_L, Q_{ext}, Q_{Leff}, Q_d$	quality factor (general, isolated empty, isolated with dielectric, loaded, external, effective, dielectric workload)
Q_h	quantity of heat
Q_i	charge production due to an external source
r, r_q	radius (general, dipole)
R_w, R_d, R_0, R_c	radii (dielectric, dielectric filled cavity, empty cavity, partial filled cavity)
$R', R_c', R_s', R_a', R_G', R_p', R_L'$	resistance (general, cavity, skin, aperture coupling network, generator, parallel plate capacitor, load)
ρ	density
$\rho, \rho^*, \rho_e, \rho_0$	reflection coefficient, its conjugate, effective, resonant
σ	conductivity
σ_T	Stefan Boltzmann's constant
$S, S_0, S_{1/2}$	VSWR (general, minimum, 3 dB)
$\boldsymbol{S}'$	surface integral
t	thickness of slab in waveguide or time variable
τ'	fraction of energy
$\tau, \tau_e, \tau_0, \tau_{mean}$	relaxation time constant (general and Debye, effective, in double well theory, mean)
T_v	voltage transmission coefficient in loop resonator
$T, T_g, T_w, T_s, T_c, T_{bp}$	temperature (general, dry bulb, wet bulb, surface, critical, boiling point)
U, U_s, U_a	energy (general, stored, activation)
v	volume (ratio (V_L/V_c), fraction of conducting material)

v_w	web speed
V, V_L, V_c, V_c'	volume (general, dielectric, cavity, clearance volume ($V_c - V_L$) in multimode applicator)
V, V_+, V_-, V_b and V_{str}	voltage vectors (general, forward, reflected, onset for gas breakdown and streamer)
w	web width
$W, W_w, W_d, W_{wp}, W_{we}, W_{te}$	weight (general, water, dry matter, water pick-up, water at quilibrium, total weight at equilibrium)
ϕ	phase angle
ϕ_0	$= \tanh(\alpha d_c)$
χ	electric susceptibility
x, x_0, x_i, x_d, x_1' or x_2', x_1	distance (general, first min from s/c sample, charge separation in dipole, between discs in disc loaded cavity, slot separations for broadside waveguide centre-line, distance of slab from narrow waveguide face)
$x_{l,m}$	mth root of $J_l(x) = 0$
$\omega, \omega_0', \omega_0, \omega_{lmn}, \omega_{clmn}, \bar{\omega}$	angular frequency (general, resonant unperturbed, resonant perturbed, pertaining to a particular mode, cutoff of a particular mode, complex)
y	distance
y_n	number of years
Y, Y_0, Y_{in}	admittance (general, characteristic, cavity input)
Y_n	Bessel function of the second kind and of order n
z, z_c, z_0	distance (general, of cutoff choke, cavity length above or below that which gives resonance in TE_{10n} cavity)
z_i, z_b	rate of production per electron (general, at breakdown)
$\mathscr{Z}$	spreading factor in Debye response
Z, Z_{in}	impedance (general, input)
Z_0, Z_{0s}, Z_{02}	characteristic impedance (general, stub, specimen filled line)

Preface

This book forms an attempt to bring together the theory and practice of industrial microwave heating. Since the publications on the subject of microwave heating by D. A. Copson (1962, 1975), H. Püschner (1966) and E. C. Okress (1968) during the nineteen-sixties there has been a noteable absence of a book dealing with this topic. During this period there has been much research and development into the subject, reported in numerous publications spanning countless scientific journals. Moreover, the theory and practice of microwave heating itself involves many disciplines from electrical and process engineering to physics and material sciences. We felt, therefore, that such fragmented information on dielectric theory and properties of materials, design of equipment and the state of the art in applications relevant to the manufacturing industry should be collated, updated, extended and presented as a single reference volume.

Microwave heating was given special emphasis at the Electricity Council Research Centre (ECRC) about ten years ago where a unit was established to carry out research and development on the future of industrial applications. One of us (A.C.M.) would like to acknowledge the positive role played by J. Lawton, DSc, of the Central Electricity Research Laboratories, Leatherhead, in introducing him to the subject of industrial microwaves and wishes to thank all his colleagues in the electrophysics group at ECRC, particularly Drs. J. L. Driscoll, P. L. Jones and T. Farrell, also R. Morrow of CSIRO, Lindfield, for many valuable discussions and from whom he has learned a great deal. It was through contacts and collaboration with Magnetronics Ltd. in those early days that brought together the authors of this book.

It would be impossible to acknowledge all the people who have in one way or another helped us with the essence of the book. However, we would particularly like to thank Mr. G. Ratcliff of the ECRC for encouraging us to write this book, for reading the manuscript and for making helpful suggestions and to Dr. R. Perkin and Mr. W. Baker of ECRC for reading and commenting on part of the manuscript. We owe a great debt to our colleagues in industry at large who have openly discussed their processes with us and to the many engineers in the Electricity Area Boards for initiating many industrial contacts and thus keeping us aware of the

problems and requirements for new industrial plant. We found stimulating the many discussions we have had over the years with countless fellow researchers in the field of industrial microwaves during the annual IMPI (International Microwave Power Institute) Symposium and whose publications in the literature have made a valuable contribution to this book. To this we would particularly like to thank Dr. R. Schiffman of R. Schiffman Associates, New York, Dr. S. Stuchly of the University of Ottawa, Mr. G. Freedman of Raytheon Co, Massachusetts, Dr. A. L. VanKoughnett of the Communications Research Centre, Ottawa, Drs. W. Wyslouzil and S. Kashyap of the NRC, Ottawa, Dr. S. Nelson of the U.S. Dept. of Agriculture, Georgia, Dr. M. Stuchly of the Radiation Protection Bureau, Ottawa, Mr. J. Gerling of Gerling Laboratories, California, Mr. B. Krieger of Cober Electronics, Inc., Connecticut, Mr. K. Ogura of Toshiba, Japan, our Swedish colleagues Dr. T. Ohlsson of the SIK Institute, Göteborg, Dr. P. Risman of Microtrans, AB, Huskvarna, Mr. B. Edin of Scanpro AB, Bromma and many others.

One of us (R.J.M.) would particularly like to thank Mr. M. P. Tahany, Chairman of Magnetronics Ltd., for his support and his many colleagues and staff, in particular Mr. J. Mitton, Mr. G. W. Geffery and Mr. G. A. Swann for frequent and helpful discussions. In addition he would like to thank his many customers who have contributed so much of the industrial environment. To his wife, Judy, R.J.M. owes a special debt for her support and encouragement in this project.

It would be impossible and invidious to mention all those who have contributed to industrial microwave heating technology over many years but nonetheless the very valuable contribution of Dr. R. Dunsmuir, Dr. J. E. Curran and J. R. G. Twistleton of the former B. T. H. Research Laboratory, Rugby, deserve special mention for the development of the 25 KW, 900 MHz magnetron and associated equipment, also Mr. H. B. Taylor for his valuable contribution to microwave applicator design.

We would also like to extend our thanks to Mr. H. Barber of Loughborough University, Mr. R. Shute of Microwave Heating Ltd., Luton, Mr. P. Giles and Mr. K. Ike of Microwave Ovens Ltd., Shirley, Dr. R. Smith of Bradford University, Mr. G. Crossley of Marconi (Specialised Components), Essex, Mr. P. Hulls and Mr. A. Witt of the Electricity Council Marketing Department, for their continuing help and support over many years. We are indebted to the ex-editor of the *Journal of Microwave Power*, Dr. S. Stuchly, and many other publishers and their authors for allowing us to reproduce some of their data. Such indebtedness extends to all the authors given in the references. We would like to acknowledge the help we have received from the secretarial staff at ECRC and especially from Margaret Metaxas for typing and editing the manuscript and for her total commitment during the last stages of the preparation of the book. Finally, we would be very grateful to receive notification of any errors or amendments from any reader.

We would like to thank our publishers for their expert advice and cooperation throughout this project.

A. C. Metaxas
R. J. Meredith

Chester, England, 1982

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Contents

	Preface		xv
1	**Introduction**		1
2	**Dielectric loss**		5
	2.1	Introduction	5
	2.2	Polarisation	5
	2.3	Complex dielectric constant	9
	2.4	Dipolar loss mechanism	11
		2.4.1 Debye equations	11
		2.4.2 Interpretation of the Debye equations	13
		2.4.3 Potential double well	15
		2.4.4 Electric dipole moment	17
	2.5	Maxwell–Wagner or interfacial loss mechanism	17
	2.6	Combined effects	20
	2.7	New physical mechanism for dielectric loss	21
	2.8	Dry, non-conducting dielectrics	23
	2.9	Magnetic loss factor	24
	2.10	References	25
3	**Dielectric properties**		26
	3.1	Introduction	26
	3.2	The need for dielectric property data	26
	3.3	Measuring techniques	32
		3.3.1 The Roberts and von Hippel method	32
		3.3.2 X-band techniques	35
		3.3.3 Cavity perturbation techniques	36
	3.4	The variation of ϵ^* with moisture content	38
		3.4.1 The dielectric properties of absorbed water	39
		3.4.2 Interpretation of the ϵ''_{eff} vs. moisture response	40
		3.4.3 Experimental data near the industrially allocated frequency bands	42
		3.4.4 Experimental data at X-band	47
	3.5	The variation of ϵ^* with temperature	48
		3.5.1 General data	48
		3.5.2 Runaway effects	54
		3.5.3 Influence of applicator characteristics on thermal runaway	56
	3.6	The variation of ϵ^* with frequency	58
	3.7	Q-factor vs. moisture content response	61

	3.8	Discussion on published data	63
	3.9	Catalysts and agents	65
	3.10	References	66
4	**Theoretical aspects of volumetric heating**		**70**
	4.1	Introduction	70
	4.2	Power dissipated	70
		4.2.1 Derivation from Maxwell's equations	70
		4.2.2 Lossy capacitor	72
	4.3	Propagation factor and penetration depth	78
	4.4	Specific heat	82
	4.5	Rate of rise of temperature	85
	4.6	The electric field strength	86
	4.7	Heat and mass transfer phenomena	89
		4.7.1 Introduction	89
		4.7.2 Physical processes	90
		4.7.3 High frequency drying	92
		4.7.4 Transport equations	94
		4.7.5 A simple drying formulation	95
		4.7.6 Temperature distribution	97
	4.8	Skin depth	97
	4.9	Wall loss	101
	4.10	References	102
5	**Travelling wave applicators**		**104**
	5.1	Introduction	104
	5.2	Plane waves	104
	5.3	Guided waves	105
	5.4	Impedance matching	109
	5.5	Voltage standing wave ratio	111
	5.6	Travelling wave applicators	113
		5.6.1 Axial travelling wave applicators	114
		5.6.2 Meander travelling wave applicators	115
		5.6.3 Standing waves in meander applicators	119
		5.6.4 Attenuation in travelling wave applicators	122
		5.6.5 Uniformity of heating	124
		5.6.6 Construction	128
	5.7	References	129
6	**Multimode oven applicators**		**130**
	6.1	Introduction	130
	6.2	Theoretical aspects of multimode oven applicators	132
	6.3	Field distribution and heating uniformity	136
		6.3.1 Movement of the workload	137
		6.3.2 Mode stirrers	137
		6.3.3 Other methods of energy feed	138
	6.4	Q-factor with a dielectric insertion	138
	6.5	Field intensity and wall currents	143
	6.6	Power density	145
	6.7	Choice of wall material	146
	6.8	Doors and door seals	147
	6.9	Multiple generator feeds	149
	6.10	References	150

7	**Single mode resonant cavities**		**151**
	7.1	Introduction	151
	7.2	Cavity modes and Q-factors	152
	7.3	Impedance matching	153
	7.4	Measurements by reflected power	155
		7.4.1 Input impedance of resonant cavity	155
		7.4.2 Determination of Q_L and Q_0	157
		7.4.3 Coupling network losses	159
		7.4.4 Graphical representation of cavity impedance	160
		7.4.5 Interpretation of Q_L and Q_0	162
	7.5	Measurements using transmitter power	166
	7.6	TE_{10n} rectangular cavity	167
		7.6.1 Introduction	167
		7.6.2 Uniform field distribution in the twin TE_{10n} cavity heater	170
		7.6.3 Unloaded Q-factor, Q_0, of a TE_{10n} cavity heater	171
		7.6.4 Impedance matching	176
		7.6.5 Shift of the VSWR vs. cavity length responses	178
		7.6.6 Q-factors from VSWR vs. frequency response	180
		7.6.7 Electric field strength in a TE_{10n} cavity heater	182
	7.7	Cylindrical cavities	183
		7.7.1 Introduction	183
		7.7.2 TM_{010} cavity heater	183
		7.7.3 TM_{010} cavity design	186
		7.7.4 Impedance matching of TM_{010} cavity heater	188
		7.7.5 Field distribution in the dielectric region of a TM_{010} cavity heater	190
		7.7.6 Higher order mode cylindrical cavities	193
		7.7.7 TM_{020} resonant cavity heater	193
		7.7.8 TM_{11n} resonant cavity heater	195
	7.8	Coupling apertures	199
		7.8.1 Introduction	199
		7.8.2 Function of the aperture as a coupling network	199
		7.8.3 Aperture susceptance	202
	7.9	Power transfer into a resonant cavity heater	204
	7.10	Efficiency of resonant cavity heaters	205
	7.11	References	207
8	**Special applicator structures**		**208**
	8.1	Introduction	208
	8.2	A modified TE_{10n} twin cavity resonant dryer	208
	8.3	A TE_{10n} applicator near cutoff	210
	8.4	Periodic structure applicator	213
	8.5	Rectangular TEM applicator	215
	8.6	Ridged applicators	216
	8.7	Disc loaded applicator	217
	8.8	Dielectric loaded applicators	220
	8.9	Travelling resonator applicator	223
	8.10	Helix applicator	225
	8.11	Radiator applicators	226
		8.11.1 Horn applicator	226
		8.11.2 Multislot waveguide applicator	228
		8.11.3 Broadside array applicator	229

8.12 Elliptical and spherical applicators 229
8.13 Miscellaneous cavity and coupling slot configurations 232
8.14 References 236

9 The microwave heating circuit, breakdown phenomena and vacuum processing 238
9.1 Introduction 238
9.2 Microwave power sources 239
9.2.1 Klystron amplifier 240
9.2.2 Magnetron oscillator 241
9.2.3 Magnetron operating characteristics 243
9.2.4 Magnetron moding 245
9.2.5 Magnetron power supplies 246
9.2.5.1 Variable ratio transformer 246
9.2.5.2 Thyristor control 246
9.2.5.3 Saturable reactor control 247
9.2.5.4 Series resistor control 248
9.2.5.5 Variable magnetic field control 248
9.2.6 Magnetron protection systems 250
9.2.7 Circulator protection 251
9.3 High frequency breakdown phenomena 252
9.3.1 Introduction 252
9.3.2 Type of discharges 252
9.3.3 Rates of production and loss of charges 254
9.3.4 Diffusion controlled discharge 254
9.3.5 Breakdown mechanism for the diffusion controlled discharge 255
9.3.6 Effects of high frequency discharges in processing plants 258
9.4 Vacuum processing 262
9.4.1 Introduction 262
9.4.2 Pressure and boiling point of solvents 262
9.4.3 Microwave freeze drying 263
9.4.4 Microwave vacuum drying 265
9.4.5 Applicator design 266
9.4.6 Pressure windows 266
9.5 Hybrid systems 267
9.5.1 Introduction 267
9.5.2 Processing of moulded rubber parts 268
9.5.3 Continuous vulcanisation of extrusions 269
9.5.4 Drying processes 269
9.5.4.1 End drying or levelling with high frequency energy 269
9.5.4.2 Combination drying using a heat pump and a high frequency dryer 270
9.5.4.2.1 Closed cycle heat pump 270
9.5.4.2.2 Steam recompression heat pump 272
9.5.5 Other hybrid systems 273
9.6 Automatic control of the process 273
9.7 Automatic tuning and matching of resonant applicators 274
9.7.1 Automatic tuning 274

9.7.2 Automatic matching 275
9.8 References 275

10 Hazards, leakage and safety 277
10.1 Introduction 277
10.2 Exposure standards 278
10.3 Emission standards 280
10.4 Communication and industrial frequency bands 281
10.5 Leakage from industrial microwave equipment 282
10.5.1 Batch systems 283
10.5.2 Continuous flow systems 283
10.5.2.1 Cut off waveguide chokes 283
10.5.2.2 Quarter wavelength stubs 286
10.5.2.3 Corrugated chokes 287
10.5.2.4 Hybrid chokes 289
10.5.2.5 Choking of large apertures 292
10.6 Safety precautions 294
10.7 References 294

11 Industrial applications and economics 296
11.1 Introduction 296
11.2 The last three decades 297
11.3 The present position 299
11.3.1 Full scale industrial microwave heating processes 299
11.3.2 Full scale industrial microwave drying processes 305
11.3.3 Pilot systems 307
11.3.4 Laboratory models 310
11.4 Economics 313
11.4.1 Introduction 313
11.4.2 Energy savings 314
11.4.3 Increased throughput 316
11.4.4 Other factors 316
11.5 Future trends 318
11.6 References 319

Appendices 322
I Definitions of moisture content 322
II Conversion of various units to SI units 324
III Some useful trigonometric functions and formulae 326
IV Some useful series and Bessel functions 328
V Some useful constants and temperature interrelation 332
VI Relation between dB and power and voltage ratio 333
VII Waveguide frequency ranges, dimensions and official designations 334
VIII Glossary of radio frequency and microwave heating terms used in this book 335

Subject Index 340
Author Index 354

Chapter 1

Introduction

Microwave heating as an industrial process is a technique which was originally conceived about forty years ago. The advent of the magnetron during the Second World War presented engineers and scientists in industry, universities and government establishments with a unique challenge to put such a device for generating microwaves into peaceful and profitable use. The task that lay ahead was quite formidable because of the lack of appropriate equipment and more importantly the lack of data on dielectric property of the materials which were considered as candidates for microwave heating. During the late forties and early fifties, a concerted effort was made to obtain reliable data on material properties, led by von Hippel and his co-workers at MIT. Their pioneering work on the properties of many organic and inorganic materials in the frequency region $100 < f < 10^{10}$ Hz has since formed, and still remains, a solid basis for the establishment of radio frequency and microwave energy techniques in industry (von Hippel, 1954). Their original work has since been expanded many times to fill the gaps which emerged as more and more industrial applications came up for consideration. In addition to this voluminous array of data on material properties, there have been significant developments on the design of magnetrons, power supplies and ancilliary equipment, giving greater reliability to this new technique. The engineering aspects of many applications in terms of scale-up, continuous operation, automatic control, etc., have considerably improved since the original days. More and more the various disciplines of physics, chemistry, electrical, mechanical and process engineering, thermodynamics, material science, etc., have blended according to need and priority, in order to optimise the requirement of each particular process.

Before we briefly introduce the topics that will form the basis of this book, it is important to define the frequency ranges for which the terms microwave and radio frequency will be subsequently used. At frequencies below 100 MHz, where conventional open wire circuits are used, the technique of industrial processing will be referred to as radio frequency heating. However, at microwave frequencies (above 500 MHz), wired circuits cannot be used and the power is transferred to the applicator containing the material to be processed in waveguides. This technique will be referred to as microwave heating. In between there exists a diffuse

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