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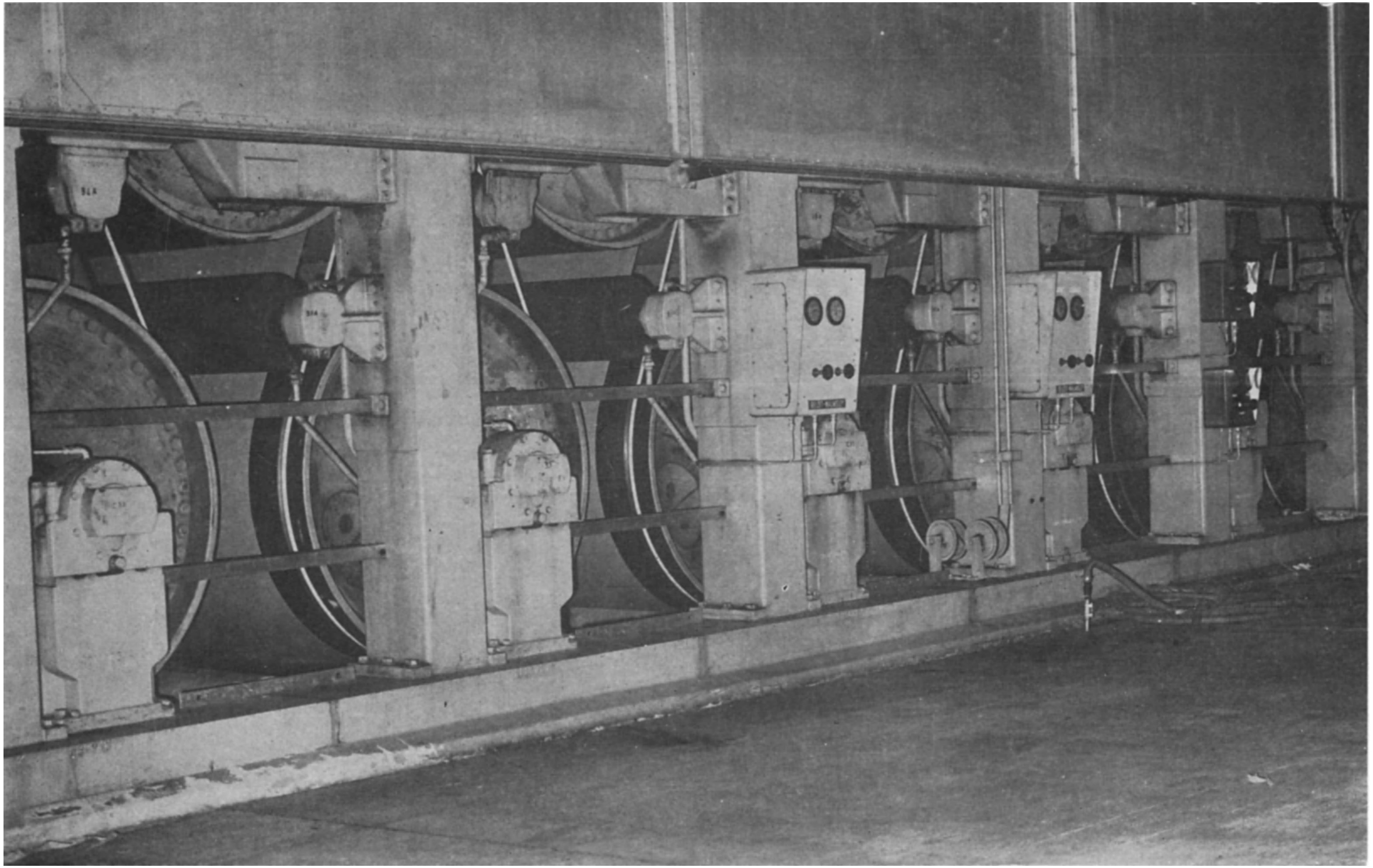

Frontispiece. Drying section of a modern papermarking machine (N.Z. Forest Products Ltd).

DRYING

PRINCIPLES AND PRACTICE

by

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To my father

Walter Leonard Keey

For hot, cold, moist and dry, four champions fierce
Strive here for mastery.

MAJOR TOPICS

PREFACE

DRYING is a commonly practised art, but a neglected science, at least by workers whose mother-tongue is English. While works exist that describe drying principles and practice as applied in specific industries or in certain operations, not one in English tries to survey the whole realm of drying technology. Few attempts hitherto have been made to describe the performance of equipment in terms of analogous criteria used successfully for mass-transfer equipment in general. The primary goal of this book is to fill these gaps.

Ehara taku toa i te toa takitaki, engari he toa takitini. My expertise is not mine alone but comes from others. The author is humbly aware of his debt to his peers who have laid the foundations for this book. Their work has enabled the author to explore the concept of the characteristic drying curve as a powerful, but essentially simple, tool for predicting the process conditions within commercial dryers. This book, then, aims at presenting the fundamental principles that underlie drying arts as a basis for explaining the behaviour of drying plant. Since we have scarcely begun to design dryers with the same degree of assurance as, say, distillation towers, the blend of principles and practice is partial. Nevertheless, the author hopes that this work will help engineers in understanding the plant they have and in designing the plant yet to be built. It is also hoped that this book will fill a gap on the shelves of those students engaged in studies of heat with mass transfer, at both the senior undergraduate and postgraduate level. To reach the broadest possible readership, the author has striven to erect the theoretical frame in its simplest possible form, which can be extended with the aid of the bibliographies to be found at the end of each chapter. With the worldwide trend towards metrication of units, it seemed appropriate to use the S.I. system of units throughout.

After an introductory chapter (Chapter 1), the book describes the phenomena that underlie the influence of moisture on its host material (Chapter 2) and the manner in which moisture may be expelled by heat into the humid surroundings (Chapters 3 to 6). These principles provide the basis for a quantitative description of the way a moist material dries (Chapter 7) and of drying under commercial conditions (Chapters 8 to 9). The remainder of the book is devoted to surveying less-common methods of drying (Chapter 10), moisture-measurement techniques and dryer-control systems (Chapter 11) and aspects of the choice and design of industrial dryers (Chapter 12).

Inevitably this work reflects the author's past experience and present interests and, in so divergent a field, observations are often fleeting. Indeed, no claim is made for comprehensiveness, nor is such a goal desirable, for a completely encyclopaedic tome would weary the reader by obscuring that which is of value by much which is trivial. Nevertheless the book is considered to cover the commanding heights of drying technology.

The author is beholden to many who, in diverse ways, helped him: to Professor S. R. Siemon of Melbourne University, who introduced the author to his subject; to my Head of

Department, Professor A. M. Kennedy, for his encouragement; to Professor R. L. Earle of Massey University and Mr. J. C. Ashworth of Canterbury University for patiently reading the manuscript and making suggestions for its improvement; and to my wife for the long devoted hours of translating my handwriting into a typed script.

To myself I ascribe the errors that remain. *E whai tonu mai te kino i a tatou.* Errors haunt us for ever. The author would be grateful to learn of where he has erred.

R. B. KEEY

Christchurch, N.Z.

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NOTATION

THE following tabulation lists all symbols used in the text except those employed occasionally and specifically defined in the text.

Moisture concentrations on a dry basis are given the symbols X and Y, and the flow of moisture-free streams the symbols L and G, to emphasize mnemonically the analogies with other mass-transfer operations, for which those symbols are commonly adopted in the chemical-engineering literature. The European convention of using λ for the thermal conductivity is employed to avoid confusion with mass-transfer coefficient K, otherwise the principal remaining symbols follow common practice.

Basic S.I. units are used to indicate dimensions of the parameters. [P] signifies that a variety of dimensions may be inserted; [—] indicates that the variable is dimensionless.

a	interfacial area per unit dryer volume	m^2/m^3
b	solids thickness	m
B	driving force (eq. (3.56))	[—]
c	concentration	$kmol/m^3$
c_A	moisture concentration	$kmol/m^3$
c_{AS}	saturated moisture concentration	$kmol/m^3$
C	capacitance	F
C_M	isothermal mass capacity (eq. (3.1))	kg/kg °M
C_P	heat capacity (eq. (1.15))	J/kg K
C_{PA}	heat capacity of moisture	J/kg K
C_{PB}	heat capacity of dry gas	J/kg K
C_{PY}	humid heat (eq. (1.19))	J/kg K
d	diameter	m
d^*	characteristic diameter (eq. (4.75))	m
d_e	equivalent diameter (eq. (6.55))	m
d_p	particle diameter	m
d_{vd}	volume-linear diameter	m
d_{vs}	volume-surface diameter	m
D	duct or shell diameter	m
$\mathcal{D}$	mass diffusivity (eq. (3.20))	m^2/s
$\mathcal{D}_{AB}$	moisture diffusivity in medium B	m^2/s
$\mathcal{D}_e$	effective moisture diffusivity (eq. (3.27))	m^2/s
$\mathcal{D}_L$	liquid-phase diffusivity for moisture transfer	m^2/s
$\mathcal{D}_V$	vapour-phase diffusivity for moisture transfer	m^2/s
e	2·718 ...	[—]
E	voltage or electrical potential	V

E	fractional loss of moisture	[—]
E	modulus of elasticity (eq. (2.39))	N/m^2
E	emissive power	W/m^2
E_b	black-body emissive power	W/m^2
E_1	modulus for elastic-plastic stretching (eq. (2.39))	N/m^2
$E(\tau)$	external-age distribution function (eq. (9.4))	[—]
f	fraction of material oriented normally to heat-flux direction	[—]
f	relative drying flux (eq. (7.21))	[—]
F	mass-transfer coefficient (eq. (3.49))	kg/m^2 s
F	emissivity factor for radiation (eq. (4.111))	[—]
F_{12}	shape factor for radiation between surfaces 1 and 2 (eq. (4.109))	[—]
$F(\tau)$	cumulative fraction passed in time τ	[—]
$\mathcal{J}$	thermodynamic flux (eq. (3.6))	[P]/s
g	gravitational acceleration	m/s^2
G	specific dry gas-flow	kg/m^2 s
$\mathcal{G}$	dynamic gain or transfer function (eq. (11.13))	[—]
h	heat-transfer coefficient (eq. (3.55))	W/m^2 K
h_c	convective heat-transfer coefficient	W/m^2 K
h_R	radiative heat-transfer coefficient	W/m^2 K
H	enthalpy (eq. (1.13))	J/kg
H_F	of frozen liquid	J/kg
H_L	of liquid	J/kg
H_{SV}	of saturated vapour	J/kg
H_V	of vapour	J/kg
i	current	A
i_G	enthalpy of moist gas (eq. (1.25))	J/kg
i_L	enthalpy of moist solid (eq. (1.21))	J/kg
$I(\tau)$	internal-age distribution function (eq. (9.5))	[—]
J	transfer flux	[P]/m^2 s
J_A	moisture-transfer flux	kg/m^2 s
J_M	mass-transfer flux	kg/m^2 s
J_Q	heat-transfer flux	J/m^2 s
K	mass-transfer coefficient (eq. (3.52))	kg/m^2 s
K_c	for concentration differences	m/s
K_p	for partial-pressure differences	kg/N s
K_Y	for humidity differences	kg/m^2 s
l	streamed length for a bluff body	m
L	streamed length for a flat plate	m
L	phenomenological transport coefficient (eq. (3.12))	[P]^2/s
L	specific dry solids flow	kg/m^2 s
M	molecular weight	[—]
M_A	molecular weight of vapour	[—]
M_B	molecular weight of dry gas	[—]
n	number of capillaries	[—]
n	number of particle layers	[—]
N	total material flux	kmol/m^2 s
N	moisture-transfer or evaporative flux	kmol/m^2 s[†]

[†] Mass or molal units may be employed depending upon the context.

N_A^0	evaporative flux from free surface	kg/m² s
N_A^{I}	drying flux in first period	kg/m² s
N_A^{II}	in second period	kg/m² s
N_A^{III}	in third period	kg/m² s
N_{Ae}	at end of drying	kg/m² s
N_G^t	number of transfer units (NTU) (eq. (8.5))	[—]
p	partial pressure	N/m²
p_A	of vapour	N/m²
p_A	moisture-vapour pressure (saturated vapour)	N/m²
p_B	partial pressure of dry gas	N/m²
P	total pressure	N/m²
P	power	W
q	heat-transfer flux	W/m²
q_B	by conduction	W/m²
q_C	by convection	W/m²
q_D	by internal heating	W/m²
q_R	by radiation	W/m³
Q	heat-transfer rate	W
r	capillary radius	m
r	radial distance	m
r	recycle ratio (eq. (8.10))	[—]
R	universal gas constant	J/kmol K
R	droplet or particle radius	m
R	electrical resistance	Ω
R	thermal resistance	K/W
s	clearance above surface	m
S	cross-section or transfer area	m²
S_0	exposed surface of porous body	m²
t	temperature (Celsius scale)	°C
t_B	base or tray temperature	°C
t_E	temperature at evaporative interface (eq. (6.27))	°C
t_G	dry-bulb temperature	°C
t_S	adiabatic-saturation temperature (eq. (6.62))	°C
t_S	surface temperature	°C
t_W	wet-bulb temperature (eq. (6.65))	°C
T	time constant (eq. (11.12))	s
T	temperature (Kelvin scale)	K
T_D	of dried-out zone (eq. (10.3))	K
T_F	of frozen zone (eq. (10.8))	K
T_G	of gas	K
T_I	of ice front (eq. (10.7))	K
T_S	of surface	K
u	velocity	m/s
u_G	at edge of boundary layer	m/s
u_m	averaged over boundary layer (eq. (4.44))	m/s
u_0	based on empty dryer	m/s
U	overall heat-transfer coefficient	W/m² K
v_0	orifice velocity	m/s

V	volume	m^3
V_A	volumetric moisture flux	$m^3/s\ m^2$
W	mass-transfer potential or degrees of moistness (eq. (3.3))	°M
W_A	mass-transfer rate	kg/s
W_F	fan work	W
x	mole fraction in heavy phase	kmol/kmol
X	reactance	Ω
X	moisture content (dry basis) of solid	kg/kg
X^*	equilibrium-moisture content	kg/kg
X_{cr}	critical moisture content	kg/kg
X^*_{max}	maximum hygroscopic-moisture content (p. 27)	kg/kg
X_0	initial moisture content	kg/kg
y	distance normal to exposed surface	m
y_A	mole fraction of moisture in damp gas mixture	kmol/kmol
y_B	mole fraction of dry gas in damp gas mixture	kmol/kmol
Y	humidity (dry basis) of moist gas	kg/kg
Y_G	bulk-gas humidity	kg/kg
Y_S	surface or saturation humidity	kg/kg
Y_W	saturation humidity at wet-bulb temperature	kg/kg
z	distance from leading edge or inlet	m
Z	total distance	m

Greek

α	absorptivity (eq. (4.100))	[—]
α_G	gas absorptivity	[—]
β	bulk-shrinkage coefficient (eq. 2.37))	[—]
γ	linear-shrinkage coefficient (eq. (2.38))	[—]
δ	thermal-gradient coefficient (eq. (3.19))	K^{-1}
ε	strain (eq. (2.39))	m/m
ε	fractional free-cross-sectional area	m^2/m^2
ε	dielectric constant	[—]
ε	emissivity (eq. (4.101))	[—]
ε_b	emissivity of black surface	[—]
ε_G	gas emissivity (eq. (4.103))	[—]
ε'_S	apparent surface emissivity (eq. (4.115))	[—]
ζ	relative distance (eq. (8.24))	[—]
ζ_L	relative distance over swept length L	[—]
η	fractional heat loss (eq. (9.89))	[—]
θ	relative time (eq. (8.25))	[—]
ϑ	deviation	[P]
ϑ	temperature difference	°C
ϑ_M	logarithmic-mean temperature difference	°C
ϑ_0	temperature difference at inlet	°C
$\varkappa$	thermal diffusivity (eq. (3.28))	m^2/s
$\varkappa_e$	effective thermal diffusivity (eq. (3.29))	m^2/s
λ	wavelength	m
λ	thermal conductivity (eq. (3.30))	W/m K

λ_C	under partial convection (eq. (4.94))	W/m K
λ_D	of dried-out zone (eq. (10.10))	W/m K
λ_e	of porous body	W/m K
λ_F	of frozen zone (eq. (10.10))	W/m K
λ_G	of gas	W/m K
λ_S	of solid	W/m K
μ	chemical potential	J/kg
μ	dynamic viscosity	Ns/m^2
μ_D	diffusion-resistance coefficient (eq. (5.5))	[—]
μ_E	effusion-resistance coefficient (eq. (5.18))	[—]
ν	kinematic viscosity	m^2/s
ξ	tortuosity (eq. (5.6))	m/m
ξ	relative depth of penetration	[—]
π	3·141 59 ...	[—]
Π	thermodynamic potential	[P]
Π	humidity potential (eq. (8.23–4))	kg/kg
Π^0	of fresh air	kg/kg
Π_0	at inlet	kg/kg
Π_{cap}	capillary potential (eq. (2.31))	J/kg
ϱ	density	kg/m^3
ϱ_G	gas density	kg/m^3
ϱ_L	density of moisture	kg/m^3
ϱ_S	bulk density of solids	kg/m^3
σ	Stefan–Boltzmann constant (eq. (4.102))	W/m^2 K^4
σ	surface tension	J/m^2
τ	time	s
τ	stress (eq. (2.39))	N/m^2
τ_R	residence time (p. 234)	s
ϕ	sphericity (p. 103)	[—]
ϕ	correction factor for influence of mass transfer (eq. (3.66))	[—]
ϕ	characteristic moisture content (eq. (8.23–24))	[—]
ϕ_0	initial characteristic moisture content	[—]
Φ	thermodynamic driving force (eq. (3.6))	J/kg K [P]
ψ	relative humidity (eq. (1.2))	[—]
Ψ	porosity	m^3/m^3
Ψ_A	volumetric moisture content	m^3/m^3
ω	angular velocity	s^{-1}

Overlines

$\widehat{\ }$	averaged over time (eq. (9.79))
—	averaged over distance
—	partial molal (eq. (2.4))

Superscripts

*	equilibrium value
0	from free surface
I	in first drying period
II	in second drying period

III	in third drying period
$'$	fluctuation in value (eq. (4.52))

Subscripts

A	moisture
B	dry gas
B	at base
B	conductive
C	convective
cr	critical
d^*	based on diameter d^*
dp	based on diameter d_p
D	dried-out zone
D	by internal heating
e	equivalent
E	at evaporative interface
F	frozen zone or on freezing
G	bulk-gas or dry-bulb
I	at ice front
l	based on streamed length l
L	based on streamed length L
L	moisture or moist solids
M	logarithmic mean
O	initial or inlet conditions
R	radiative
S	surface or saturation
s	dry solids
V	vapour or on vaporization
W	wet-bulb
W	on wetting
Y	humid
Z	at distance Z from inlet

Commonly used dimensionless groups

Bi	Biot number (eq. (4.32))
Fo	Fourier number (Table 3.1)
Gr	Grashof number (eq. (4.95))
Le	Lewis number (Table 3.1)
Lu	Luikov number (Table 3.1)
Nu	Nusselt number (eq. (4.45))
Pe	Peclet number (eq. (4.79))
Pr	Prandtl number (eq. (4.47))
Re	Reynolds number (eq. (4.47))
Sc	Schmidt number (eq. (6.4))
Sh	Sherwood number (Table 3.5)

Mathematical operators

erf x	error function of x
erfc x	$1-\text{erf}\,x$
exp x	exponential function of x
ln x	logarithm of x to base e
$\mathcal{L}$	Laplace operator
$\varDelta$	finite difference (e.g. $\varDelta H_V$ is the difference in enthalpy on vaporization between the saturated-liquid and saturated-vapour states)
$\varGamma$	gamma function
∇	nabla operator

APPROXIMATE VALUES OF SOME COMMON PROPERTIES

Density of water	1000 kg/m^3
Viscosity of water	1/1000 Ns/m^2
Heat capacity of water	4 kJ/kg °C
Thermal conductivity of water	0·6 W/m °C
Latent heat of boiling water	2000 kJ/kg
Density of air at s.t.p.	1·2 kg/m^3
Heat capacity of air at s.t.p.	1 kJ/kg °C
Heat capacity of water vapour at s.t.p.	2 kJ/kg °C
Thermal conductivity of air at s.t.p.	1/40 W/m °C
Atmospheric pressure	100 kN/m^2

CHAPTER 1

INTRODUCTION

THE word *drying* is commonly used to describe any process in which water is removed from a substance. This concept, however, imprecisely fits the scope of this book. While the underlying phenomena are the same whatever the composition of the moisture being removed, the moisture may be severed from its associated material under pressure or by heat. Mechanical means of removing moisture, as by expression between the plates of a filter-press, will not be considered: only thermal means will be discussed. Moreover, one must distinguish between thermal methods that are akin to distillation, such as the azeotropic dehydration of some organic liquids, and those methods which involve the evaporation of moisture into a carrier gas. These latter methods form the province of this book together with similar vacuum processes when the carrier gas may be almost absent.

Drying may thus be defined as the removal of volatile substances (moisture) by heat from a mixture that yields a solid product. Commonly, though not exclusively, the principal volatile substance is water, and is the only constituent whose removal is sought. Under such circumstances, it is the aqueous portion alone that we call "moisture".

The reasons for drying are almost as diverse as the materials that are dried. Sometimes drying is carried out to effect economics in freight or to ease handling. Ores may be dried to increase the capacity of calcining plant. Many materials must be dried to bring their moisture content to a prescribed value before being sold. Others such as foodstuffs are dried to preserve them for storage and shipment without the need for refrigeration. Huge quantities of heat in aggregate are expended to sustain these industrial drying operations; about 15% of the total fuel extracted in the U.S.S.R., for example, is used for drying.

The diversity of purpose is matched by diversity of methods. Throughout his history man has used wind and sun to dry materials for his daily needs. While informal methods are still employed in areas where the climate is favourable, mere exposure to the elements is too slow and uncertain a way of drying for general use. Forced-drying methods were thus adopted from the earliest of times. The available wind was channelled by careful stacking of the goods, and the sun's warmth was replaced by fire. Kilns for drying corn after harvesting were built in the damp western and northern fringes of Europe from the Iron Age onwards. Ovens for drying claywares before firing were in use by the thirteenth century in England.

For many centuries drying methods were still very crude. The techniques of French industry prior to the so-called Industrial Revolution are well described in Diderot's pictorial encyclopedia of Trades.(3) Paper was dried sheet by sheet in a well-aired room (Fig. 1.1). Hanks of dyed yarn were hung on racks in the drying-room, which was heated by a coal stove in all seasons, while woollen cloth was left "in suspense" by being spread over pegs called "tenterhooks". Sun-baked tiles before being fired were finally dried in a shed, where