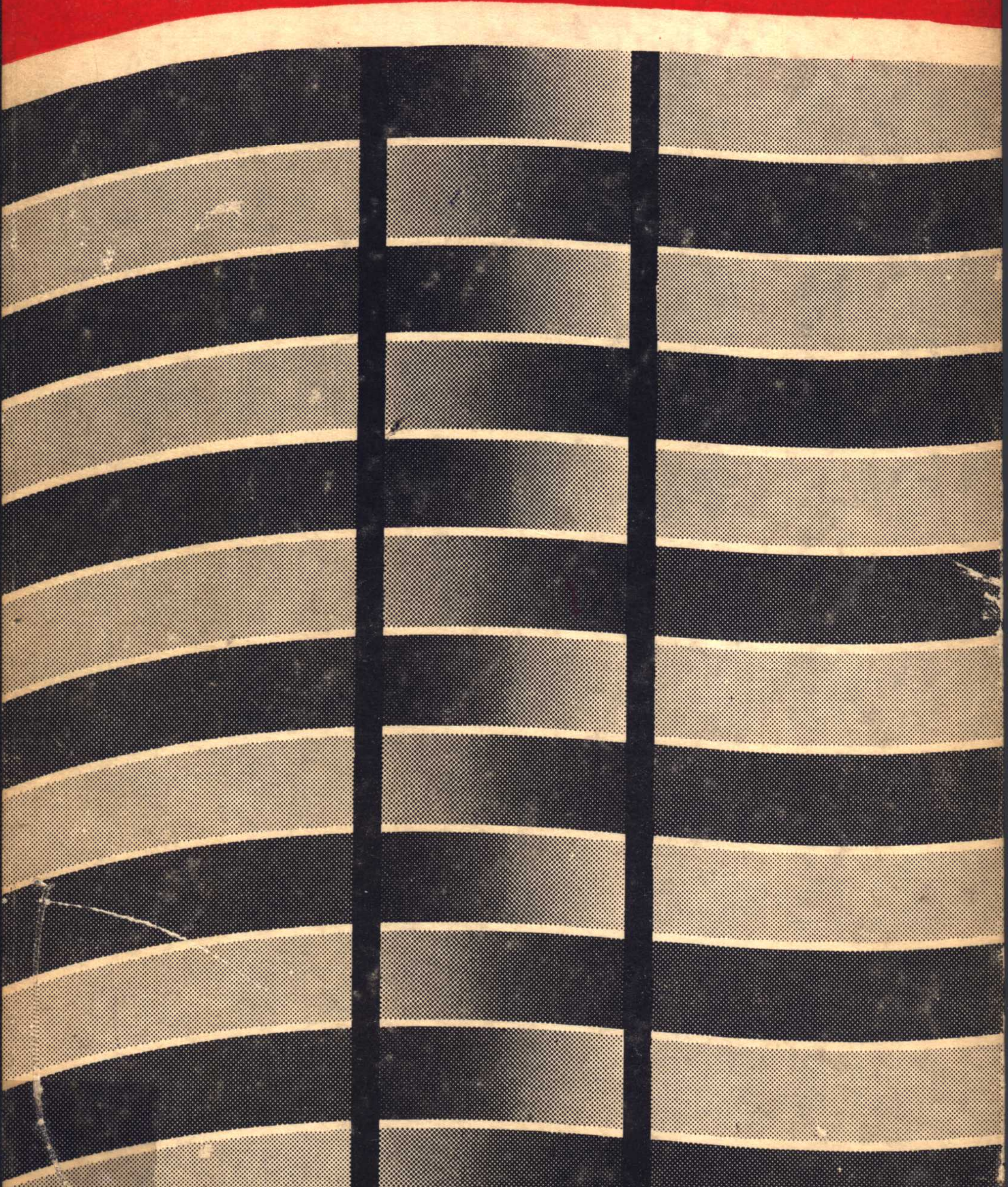
Air Conditioning Engineering



Air Conditioning Engineering

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EDWARD ARNOLD

Preface to the Second Edition

The change to the use of the Systême International d'Unités (SI) has meant a revision of all worked examples and exercises in this volume. In addition, alteration to some of the standards adopted and the methods of calculation has changed the basis of some examples; new values in whole numbers have been used for many design parameters because a simple translation from Imperial to metric would have yielded unworkable fractions. In most cases, the units in the text are pure SI, it being impossible at this early stage in the life of the new system to forecast future development and decide which units will be discarded as impractical and which retained. Only evolution will show this, but where it has seemed likely that alternative forms may become popular (e.g. litre/s instead of dm^3/s) they have been adopted on occasion.

Some errors in the original text have been corrected and several new sections added. In particular, additional text has been provided to deal with the modern views on psychrometry which form the basis of the latest I.H.V.E. tables. The chapters dealing with heat gains and automatic controls have been partly revised and the opportunity has been taken to add sections on the increasingly popular variable air volume system and the interesting development of integrated environmental design.

W.P.J.

Preface to the First Edition

Air conditioning (of which refrigeration is an inseparable part) has its origins in the fundamental work on thermodynamics which was done by Boyle, Carnot and others in the seventeenth and eighteenth centuries, but air conditioning as a science applied to practical engineering owes much to the ideas and work of Carrier, in the United States of America, at the beginning of this century. An important stepping stone in the path of progress which has led to modern methods of air conditioning was the development of the psychrometric chart, first by Carrier in 1906 and then by Mollier in 1923, and by others since.

The summer climate in North America has provided a stimulus in the evolution of air conditioning and refrigeration which has put that semi-continent in a leading position amongst the other countries in the world. Naturally enough, engineering enterprise in this direction has produced a considerable literature on air conditioning and allied subjects. The *Guide and Data Book* published by the American Society of Heating, Refrigeration and Air Conditioning Engineers has, through the years, been a foremost work of reference but, not least, the *Guide to Current Practice* of the Institution of Heating and Ventilating Engineers has become of increasing value, particularly of course in this country. Unfortunately, although there exists a wealth of technical literature in textbook form which is expressed in American terminology and is most useful for application to American conditions, there is an almost total absence of textbooks on air conditioning couched in terms of British practice. It is hoped that this book will make good the deficiency.

The text has been written with the object of appealing to a dual readership, comprising both the student studying for the associate membership examinations of the Institution of Heating and Ventilating Engineers and the practising engineer, with perhaps a 75 per cent emphasis being laid upon the needs of the former. To this end, the presentation follows the sequence which has been adopted by the author during the last few years in lecturing to students at the Polytechnic of the South Bank. In particular, wherever a new idea or technique is introduced, it is illustrated immediately by means of a worked example, when this is possible. It is intended that the text should cover those parts of the syllabus for the corporate membership examination that are relevant to air conditioning.

Inevitably some aspects of air conditioning have been omitted (the author particularly regrets the exclusion of a section on economics). Unfortunately, the need to keep the book within manageable bounds and the desire to avoid a really prohibitive price left no choice in the matter.

W.P.J.

ACKNOWLEDGEMENTS

Originally this book was conceived as a joint work, in co-authorship with Mr. L. C. Bull. Unfortunately, owing to other commitments, he was compelled largely to forego his interest. However, Chapters 9 and 14 (on the fundamentals of vapour compression and vapour-absorption refrigeration) are entirely his work. The author wishes to make this special acknowledgement to Mr. Bull for writing these chapters and also to thank him for his continued interest, advice and encouragement. Equations (7.30) and (7.35) are derived from his work.

The helpful comment of Mr. E. Woodcock is also appreciated.

The author is additionally grateful to the following for giving their kind permission to reproduce copyright material which appears in the text.

The Institution of Heating and Ventilating Engineers for various questions from external examination papers and also Table 7.1 and Figure 7.16 from the Guide to Current Practice.

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Buffalo Forge Company, Buffalo, N.Y. for equations (4.1) and (4.2), from Fan Engineering.

H.M. Stationery Office for equation (4.3), from War Memorandum No. 17, Environmental Warmth and its Measurement by T. Bedford.

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Notatior

Symbol	*Description*	*Unit*
Chapter 2		
A	surface area of a water droplet	m^2
$A_{ik}(T)$	second virial coefficient, molecules considered two at a time	m^3/kg
$A_{ijk}(T)$	third virial coefficient, molecules considered three at a time	m^3/kg
A_{aa}	second virial coefficient of dry air	m^3/kg
A_{ww}	second virial coefficient of water vapour	m^3/kg
A_{www}	third virial coefficient of water vapour	m^3/kg
A_{aw}	interaction coefficient	m^3/kg
A, B, C, D	constants	
A', B', etc.	constants	
a	constant	
c	specific heat of moist air	J/kg °C
c_a	specific heat of dry air	J/kg °C
c_s	specific heat of water vapour (steam)	J/kg °C
f_s	dimensionless coefficient	
g	moisture content	kg/kg dry air
g_{ss}	moisture content of saturated air	kg/kg dry air
H	enthalpy	kJ
h	specific enthalpy of moist air	kJ/kg dry air
h_a	enthalpy of 1 kg of dry air	kJ/kg
h_g	latent heat plus sensible heat in the water vapour associated with 1 kg of dry air	kJ/kg
h_s	enthalpy of 1 kg of water vapour at a temperature t, the temperature of the dry bulb	kJ/kg
h_c	coefficient of heat transfer through the gas film surrounding a water droplet, by convection	W/m^2 °C

Symbol	*Description*	*Unit*
h_r	coefficient of heat transfer to a water droplet by radiation from the surrounding surfaces	W/m² °C
h	$= h_c + h_r$	W/m² °C
h_{fg}	latent heat of evaporation	kJ/kg
(Le)	Lewis number	
M	molecular mass	
M_a	molecular mass of dry air	
M_s	molecular mass of water vapour (steam)	
m	mass of a gas	kg
m_a	mass of dry air	kg
m_s	mass of water vapour (steam)	kg
n_a	number of molecules of constituent a	
n_w	number of molecules of constituent w	
p	gas pressure	N/m²
p_a	pressure of dry air	N/m²
p_{at}	atmospheric pressure (barometric pressure)	N/m²
p_s	pressure of water vapour (steam)	N/m²
p_{ss}	saturation vapour pressure	N/m²
p'_{ss}	saturation vapour pressure at the wet-bulb temperature	N/m²
R_o	universal gas constant	J/kmol K
R	particular gas constant	J/kg K
R_a	particular gas constant of dry air	J/kg K
R_s	particular gas constant of water vapour (steam)	J/kg K
R_{ss}	particular gas constant of dry saturated steam	J/kg K
T	absolute temperature	K
t	temperature	°C
t_c	critical temperature	°C
t_d	dew-point temperature	°C
t_{ss}	saturation temperature	°C
t'	wet-bulb temperature	°C
t^*	temperature of adiabatic saturation	°C
U	internal energy	kJ
v	specific volume	m³/kg
V	gas volume	m³
V_a	volume of dry air	m³
V_m	volume of 1kmol	m³
V_s	volume of steam	m³
x	mole fraction	
α	coefficient of diffusion	kg/N

Symbol	*Description*	*Unit*
μ	percentage saturation	
ϕ	relative humidity	

Chapter 3

Symbol	*Description*	*Unit*
c_a	specific heat of dry air	J/kg °C or kJ/kg °C
E	effectiveness of an air washer or spray chamber	
g	moisture content	kg/kg dry air or g/kg dry air
h	enthalpy of most air	J/kg dry air
m_a	mass or mass flow of dry air	kg or kg/s
m_w	mass of feed water evaporated	kg/s
t	dry-bulb temperature	°C
t_d	dew-point temperature (or the dry-bulb temperature at a state D)	°C
t_w	feed-water temperature	°C
β	contact factor	
η	humidifying efficiency	

Chapter 4

Symbol	*Description*	*Unit*
a, b, T	constants	
C	rate of heat loss or gain by convection	W or kW
E	rate of heat loss by evaporation	W or kW
H	cooling power of a Kata thermometer	
M	metabolic rate	W or kW
p_s	partial pressure of the water vapour in the air	N/m^2
p_w	vapour pressure of water	N/m^2
R	rate of heat loss or gain by radiation	W or kW
S	rate at which heat is stored in the body	W or kW
t	dry-bulb temperature	°C
T_a	air dry-bulb temperature	K
T_g	reading of a globe thermometer	K
T_{rm}	mean radiant temperature	K
v	relative velocity of air flow	m/s
V	air velocity measured by a Kata thermometer	m/s
W	rate of useful working	W or kW

Chapter 6

Symbol	*Description*	*Unit*
A	surface area	m^2

Symbol	*Description*	*Unit*
c	specific heat of air	kJ/kg °C or J/kg °C
g	moisture content	g/kg dry air
g_a	moisture content at the apparatus dew point	g/kg
g_o	moisture content of outside air	g/kg
g_r	room moisture content	g/kg
g_s	supply air moisture content	g/kg
h_a	enthalpy of air at the apparatus dew point	kJ/kg
h_o	enthalpy of the outside air	kJ/kg
h_w	enthalpy of the air leaving the cooler coil	kJ/kg
h_{fg}	latent heat of evaporation	kJ/kg
m	mass of air supplied	kg or kg/s
m_a	mass flow rate of dry air	kg/s
n	air change rate per hour	
Q	rate of production of heat	kW
T	dry-bulb temperature	K
t_o	outside environmental dry-bulb temperature	°C
t_r	room dry-bulb temperature	°C
t_s	supply air temperature	°C
t_w	dry-bulb temperature of air leaving the cooler coil	°C
U	overall thermal transmittance	kW/m^2 °C
V	volume	m^3
v	specific volume	m^3/kg dry air
β	contact factor	
ρ	density of air	kg/m^3
η	total fan efficiency	%

Chapter 7

A	area	m^2
A, B	internal duct dimensions	m
A_f	floor area	m^2
A_w	window area	m^2
a	altitude of the sun	
a'	altitude of the sun at noon	
a_n	harmonic phase angle	
C	dimensionless constant	
c	specific heat	kJ/kg °C
D	internal duct diameter	m
d	declination of the sun	

Symbol	*Description*	*Unit*
F_g	angle factor for the ground	
F_s	angle factor for the sky	
f	decrement factor	
h	hour-angle, stack height in metres or coefficient of heat transfer according to the context	
h_{si}	inside surface film coefficient of heat transfer	W/m^2 °C
h_{so}	outside surface film coefficient of heat transfer	W/m^2 °C
I	intensity of direct solar radiation on a plane at right angles to the path of the rays of the sun	W/m^2
I_h	component of I which is normally incident upon a horizontal surface	W/m^2
I_r	intensity of radiation reflected from surrounding surfaces	W/m^2
I_s	intensity of diffuse radiation normally incident on a surface	W/m^2
I_t	intensity of total radiation on a surface	W/m^2
I_v	component of I which is normally incident upon a vertical surface	W/m^2
I_δ	component of I which is normally incident upon a surface which is tilted at an angle δ to the horizontal	W/m^2
i	angle of incidence	
k	thermal conductivity of a wall or of duct insulation	W/m °C
L	wall thickness, or duct length	m
	latitude of a place on the surface of the earth	
l	thickness of insulation on a duct	m
n	solar-wall azimuth	
P	external duct perimeter	m
Q	rate of heat flow	W or W/m^2
Q_m	mean rate of heat flow into a room	W
Q'	rate of heat flow into the outer surface of a wall	W/m^2
Q_θ	rate of heat flow into a room at time θ	W
$Q_{(\theta+\varphi)}$	rate of heat flow into a room at time $(\theta+\varphi)$	W
q	rate of airflow	m^3/s

Symbol	*Description*	*Unit*
q_i	instantaneous solar gain	W/m^2
q_{max}	maximum solar gain	W/m^2
R	depth of a window recess, in metres or millimetres as appropriate, or a remainder term, according to the context	
r_{si}	thermal resistance of the air film inside a duct	$m^2\ °C/W$
r_{so}	thermal resistance of the air film outside a duct	$m^2\ °C/W$
T	sun-time	h
t	time or temperature	h or °C
t_e	sol-air temperature	°C
t_{em}	mean sol-air temperature, over 24 hours	°C
$t_{e\theta}$	sol-air temperature at time θ	°C
t_g	mean glass temperature	°C
t_n	harmonic temperature coefficient	
t_o	outside air temperature	°C
t_r	room air temperature	°C
t_{si}	inside surface temperature	°C
t_{sm}	mean inside surface temperature	°C
t_{so}	outside surface temperature	°C
v	mean velocity of airflow	m/s
U	overall thermal transmittance	$W/m^2\ °C$
V	air velocity in a duct	m/s
x, y	co-ordinates	m or mm
x	thickness of a floor slab	m or mm
z	azimuth of the sun	
α	coefficient of absorption for direct solar radiation	
α'	coefficient of absorption for diffuse solar radiation	
Δp	pressure difference	N/m^2
Δt	equivalent temperature differential $(t_o - t_r)$	°C
θ	time or temperature difference	h or °C
λ_e	equivalent decrement factor	
λ_1	fundamental decrement factor	
λ_n	decrement factor for the *n*th harmonic	
ρ	density	kg/m^3
τ	coefficient of transmissivity for direct solar radiation	
τ'	coefficient of transmissivity for diffuse solar radiation	

Symbol	*Description*	*Units*
φ	time lag or phase constant	h
φ_1	fundamental lag angle, in degrees	
φ_n	harmonic lag angle, in degrees; hence the time lag in hours is $\varphi_n/15$	
ω	angular velocity of the sun	h^{-1}
$1/K$	time constant	h^{-1}

Chapter 8

c	humid specific heat of air	kJ/kg °C
g	moisture content of air	kg/kg or g/kg
h	enthalpy of air	kJ/kg
m	mass flow of air	kg/s
t	dry-bulb temperature of air	°C
Q_L	latent heat gain	W or kW
Q_S	sensible heat gain	W or kW
L	sensible heat gain due to electric lighting	W or kW
P	sensible heat gain due to people	W or kW
S	sensible heat gain due to solar radiation	W or kW
T	sensible heat gain due to transmission by virtue of air-to-air temperature difference	W
β	contact factor	

Chapter 9

COP	coefficient of performance	
c	constant in equation $pv^n = c$ (see §9.4)	
c_1	specific heat of liquid	kJ/kg °C
c_p	specific heat of gas at constant pressure	kJ/kg °C
c_v	specific heat of gas at constant volume	kJ/kg °C
f	mass in kg of refrigerant which vaporises during throttling, per kg circulated	
f_1	mass in kg of refrigerant which vaporises during expansion in an engine, per kg circulated	
f_2	mass in kg of refrigerant which vaporises during compression, per kg circulated	
h_j	heat transferred to the cylinder jacket during compression	kJ/kg
h_{1c}	enthalpy of saturated liquid at condensing pressure	kJ/kg
h_{1e}	enthalpy of saturated liquid at evaporating pressure	kJ/kg

Symbol	*Description*	*Unit*
h_{m1}	enthalpy of mixture of liquid and vapour entering evaporator	kJ/kg
h_{m2}	enthalpy of mixture of liquid and vapour entering compressor	kU/k
h_{vc}	enthalpy of saturated vapour at condensing pressure	kJ/kg
h_{vd}	enthalpy of superheated vapour at discharge condition	kJ/kg
h_{ve}	enthalpy of saturated vapour at evaporating pressure	kJ/kg
h_{fg}	latent heat of vaporisation at evaporating temperature	kJ/kg
m	mass of refrigerant circulated	kg/s
n	exponent in equation $pV^n = C$(see §9.4)	
p	pressure	N/m^2
p_1	pressure at the beginning of a process	N/m^2
p_2	pressure at the end of a process	N/m^2
p_c	condensing pressure	N/m^2
p_d	discharge pressure	N/m^2
p_e	evaporating pressure	N/m^2
Q	quantity of heat per unit mass	kJ/kg
R	particular gas constant	kJ/kg K
s	entropy	kJ/kg K
s_1	entropy at the beginning of a process	kJ/kg K
s_2	entropy at the end of a process	kJ/kg K
s_{AB}	entropy during process depicted by line *AB*	kJ/kg K
s_{CD}	entropy during process depicted by line *CD*	kJ/kg K
s_{1c}	entropy of saturated liquid at condensing pressure	kJ/kg K
s_{1e}	entropy of saturated liquid at evaporating pressure	kJ/kg K
s_{vc}	entropy of saturated vapour at condensing pressure	kJ/kg K
s_{ve}	entropy of saturated vapour at evaporating pressure	kJ/kg K
T	absolute temperature	K
T_1	temperature at beginning of process	K
T_2	temperature at end of process	K
T_c	condensing temperature	K
T_d	discharge temperature	K
T_e	evaporating temperature	K
TR	tons of refrigeration (*see* §9.2)	

Symbol	*Description*	*Unit*
V	volume per unit mass	m^3/kg
V_1	volume at the beginning of a process	m^3/kg
V_2	volume at the end of a process	m^3/kg
V_d	volume at discharge condition	m^3/kg
V_e	volume of saturated vapour at evaporating pressure	m^3/kg
W_c	work of compression	kW
X	cooling capacity or load, in kW of refrigeration	
γ	$= c_p/c_v$	

Chapter 10

A_f	face area of the cooler coil	m^2
A_r	total external surface area per row of the cooler coil	m^2
A_t	total external surface area of the cooler coil	m^2
c	specific heat of humid air	kJ/kg °C
h	enthalpy of humid air	kJ/kg °C
h_a	coefficient of heat transfer on the air-side of the cooler coil	kJ/kg °C
k	constant	
$LMTD$	logarithmic mean temperature difference	°C
m_a	mass flow of dry air	kg/s
m_w	mass flow of water inside the cooler coil tubes in kg water/kg dry air flowing over the outside of the cooler coil	
Q_s	rate of sensible heat transfer	kW
Q_t	rate of total heat transfer	kW
R_a	thermal resistance of the surface film on the air-side of a cooler coil	m^2 °C/W
R_m	thermal resistance of the metal of the cooler coil (wall + fins)	m^2 °C/W
R_r	thermal resistance of the surface film on the refrigerant side of a cooler coil	m^2 °C/W
R_w	thermal resistance of the surface film on the water-side of the cooler coil	m^2 °C/W
r	the number of rows in the cooler coil	
S	sensible heat removed by the coil/total heat removed by the coil	
t, t_a	dry-bulb temperature of the air flowing over a cooler coil	°C
t'	wet-bulb temperature	°C

Symbol	*Description*	*Unit*
t_d	dew-point temperature of the air	°C
t_w	chilled water temperature	°C
t_{wa}, t_{wb}	entering, leaving chilled water temperature	°C
t_{w1}	mean surface temperature for the first row of a cooler coil	°C
t_{w2}	mean coil surface temperature for the second row of a cooler coil	°C
t_{sm}	mean coil surface temperature for the whole cooler coil	°C
U_t	U-value for the cooler coil	W/m² °C
v_f	velocity of airflow over the face of the cooler coil	m/s
β	contact factor	

Chapter 11

a	cross-sectional area of the tower	m²
h_a	enthalpy of humid air kJ/kg of dry air	
k	coefficient of vapour diffusion for a unit value of Δh_m	kg/s m²
ks	volume transfer coefficient	
m_a	rate of mass flow of air	kg/s
m_w	rate of mass flow of water	kg/s
s	wetted surface area per unit volume of packing	m^{-1}
t	air temperature	°C
t_w	cooling water temperature	°C
Z	height of a cooling tower	m
Δh_m	mean driving force	kJ/kg

Chapter 13

A_v	flow coefficient	
a	cross-sectional area of a valve opening	m²
d	diameter of the pipe or duct	m
f	dimensionless coefficient of friction (Fanning)	
f_m	dimensionless coefficient of friction (Moody) $= 4f$	
g	acceleration due to gravity	m/s²
H_1, H_0	head in a reservoir or sink, in m of fluid	
h_l	head lost along a pipe, in m of fluid	
h_v	head lost across the valve	m

Symbol	*Description*	*Unit*
h	static head, in m of fluid	
K, K_1	constants of proportionality	
k_d	derivative control factor	
k_i	integral control factor	
k_p	proportional control factor	
l	length	m
q	volumetric flow rate	m^3/s
q_0, z_0	maximum flow rate and maximum value lift	m^3/s and m
v	mean velocity of fluid flow	m/s
z	position of a valve stem	m
α	valve authority $= 1/(1+\beta z^2)$	
$\beta =$	$16 f_m l K_1{}^2/\pi^2 d^5$	
ϕ	potential correction	
θ	deviation	°C

Chapter 14

C_a	concentration of LiBr, per cent by weight, in the absorber	
C_g	concentration of LiBr, per cent by weight, in the generator	
COP	coefficient of performance	
c_1	specific heat of the liquid refrigerant	kJ/kg °C
H_a	heat removed at the absorber	kW/kW of refrigeration
H_c	heat removed at the condenser	kW/kW of refrigeration
H_g	heat added at the generator	kW/kW of refrigeration
h_a	enthalpy of the solution leaving the absorber	kJ/kg
h_g	enthalpy of the solution leaving the generator	kJ/kg
h_{1c}	enthalpy of the refrigerant liquid leaving the condenser	°C
h_{ve}	enthalpy of the refrigerant vapour leaving the evaporator	°C
h_{vg}	enthalpy of the vapour leaving the generator	kJ/kg
m_r	mass of refrigerant circulated	kg/s kW
m_{sa}	mass of solution leaving the absorber	kg/s kW
m_{sg}	mass of solution leaving the generator	kg/s kW
p_c	condensing pressure of the refrigerant	kN/m^2

Symbol	*Description*	*Unit*
p_e	evaporating pressure of the refrigerant	kN/m^2
Q_g	heat supplied at the generator, in kJ/kg of refrigerant	
Q_r	refrigerating effect, in kJ/kg of refrigerant	
T_c	$273+t_c$	
T_g	$273+t_g$	
t_c	temperature of the refrigerant leaving the condenser	°C
t_e	temperature of the refrigerant leaving the evaporator	°C
t_a	temperature of the refrigerant in the absorber	°C
t_g	temperature of the refrigerant in the generator	°C
W	work done per kg of refrigerant	kW/kg

Chapter 15

A	cross-sectional area of a duct	m^2
A'	reduced area available for airflow through the vena-contracta	m^2
a, b	duct dimensions	m or mm
a_1, a_2	cross-sectional areas	m^2
C	constant, or correction factor, or curve ratio, according to the context	
C_A	coefficient of area	
C_E	coefficient of entry	
C_V	coefficient of velocity	
d	internal duct diameter	m or mm
E	correction factor	
FP	fan power	kW
FTP	fan total pressure	N/m^2
f	dimensionless coefficient of friction	
g	acceleration due to gravity	m/s^2
H	head lost, in m of fluid flowing	
h	height	m
h_s	static suction set up in the plane of the vena-contracta	N/m^2
K	R_0/R_{n+1}	
k	loss coefficient	
k_s	absolute surface roughness	m
l	length of a duct	m
m	hydraulic mean gradient	