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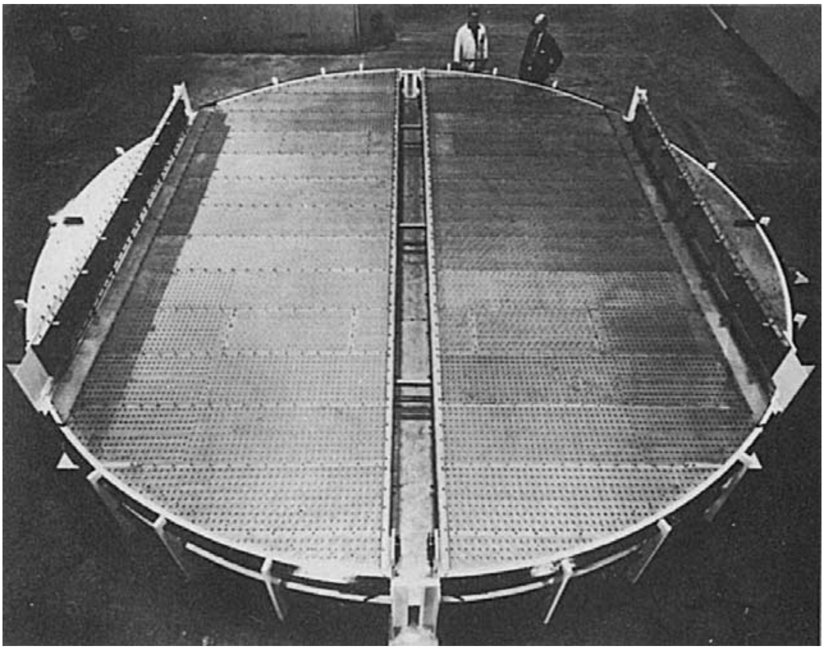

Trial assembly of large two-pass slotted sieve trays. (Courtesy of Union Carbide Corporation.)

Distillation tray fundamentals

M.J.LOCKETT
Union Carbide Corporation

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CAMBRIDGE UNIVERSITY PRESS
Cambridge
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CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo, Delhi

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521105873

First published 1986
This digitally printed version 2009

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data

Lockett, M. J.
Distillation tray fundamentals.

Bibliography
Includes index.
1. Distillation apparatus. I. Title.
TP159.D5L63 1986 660.2′8425 85-30891

ISBN 978-0-521-32106-8 hardback
ISBN 978-0-521-10587-3 paperback

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Preface

The design and performance of distillation trays is one of the most thoroughly studied topics in chemical engineering. Papers dealing with trays are available in abundance but the information they contain is often conflicting. Indeed, by searching hard enough it is usually possible to find some published information to support nearly any contention one cares to make about how trays work. One aim of this book has been to draw together and interpret much of this previous work.

It has not been my intention to write a design manual for tray design. Others have done this far more effectively than I, and some such sources are cited in Chapter 1. The approach I have taken is to assume that the reader is already familiar with elementary design methods as given in the standard undergraduate textbooks. What I have attempted is to delve a little deeper into the empirical correlations and equations which are used for tray design and to indicate their origins and shortcomings. The sequence of the material covered is such that, when coupled with the outline design procedure given in Chapter 1, it is relatively straightforward to adapt it to and improve existing design methods. Having said all that, I suppose this book was mainly written for the same reason that most books of its type are written – having worked in an area, in this case distillation trays, for some time with considerable enjoyment, it felt appropriate to convey my enthusiasm for the subject to others.

Distillation trays are seemingly so simple that it may be surprising that they warrant a whole book, albeit a small one, to themselves. Sieve tray decks are, after all, hardly more than sheets of metal with a few holes punched in them. This of course is part of the fascination – that the behaviour of something so simple can be so difficult to predict with regard to its hydrodynamic and mass transfer performance. Another equally intriguing aspect is the interplay between the topics covered in this book and the marketing and selling of trays. Distillation column internals are marketed very competitively as a glance at the advertisements in the popular chemical engineering magazines will testify. It is necessary to be aware that however erudite and interesting in their own right are theories of tray behaviour, they must in the end be translated into the design of pieces of metal which work reliably and at reasonable cost. Thus, those involved with trays span a wide range from those concerned solely with metal fabrication through to researchers into fairly esoteric irreversible thermodynamics. This complex mix of concerns and priorities also provides much of the subject's interest.

It is hoped that most people who deal with distillation trays at any level will find something of value in the pages that follow. However, the book is primarily aimed at the process engineer involved with design who wishes to know more than can be obtained by simply applying correlations. In addition, those concerned with specifying and buying trays should find it useful, as should those troubleshooting malfunctioning columns. I know from experience that it forms a reasonable basis for a graduate course, and the lack of answers to many of the questions posed should also provide a reasonable stimulus for research workers in this area of chemical engineering.

The book had its origins in a course of lectures I gave on distillation in the late 1970s to graduate students at the University of Manchester Institute of Science and Technology. When I was asked to give a course on distillation trays at the University of Aston to practising engineers as part of the continuing education series of the Institution of Chemical Engineers, the idea took hold of developing the material into a book. A further impetus was provided when I joined the Linde Division of Union Carbide, responsible for distillation engineering and development. This helped me put some of the more theoretical material into context as it impacts on the practising engineer.

Although the book was started while I was at UMIST, 95% of it was completed at nights and weekends while working for Union Carbide. In retrospect I doubt whether I would have started it if I had known it would be written outside the cloistered life of the university. In the event, my wife and children were extremely patient and understanding during its completion in spite of my absence from numerous school concerts, baseball games and skiing trips.

There are of course many other people to whom acknowledgement is due. In particular I would like to thank K E Porter who introduced me to the subject and taught me the importance of asking the right questions about research problems. I also appreciated working with the late G L

Standart, who impressed on me the other aspect – the importance of giving the right answers! A source of inspiration has been the research students with whom I have had the good fortune to work over the years, and this book is built substantially on their efforts. Colleagues who have read the manuscript and contributed suggestions include M R Resetarits and D R Summers to whom thanks are also due, although errors and omissions are of course solely my own responsibility. Mrs Anita Strzalkowski did a sterling job of transforming my ill-written scrawl into a typewritten manuscript with good-humour and patience, and J D Augustyniak drew the figures with his usual skill and attention to detail. Finally I would like to thank the directors of Union Carbide for permission to publish the book.

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Acknowledgements

The author is grateful to the following organisations for permission to reproduce or adapt figures which have been published by other authors. American Institute of Chemical Engineers: Figs. 4.3 and 9.20; Energy Publications: Figs. 5.1 and 5.6; Glitsch, Inc.: Fig. 5.2; Institution of Chemical Engineers: Figs. 1.3, 1.6, 2.2, 2.4, 2.8, 2.12, 2.18, 2.20, 2.21, 2.22; Pergamon Press, Ltd.: Figs. 2.3, 2.7, 2.11, 2.13, 2.14; VCH Verlagsgesellschaft: Figs. 4.2 and 5.7.

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Nomenclature

Unless otherwise stated locally, the units used are as given below. In particular, the following units should be used in equations which are not dimensionless. The nomenclature of the original sources has been retained as far as possible. The terms gas and vapour are used interchangeably.

A	Cross-sectional area, m^2
A	Constant in eqn. (4.11)
A	Defined by eqn. (9.32)
A_b	Tray bubbling area, m^2
A_d	Downcomer cross-sectional area, m^2
A'_{da}	Area under splash baffle, m^2
A_h	Area of holes in tray deck, m^2
A_n	Net area for liquid disengagement above tray, m^2
A_{sc}	Curtain area of 'closed' valves, m^2
A_V	Area of valve disk, m^2
a	Interfacial area per unit volume of two-phase dispersion, $m^2\,m^{-3}$
a	Parameter describing jet shape, eqn. (2.17)
a	Parameter in eqn. (2.31)
a	Defined by eqns. (10.8)
a'	Interfacial area per unit volume of vapour, $m^2\,m^{-3}$
$\bar{a}$	Interfacial area per unit volume of liquid, $m^2\,m^{-3}$
B	Defined by eqns. (9.32)
B_s	Oscillation number, eqn. (5.23)
b	Intercept of equilibrium line (binary)
b	Constant in eqn. (4.16)
b	Defined by eqns. (10.8)
C	Defined by eqn. (3.25)
C	Defined by eqn. (9.32)
C_d	Discharge coefficient

C_0	Drop drag coefficient
CF	Capacity factor based on A_b, m s^{-1}
CF'	Capacity factor based on A_n, m s^{-1}
CF''	Capacity factor from Fig. 5.1, m s^{-1}
CF_{max}	Theoretical maximum capacity factor, eqn. (5.10), m s^{-1}
CF_0	Capacity factor at zero liquid load, m s^{-1}
c	Velocity of sound, m s^{-1}
D	Column diameter, m
D	Defined by eqn. (9.32)
D_G, D_L	Diffusion coefficient in vapour and liquid phase, m^2 s^{-1}
D_L^0	Diffusion coefficient in liquid phase at infinite dilution, m^2 s^{-1}
De	Eddy diffusivity for liquid mixing, m^2 s^{-1}
De_G	Eddy diffusivity for vapour mixing, m^2 s^{-1}
d_b	Bubble diameter, m
d_{bs}	Sauter mean bubble diameter, m
d_h	Hole diameter, m
d_j	Jet diameter, m
d_p	Drop diameter, m
d_{pm}	Mean drop diameter, m
d_{ps}	Sauter mean projected drop diameter, m
$d_p(j)$	Diameter of drops in subgroup j, m
E^+	Liquid entrainment rate, kg-mol s^{-1}
E_H	Hausen tray efficiency
E_{HL}, E_{HV}	Hausen liquid and vapour tray efficiency
E_m	Liquid entrainment rate, kg s^{-1}
E_{ML}	Murphree liquid phase tray efficiency
E_{MV}	Murphree vapour phase tray efficiency
E_{MV}^a	Apparent Murphree vapour phase tray efficiency
E_{ni}^v	Vaporisation tray efficiency for component i on tray n
E_0	Section efficiency
E_{OG}	Murphree vapour phase point efficiency
E_S	Standart material efficiency
E_{SH}	Standart enthalpy efficiency
E_{Si}	Standart component efficiency
E_{TL}, E_{TV}	Thermal efficiency in liquid and vapour phase
e	Liquid entrainment rate ÷ vapour rate, (kg-mol s^{-1}) ÷ (kg-mol s^{-1})
e_m	Liquid entrainment rate ÷ vapour rate, (kg s^{-1}) ÷ (kg s^{-1})
e_0	E^+/L_0
F	Defined by eqn. (9.39)
$F(j)$	Number fraction of drops having size $d_p(j)$
F_h	Hole F factor, $u_h\rho_G^{0.5}$, kg$^{0.5}$ m$^{-0.5}$ s^{-1}
$(F_h)_{crit}$	Critical value of hole F factor

F_R	Reaction at the plate, N
F_s	Superficial F factor, $u_s \rho_G^{0.5}$, $kg^{0.5}\, m^{-0.5}\, s^{-1}$
F_w	Frictional force due to walls, N
F_x	Force, N
FF	Flood factor or fractional approach to flooding
FP	Flow parameter, eqn. (1.1)
Fr	Froude number, u_s^2/gh_{cl}
Fr'	Modified Froude number, $Fr\ \rho_G/(\rho_L-\rho_G)$
Fr_1	Froude number for liquid flow, $u_{L1}/(gh_1)^{0.5}$
Fr_h	Froude number, $u_h[\rho_G/gh_{cl}(\rho_L-\rho_G)]^{0.5}$
f	Friction factor for froth flow
f_i	Fraction of vapour flow carried by bubbles of species i
$\bar{f}_{ni}^L, \bar{f}_{ni}^V$	Fugacity of component i in liquid and vapour leaving tray n, bar
G	Vapour flow rate, kg-mol s^{-1}
G	Defined by eqn. (9.39)
G'	Vapour flow rate per unit bubbling area, kg-mol $s^{-1}\, m^{-2}$
G_{ij}	Matrix coefficients defined by eqn. (10.8)
g	Acceleration due to gravity, m s^{-2}
H	Vapour enthalpy, kJ (kg-mol)$^{-1}$
H	Defined by eqn. (9.39)
h	Liquid enthalpy, kJ (kg-mol)$^{-1}$
h	Distance from tray floor, m
$\Delta h(i)$	Height increment at height $h(i)$, m
h_{cl}	Clear liquid height, m
h_{clD}	Dynamic liquid head at tray floor, m
$(h_{cl})_{ow}$	Height of clear liquid flowing over weir, m
h_{cli}	Clear liquid height at liquid entry, m
h_{co}	Height of clear liquid in exit calming zone, m
h'_{da}	Head loss for liquid flowing under splash baffle, m of liquid
h_{DT}	Dry tray pressure drop, m of liquid
h'_{DT}	$h_{DT}+h_R$, m of liquid
h_f	Height of two-phase dispersion on tray, m
h_{fd}	Froth height in downcomer, m
h_G, h_L	Heat transfer coefficients in vapour and liquid phases, kW $m^{-2}\, K^{-1}$
h_i	Depth of liquid at liquid entry, m
h_j	Jet height, m
h_L	Depth of liquid in vessel, m
h_m	Head of liquid measured by manometer, m of liquid
h_n	Pressure increase across the nappe, m of liquid
h_{ow}	Height of froth flowing over weir, m
h_R	Residual pressure drop, m of liquid
h_{udc}	Pressure drop for flow under downcomer, m of liquid
h_w	Weir height, m

h_{WT}	Wet (or total) tray pressure drop, m of liquid
h_1	Clearance under downcomer, m
h_1, h_2	Depth of liquid at positions 1 and 2, m
i	Height increment number
j	Drop subgroup number
K	Coefficient in eqn. (4.20)
K_{ni}	Ideal solution K value for component i on tray n
K_{OG}	Overall mass transfer coefficient based on vapour, kg-mol s^{-1} m^{-2}
K'_{OG}	Overall mass transfer coefficient based on vapour, m s^{-1}
K_w	Parameter used in eqn. (4.10)
K_1, K_2	Constants in eqn. (5.17)
k	Correction factor, eqn. (3.17)
k'	Correction factor, eqn. (3.32)
k_G	Vapour phase mass transfer coefficient, kg-mol s^{-1} m^{-2}
k'_G	Vapour phase mass transfer coefficient, m s^{-1}
k_L	Liquid phase mass transfer coefficient, kg-mol s^{-1} m^{-2}
k'_L	Liquid phase mass transfer coefficient, m s^{-1}
L	Liquid flow rate, kg-mol s^{-1}
L_0	Liquid flow rate on tray in absence of entrainment or weeping, Figs. 9.11, 9.14, kg-mol s^{-1}
L_w	Weeping rate, kg-mol s^{-1}
L'_w	Weeping rate per unit tray area, kg-mol s^{-1} m^{-2}
l	Latent heat, kJ $(kg\text{-}mol)^{-1}$
l	Maximum valve lift, mm
l	Parameter in eqn. (2.32), m
M	Molecular weight, kg $(kg\text{-}mol)^{-1}$
M_G	Vapour flow rate, kg s^{-1}
M_L	Liquid flow rate, kg s^{-1}
M_V	Valve mass, kg
m	Slope of equilibrium line (binary)
m	$\Delta y/\Delta x$ defined variously by eqns. (10.2), (10.4), (10.6)
N	Molar flux, kg-mol s^{-1} m^{-2}
N	Number of completely mixed liquid pools
N_A	Number of actual trays
N_G	Number of binary vapour phase transfer units
N_L	Number of binary liquid phase transfer units, eqn. (8.12)
N'_L	Number of binary liquid phase transfer units, eqn. (8.22)
N_{OG}	Number of overall binary vapour phase transfer units
N_p	Total rate of drop generation per unit tray area, m^{-2} s^{-1}
N_T	Number of theoretical trays
n	Tray number from bottom of column

n	Total number of bubble subgroups
n	Number of holes in area A_b
n	Parameter in eqn. (2.26)
n	Parameter describing jet shape, eqn. (2.17)
n_1, n_2	Number of light and heavy valves, respectively
P	Pressure, $N\,m^{-2}$
P_b	Pressure within bubble, $N\,m^{-2}$
P_c	Chamber pressure, $N\,m^{-2}$
P_I	Excess pressure in bubble due to liquid inertia, $N\,m^{-2}$
P_s	Pressure above liquid surface, $N\,m^{-2}$
ΔP_R	Residual pressure drop, $N\,m^{-2}$
P_1^d	Pressure at position 1 for dry tray, $N\,m^{-2}$
P_1^w	Pressure at position 1 for wet tray, $N\,m^{-2}$
ΔP_{12}	Pressure difference between 1 and 2, $N\,m^{-2}$
Pe	Liquid Peclét number, $Q_L D/Wh_{cl}De$ for two-dimensional model or $Q_L Z/Wh_{cl}De$ for one-dimensional model
Pe_G	Vapour Peclét number
p	Hole pitch, m
Q_G	Gas or vapour flow rate, $m^3\,s^{-1}$
Q_F	Froth flow rate, $m^3\,s^{-1}$
Q_h	Gas flow rate through hole, $m^3\,s^{-1}$
Q_L	Liquid flow rate, $m^3\,s^{-1}$
Q_n	Rate of heat loss from tray n to the surroundings, kW
q	Heat flux, $kW\,m^{-2}$
R_h	Hydraulic radius, m
Re_f	Reynolds number for flowing two-phase mixture
Re_h	Reynolds number for vapour flow through hole
r	Bubble radius, m
r	Ratio of N_1 to total flux
r_h	Hole radius, m
r_m	Manometer tube radius, m
r_n	Fraction of heat lost by vapour from tray n
S	Stabilisation index, $N\,m^{-1}$ or $N^2\,m^{-2}$
S	Effective liquid flow path width for circular tray, m
SF	System factor
Sc_G, Sc_L	Schmidt number ($\mu_G/\rho_G D_G$ or $\mu_L/\rho_L D_L$)
s	Distance of bubble centre from tray surface, m
s	Parameter in drop size distribution, eqn. (2.33)
s	Distance normal to curved wall, m
s'	Parameter in drop size distribution, eqn. (2.31)
T	Temperature, K
T_{Ln}	Temperature of liquid leaving tray n, K

T^*_{Ln} Bubble point temperature of liquid leaving tray n, K
T_s Tray spacing, m
T_{Vn} Temperature of vapour leaving tray n, K
T^*_{Vn} Dew point temperature of vapour leaving tray n, K
t Time, s
t Tray thickness, m
t_G Mean residence time of vapour in dispersion, s
t_L Mean residence time of liquid on tray, s

u Gas velocity in jet, m s^{-1}
u_b Bubble rise velocity, m s^{-1}
u_{b0} Terminal rise velocity of isolated bubble, m s^{-1}
u_d Liquid velocity in downcomer on vapour-free basis, m s^{-1}
u_{dc} Critical value of u_d for downcomer choking, m s^{-1}
u_f Mean horizontal froth velocity, m s^{-1}
u_G Mean vapour velocity through dispersion, m s^{-1}
u_h Gas velocity through hole(s), m s^{-1}
u_L Mean liquid velocity across tray, m s^{-1}
u_{L1} Liquid velocity at position 1, m s^{-1}
u_s Superficial vapour velocity based on A_b, m s^{-1}
u'_s Superficial vapour velocity based on A_n, m s^{-1}
u_{smax} Maximum value of u_s, m s^{-1}
$(u_s)_{OBP}, (u_s)_{CBP}$ Value of u_s at open and closed balance points, m s^{-1}

V_b Bubble volume, m^3
V_c Chamber volume, m^3
V_i Liquid molar volume at normal boiling point, cm^3 (g-mol)$^{-1}$
v Drop velocity, m s^{-1}
v_o Fraction of open valves
v_p Drop projection velocity, m s^{-1}

W Weir length, m
We Weber number
w, w_1 $w = w'/D$, $w_1 = W/2D$
w' Distance from centre line measured parallel to weir, m

X Mole fraction in pseudo-binary liquid mixture
x Mole fraction in liquid
x_{in} Tracer concentration at tracer injection point
x_0 Tracer concentration in liquid entering tray
x_R Mole fraction in liquid leaving reboiler, Fig. 9.5
x^L Mole fraction of low surface tension component
x_+ Value of x immediately downstream of liquid entry
x^*_{en-1} Mole fraction of liquid in equilibrium with vapour entering tray n
$\bar{x}_n$ Mean mole fraction in liquid leaving tray n via downcomer

x_n^* Mole fraction of liquid in equilibrium with mean vapour concentration leaving tray n
x_n' Mole fraction in liquid weeping or entrained from a point on tray n
$\bar{x}_n'$ Mean mole fraction in liquid weeping or entrained from tray n averaged over the tray

Y Mole fraction in pseudo-binary vapour mixture
$\bar{Y}_n$ Defined by eqn. (9.24) for entrainment, eqn. (9.33) for weeping
y Depth below free surface, m
y Parameter in eqns. (2.31), (2.33)
y Mole fraction in vapour
y_n Value of y in vapour leaving a point on tray n
$\bar{y}_n$ Mean value of y in vapour leaving tray n
y^* Mole fraction in vapour which is in equilibrium with liquid
y_n^* Mole fraction in vapour in equilibrium with mean concentration of liquid leaving tray n via the downcomer

Z Parameter in eqn. (4.19)
Z Liquid flow path length, m
Z_e Length of exit calming zone, m
Z_F Film thickness, m
z Distance normal to interface, Chapter 8, m
z $z = z'/D$ in two-dimensional model; $z = z'/Z$ in one-dimensional model
z' Distance from inlet weir, m
z_1 Value of z at exit weir
z_{in} Value of z at tracer injection point

α Volume of liquid per unit volume of two-phase dispersion (liquid holdup fraction)
α Relative volatility, eqn. (7.23)
α Similarity ratio, Chapter 9
$\alpha_d, \bar{\alpha}_d$ Local and mean liquid volume fraction in the downcomer
α_e Effective liquid volume fraction defined by eqn. (3.24)
$\alpha(i)$ Local liquid volume fraction at height $h(i)$
α_R Liquid volume fraction in froth flowing under downcomer
$\alpha_{OG}, \alpha_G, \alpha_L$ Parameters in eqns. (10.7)
β_0 Fractional weeping rate, L_w/L_0
γ Parameter in eqns. (10.10)
γ_{ni}^L Activity coefficient of component i in liquid leaving tray n
ε Volume of gas or vapour per unit volume of two-phase dispersion (gas holdup fraction)
ε_w Value of ε in froth flowing over weir
ε_1' Local volume fraction of small bubbles
η $\varepsilon/(1-\varepsilon)$, eqn. (3.10)
θ Contact angle
$\theta(ij)$ Residence time of drops j in height increment at height $h(i)$, s

λ	Stripping factor or ratio of slope of equilibrium line to slope of operating line, mG/L
λ_0	mG/L_0
μ_G, μ_L	Vapour and liquid viscosity, N s m^{-2}
v	Volume fraction of drops having diameter less than y, eqn. (2.31)
ξ	Orifice coefficient
ξ'	Modified orifice coefficient, eqn. (4.18)
ξ_0	Orifice coefficient as $\phi \to 0$, Fig. 4.2
ξ_{VC}	Orifice coefficient for valves resting on tray deck
ξ_{VD}	Orifice coefficient for valve tray deck
ξ_{Vi}	Orifice coefficient for combination of light and heavy valves
ξ_{VO}	Orifice coefficient for open valves
ρ_F	Density of two-phase dispersion, kg m^{-3}
ρ_G, ρ_L	Vapour and liquid density, kg m^{-3}
ρ'_G, ρ'_L	Vapour and liquid density, kg-mol m^{-3}
ρ_{H_2O}	Density of water, kg m^{-3}
σ	Surface tension, N m^{-1}
$\sigma^+, \sigma^-, \sigma^0$	Surface tension positive, negative or neutral system
ϕ	Fractional perforated tray area (hole area/bubbling area); also called fractional free area
ϕ_A	Association factor
ψ	Defined by eqn. (3.22*a*), m
ψ	Parameter in eqn. (10.5)
$\mathcal{N}_{OG}, \mathcal{N}_G, \mathcal{N}'_L$	Number of overall vapour phase, vapour phase and liquid phase ternary transfer units

Subscripts

b	In bulk phase
G	In gas or vapour phase
i	For bubble subgroup i
i	For component i
i	At interface
ij	For the binary ij
j	For the jet
j	For component j
L	In liquid phase
n	Leaving tray n
V	In vapour phase
1 or 2	For component 1 or 2, respectively *or* for small or large bubbles, respectively

Superscripts

e	Exit stream from ideal tray
0	Local value at the exit weir

—	Mean value
·, ··	First and second derivatives with respect to time
″	Entering value used in ideal tray definition, Fig. 7.1