Emmanuil G. Sinaiski and Eugeniy J. Lapiga

Separation of Multiphase, Multicomponent Systems

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The Authors

E. G. Sinaiski
Leipzig, Germany
e-mail: egsin@t-online.de

E. J. Lapiga
Moscow, Russia
e-mail: npfeitek@mtu-net.ru

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E. J. Lapiga: Oil rig, developed by EITEK

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Preface

This book sets out the theoretical basis underpinning the separation of multi-phase, multi-component systems with application to the processes used to prepare hydrocarbon mixtures (oil, natural gas, and gas condensate) for transportation. The text is divided into seven sections.

Section I provides an introduction to the basic processes, the technological schemes, and the components of the equipment employed in systems for the field preparation of oil, natural gas, and gas condensate. The emphasis is on the designs and the principles of operation of separators, absorbers, and cooling devices. Mathematical modeling of the processes in these devices is covered in subsequent sections of the book.

The media with which one has to deal when investigating preparation processes of hydrocarbon systems are invariably multi-phase and multi-component mixtures. Section II thus covers the aspects of the hydromechanics of physical and chemical processes necessary for an understanding of the more specialized material contained in following sections. Among these are transfer phenomena of momentum, heat, mass, and electrical charge; conservation equations for isothermal and non-isothermal processes for multi-component and multi-phase mixtures; equations of state, and basic phenomenological relationships.

Natural hydrocarbon systems exist as solutions, suspensions, colloidal systems, emulsions, gas-liquid and liquid-gas mixtures. Accordingly, Sections III–VII are devoted to each of the aforementioned kinds of systems.

Section III covers the theory and methods for investigating the behavior of multi-component charged and uncharged solutions. Considering non-charged solutions, the main focuses of attention are on diffusion processes with and without the possibility of chemical reactions, the flow of solutions in channels and pipes, processes on semi-permeable membranes (return osmosis), and mass exchange of particles, drops, and bubbles with the ambient media. For charged solutions, consideration is given to processes in electrolytic cells, electrodialysis, the structure of electrical double layers, electrokinetic phenomena, and electro-osmosis.

The behavior and stability of suspensions and colloidal systems, including non-charged and charged suspensions, along with the coagulation and sedimentation of particles and their deposition on obstacles, are considered in Section IV. Chapter 8 (devoted to non-charged suspensions) provides an introduction to the micro-hydrodynamics of particles, covering the fundamentals of Brownian motion, the viscosity of dilute suspensions, and the separation of suspensions in a gravitational field or under centrifugal forces. Chapter 9, devoted to charged suspensions, deals with the definition of particle charge, electrophoretic effects, the motion of conductive drops in an electric field, and sedimentation potential. Chapter 10 deals with the problem of colloidal system stability, various mechanisms of particle coagulation, and the capture of particles by obstacles when a suspension is passed through a filter.

The behavior of emulsions is considered in Section V in connection with the process of oil dehydration. Actual problems of drop integration in emulsions are discussed. It is shown that this process occurs most effectively if the emulsion is subjected to an electric field. In this context, the behavior of conducting drops in emulsions, the interaction of drops in an electric field, and the coalescence of drops in emulsions are examined in detail. In terms of applications, processes of emulsion separation in settling tanks, electro dehydrators, and electric filters are considered.

Separation processes of gas-liquid (gas-condensate) mixtures are considered in Section VI. The following processes are described: formation of a liquid phase in a gas flow within a pipe; coalescence of drops in a turbulent gas flow; condensation of liquid in throttles, heat-exchangers, and turboexpanders; the phenomena related to surface tension; efficiency of division of the gas-liquid mixtures in gas separators; separation efficiency of gas-condensate mixtures in separators equipped with spray-catcher nozzles of various designs – louver, centrifugal, string, and mesh nozzles; absorbtive extraction of moisture and heavy hydrocarbons from gas; prevention of hydrate formation in natural gas.

Section VII is devoted to liquid-gas (oil-gas) mixtures. The topics discussed are the dynamics of gas bubbles in multi-component solutions; the separation of liquid-gas mixtures in oil separators both neglecting and taking into account the hindrance due to the floating-up of bubbles; and the coagulation of bubbles in liquids.

A list of literature is given at the end of each section.

All of the considered processes relate to the separation of multi-phase, multi-component media, hence the title of the book. It should be noted that in the preparation technology for the transportation of oil, natural gas, and gas condensates, the term separation is traditionally understood only as the process of segregation of either a condensate and water drops or of gas and gas bubbles (occluded gas) from an oil. The concept of separation used herein can mean any segregation of components in multi-component mixtures or of phases in multi-phase systems.

List of Symbols

Symbol	Definition	Dimension, SI
a	Sound velocity	$m \cdot s^{-1}$
a_i	Activity of i-th component	
a	Radius of tube, pipe, capillary, particle	m
a	Semi-axis of ellipsoid	m
a	Parameter of repulsive electrostatic force	
a	Specific surface of grid (mesh)	m^{-1}
a_t	Radius of particle	m
A	Dimensionless parameter	
A^*	Reduced gas constant	$J \cdot kg^{-1} \cdot K^{-1}$
A_{cyl}	Parameter of stream function at flow around cylinder	
A_i	Chemical affinity of reaction	$J \cdot mole^{-1}$
A_i	Dimensionless parameters of charged particles, of jalousie separator	
A_s	Parameter of stream function at flow around sphere	
Ar	Archimedean number	
Ar_{av}	Archimedean number calculated by average radius of particles	
b	Adsorption constant	
b	Ellipsoid semi-axis; radius of cell boundary, of collision section of particles with cylinder	m
b	Dimensionless parameter	
B	Constant of reaction of ν-th order	$mole^{1-\nu} \cdot m^{3\nu-2} \cdot s^{-1}$
B_i	Henry constant of i-th component	Pa
Bo	Bond number	
c	Specific heat capacity	$J \cdot kg^{-1} \cdot K^{-1}$
c	Wave velocity	$m \cdot s^{-1}$

c_{cap}	Capillary wave velocity	$m \cdot s^{-1}$
c_i	Inflow of energy to ***i***-th phase due to work of external forces	$J \cdot m^{-2} \cdot s^{-1}$
c_i^n	Work of external surface forces	$J \cdot m^{-2} \cdot s^{-1}$
c_p	Specific heat capacity at constant pressure	$J \cdot kg^{-1} \cdot K^{-1}$
c_v	Specific heat capacity at constant temperature	$J \cdot kg^{-1} \cdot K^{-1}$
C	Molar concentration	$mole \cdot m^{-3}$
C	Reduced concentration of ions	$mole \cdot m^{-3}$
C	Euler constant	
C_{cr}	Critical concentration of electrolyte	$mole \cdot m^{-3}$
C_D	Resistance factor	
C_{ij}	Pair interaction factor of molecules of ***i***-th and ***j***-th components	
C_0	Initial concentration	$mole \cdot m^{-3}$
C_s	Saturation concentration of dissolved substance	$mole \cdot m^{-3}$
Ca	Capillary number	
d	Diameter of pipeline	m
d	Dimensionless parameter	
d_e	Hydraulic diameter of microchannel in porous environment medium	m
d_w	Wire diameter	m
D	Diffusion factor	$m^2 \cdot s^{-1}$
D^0	Diffusion factor of non-hindered (free) particle	$m^2 \cdot s^{-1}$
D^2	Variance distribution	m^2
D	Diameter of separator	m
D_{av}	Average diameter	m
D_{cr}	Critical diameter of drop to be broken	m
D_{br}	Factor of Brownian diffusion	$m^2 \cdot s^{-1}$
D_{eff}	Effective diffusion factor	$m^2 \cdot s^{-1}$
D_{ij}	Binary diffusion factor	$m^2 \cdot s^{-1}$
D_{max}	Maximal diameter of stable drop	m
D_{max}	Maximal drop diameter behind atomizer	m
D_{rot}	Rotation diffusion factor	s^{-1}
D_T	Turbulent diffusion factor	$m^2 \cdot s^{-1}$
Da	Damköhler number	
e	Specific internal energy	$J \cdot kg^{-1}$
E	Internal energy	J
E	Total energy	J
E	Strain rate tensor	$m \cdot s^{-2}$
E	Electric field strength	$W \cdot m^{-1}$

E	Activation energy	J·mole^{-1}
E	Dimensionless parameter	
E_{cr}	Critical strength of electric field	W·m^{-1}
E_{cyl}	Capture efficiency of particles by cylinder	
E_n	Normal component of electric field strength	W·m^{-1}
E_s	Capture efficiency of particles by sphere	
f	Friction factor	kg·s^{-1}
f	Resistance factor	
$f(W)$	Hinderness factor	
F	Stability factor	
f_i	Molar density of free energy	J·mole^{-1}
f_i	Fugacity of $\boldsymbol{i}$-th component	Pa
f_k	Dimensionless parameter of $\boldsymbol{k}$-th component of electric force of interaction between two charged particles	
$\boldsymbol{f}_k^0$	Dimensionless parameter of $\boldsymbol{k}$-th component of electric force of interaction between two far-spaced charged particles	
$\boldsymbol{f}_k^1$	Dimensionless parameter of $\boldsymbol{k}$-th component of electric force of interaction between two far-spaced charged particles, found with greater accuracy	
$\tilde{\boldsymbol{f}}_\mathrm{k}$	Dimensionless parameter of $\boldsymbol{k}$-th component of electric force of interaction between two touching charged particles	
f_{ij}	Components of friction tensor	kg·s^{-1}
f_{sr}, $f_{s\theta}$, f_{er}, $f_{e\theta}$, $f_{e\theta 1}$	Correction factors of hydrodynamic forces	
$f(D)$	Distribution of drops over diameters at jet disintegration	
$f(V)$	Breakage frequency of drop of volume V	m^{-3}·s^{-1}
$\boldsymbol{f}$	Density of mass force	N·m^{-3}
$\boldsymbol{f}$	Friction tensor	kg·s^{-1}
$\boldsymbol{f}_E$	Density of electric force	N·m^{-3}
$\boldsymbol{f}^{\boldsymbol{r}}$	Rotation friction tensor	m^2·kg·s
F	Free energy	J
F_{cap}	Capillary force	N

F_e	Electric force	N
F_{fr}	Friction force	N
F_h	Hydrodynamic force	N
F^{hyd}	Hydrodynamic force	N
F^{el}	Electric force	N
F_i	Component of i-th force	N
F^{mol}	Molecular force	N
F_n	Normal component of force	N
F_τ	Tangential component of force	N
F_{th}	Thermodynamic force	N
F_v	Viscous friction force	N
F_w	Resistance force	N
$\boldsymbol{F}$	Force	N
$\boldsymbol{F_a}$	Molecular attraction force	N
$\boldsymbol{F_\alpha^s}$	Molecular attraction force between two spherical particles	N
$\boldsymbol{F_e}$	Force induced by particle own motion	N
$\tilde{\boldsymbol{F}}_{\boldsymbol{i}}$	Electric force acting on i-th resting charged particle	N
$\boldsymbol{F_n}$	Normal to particle surface force component	
F_R^s	Electrostatic repulsion force between two spherical particles	N
$\boldsymbol{F_s}$	Stokes force	N
Fr	Froude number	
g_{eff}	Effective gravity acceleration at wave motion	m·s^{-2}
G	Free energy (Gibbs energy)	J
G	Absolute value of vorticity vector	m·s^{-2}
G	Dimensionless parameter	
G	Mass flow rate	kg·s^{-1}
G	Capture (collision) section	m^2
$G(t)$	Random force	N
Gr	Grashoff number	
h	Specific enthalpy	J·kg^{-1}
h	Half the channel height	m
h	Distance between particle centre and wall	m
h	Hydrodynamic resistance factor	kg·s^{-1}
h	Dimensionless vorticity	
h	Distance between mash layers	m
h^0	Factor of hydrodynamic resistance at motion of non-hindered (free) particle	kg·s^{-1}

h_{cr}	Critical thickness of liquid film on cylindrical string	m
h_N	Height of deposit layer	m
H	Height	m
H	Enthalpy	J
i_m	Limiting density of electric current	A
$\boldsymbol{i}$	Density of electric current	$A \cdot m^{-2}$
I	Nucleation rate in a unit volume	$m^{-3} \cdot s^{-1}$
I	Total mass flux	$mole \cdot s^{-1}$, $kg \cdot s^{-1}$
I	Electric current	A
$I(R_0)$	Correction factor for condensate growth of drop	
I_a	Rate of distribution change due to drop sedimentation	$m^{-3} \cdot s^{-1}$
I_b	Rate of distribution change due drop breakage	$m^{-3} \cdot s^{-1}$
I_D	Diffusion flux	$kg \cdot m^{-2} \cdot s^{-1}$
I_k	Rate of distribution change due to drop coagulation	$m^{-3} \cdot s^{-1}$
I_m	Rate of distribution change due to drop ablation	$m^{-3} \cdot s^{-1}$
I_n	Intensity of particle generation in a unit volume	$m^{-3} \cdot s^{-1}$
j	Mass flux through a unit surface	$kg \cdot m^{-2} \cdot s^{-1}$
j	Diffusion flux of particles	$m^{-3} \cdot s^{-1}$
j_0	Non-hindered (free) diffusion flux of particles	$m^{-3} \cdot s^{-1}$
j_{rw}	Diffusion flux of particles through a unit surface of solid angle	$m^{-2} \cdot s^{-1}$
j_s	Entropy flux through a unit surface	$J \cdot m^{-2} \cdot s^{-1}$
j_i	Individual mass flux of $\boldsymbol{i}$-th component	$kg \cdot m^{-2} \cdot s^{-1}$
j_i^*	Individual mole flux of $\boldsymbol{i}$-th component	$mole \cdot m^{-2} \cdot s^{-1}$
J	Diffusion flux of drops	s^{-1}
J	Mass flux	$kg \cdot s^{-1}$
J_0	Non-hindered (free) diffusion flux of drops	s^{-1}
J_A	Diffusion flux of drops with regard to molecular attraction force	s^{-1}
J_{A+R}	Diffusion flux of drops with regard to both molecular attraction force and electrostatic repulsion force	s^{-1}
J_{br}	Diffusion flux of drops at Brownian coagulations	s^{-1}

J_i	Moment of inertia of *i*-th particle	$kg{\cdot}m^2$
J_i	Mass flux *i*-th component	$kg{\cdot}s^{-1}$
$J_i^{(r)}$	Rate of *i*-th chemical reaction	$mole{\cdot}m^{-3}{\cdot}s^{-1}$
J_{ji}	Mass-exchange rate between *j*-th and *i*-th phases in a unit volume	$kg{\cdot}m^{-3}{\cdot}s^{-1}$
J_g	Diffusion flux of drops at gradient coagulation	s^{-1}
J_G	Gas flux from a unit surface of solution	$kg{\cdot}m^{-2}{\cdot}s^{-1}$
J_t	Diffusion flux of drops at turbulent coagulation	s^{-1}
J_i	Relative mass flux of *i*-th component	$kg{\cdot}m^{-2}{\cdot}s^{-1}$
J_i^*	Relative mole flux of *i*-th component	$mole{\cdot}m^{-2}{\cdot}s^{-1}$
J_q	Heat flux to a unit surface	$W{\cdot}m^{-2}$
J_s	Entropy flux to a unit surface	$W{\cdot}m^{-2}$
k	Heat conductivity factor	$W{\cdot}m^{-1}{\cdot}K^{-1}$
k	Specific kinetic energy	$J{\cdot}m^{-3}$
k	Permeability of porous medium	m^2
k	Wave number	m^{-1}
k_1	Equilibrium constant	
k_i	Constant of *i*-th heterogeneous reaction of v_i-th order	$mole^{1-v_i}{\cdot}m^{3v_i-2}\cdot s^{-1}$
k	Ratio of particle radiuses	
k	Adiabat constant	
k	Wetting factor	
k	Energy density	
k_T	Heat exchange factor	$W{\cdot}m^{-2}{\cdot}K^{-1}$
K	Kinetic energy	J
K	Kozeny factor	
K	Ablation factor of separator	
K	Dimensionless parameter	
$K(V,u)$	Kernel of kinetic equation (coagulation constant)	s^{-1}
K_i	Equilibrium constant of *i*-th component	
l	Characteristic linear size	m
l	Mean free path	m
l	Distance between centres of particles	m
l	Specific heat of evaporation	$J{\cdot}kg^{-1}$
l	Step of particle random walk	m
$l\times l$	Average size of mesh cell	m × m
l	Radius of capture section	m
L	Length	m
L	Characteristic linear size	m

L	Mole fraction of liquid phase	
L	Work of friction forces	J
L	Work done on a unit mass of gas	$J{\cdot}kg^{-1}$
L_0	Distance between device of preliminary condensation (DPC) and separator	m
L_B	Distance from the point of jet outflow up to the place of jet disintegration	m
L_d	Throttle length	m
L_e	Height of separation contact element	m
L_{ik}	Phenomenological factor	
L_k	Length of absorber contact zone	m
L_c	Cyclone length	m
L_D	Length of entrance concentration region	m
L_{eq}	Length of equilibrium establishment	m
L_U	Length of entrance dynamic region	m
Le	Lewis number	
m	Mass	kg
$m_{C_{k+}}$	Relative amount of extracted components of fraction C_{k+}	
m_i	Mass of i-th component	kg
m_k	Distribution moment of k-th order	m^{3k-3}
$\hat{m}_k$	The dimensionless moment of k-th order	
M	Molecular mass	$kg{\cdot}mole^{-1}$
$\bar{M}$	Average molecular mass	$kg{\cdot}mole^{-1}$
M	Mach number	
Me^{z+}	Metal cation of charge z	
n	Number of moles	
n	Numerical concentration	m^{-3}
n	Number of absorbent recirculations in separation-contact element	
$\mathbf{n}$	Vector of a normal	
$n(R, t, P)$	Distribution of drops over radiuses	m^{-4}
$n(m, t, P)$	Distribution of bubbles over mass	$kg^{-1}{\cdot}m^3$
$n(V, t, P)$	Distribution of drops over volumes	m^{-6}
$n_d(D)$	Distribution of drops over diameters behind atomizer	m^{-4}
n_i	Components of normal vector	
n_i	Number of moles of i-th component	mole
nm^3	Cubic metre of gas under normal conditions	m^3
N	Number of moles	mole

N	Numerical concentration of particles	м$^{-3}$
N	Number of mesh layers	
N	Number of plates in absorber	
N_{ad}	Adhesion parameter of cylinder	
N_{ad}^{sph}	Adhesion parameter of sphere	
N_d	Number of moles in drop	mole
N_d	Numerical concentration of drops behind atomizer	m^{-3}
N_e	Number of separation-contact elements on the plate of absorber	
N_i	Dimensionless parameter	
$N_n(x_0, t)$	Rate of bubble nucleation at depth x at moment t	s^{-1}
Nu_D	Diffusion Nusselt number	
Nu_T	Temperature Nusselt number	
Oh	Ohnesorge number	
p	Pressure	Pa
p	Parameter of electromagnetic retardation	
p_a	Atmospheric pressure	Pa
p_c	Critical pressure	Pa
p_∞	Pressure above solution surface	Pa
$p_\infty^{(eq)}$	Established pressure above solution surface	Pa
p_e	Additional pressure at wave motion of liquid	Pa
p_i	Partial pressure	Pa
p_{iv}	Partial pressure of i-th solution component vapor	Pa
p_r	Reduced pressure	
p_s	Saturation pressure	Pa
p_v	Partial pressure of vapor	Pa
p_{vt}	Partial pressure of saturated vapor above drop surface	Pa
$p_{v\infty}$	Partial pressure of saturated vapor above flat surface	Pa
p_σ	Capillary pressure	Pa
$\boldsymbol{p}$	Unit vector	
P	Point of volume	
P	Probability of particle displacement	
$P(V, \omega)$	Probability of drop formation	
$\boldsymbol{P}_{ji}$	Intensity of momentum exchange between j-th and i-th phases	kg·m^{-2}·s^{-2}
Pe_D	Diffusion Peclet number	

Pe_T	Temperature Peclet number	
Pr	Prandtl number	
q	Specific quantity of heat	$J{\cdot}kg^{-1}$
q	Electric charge	C
q	Specific heat flux	$J{\cdot}m^{-2}{\cdot}s^{-2}$
q	Dimensionless parameter	
q_a	Specific flow rate of absorbent	$10^{-3}{\cdot}kg{\cdot}m^{-3}$
q_i	Electric charge of *i*-th component	C
q_i^n	Normal component of heat flux of *i*-th component	$W{\cdot}m^{-2}$
q_s	Density of surface charge	$C{\cdot}m^{-2}$
$\mathbf{q}$	Heat flux	$W{\cdot}m^{-2}$
$\mathbf{q}_i$	Heat flux of *i*-th component	$W{\cdot}m^{-2}$
Q	Mole mass flux	$mole{\cdot}s^{-1}$
Q	Volume flow rate	$m^3{\cdot}s^{-1}$
Q	Dynamic pressure	Pa
Q	Total charge	C
Q	Heat brought to a unit mass of gas	$J{\cdot}kg^{-1}$
Q_a	Absorbent flow rate	Tonne/day
Q_{cr}	Critical gas flow rate	Mill.m^3/day
Q_G	Gas flow rate	Mill.m^3/day
Q_h	Amount of hydrocarbons extracted from gas	Tonne/day
Q_i	Specific heat released due to work of friction forces	$J{\cdot}K\Gamma^{-1}$
$\mathbf{Q}_i$	Mass flux of *i*-th component	$kg{\cdot}m{\cdot}s^{-1}$
Q_{in}	Specific heat released by condensation	$J{\cdot}m^{-3}{\cdot}s^{-1}$
Q_s	Specific heat due to heat transfer through pipe wall	$J{\cdot}kg^{-1}$
Q_w	Heat transfer from pipe wall	J
r_c	Radius of wire	m
r_i	Rate of mass formation of *i*-th component in a unit volume	$kg{\cdot}m^{-3}{\cdot}s^{-1}$
R_{av}	Average drop radius	m
R_{av}^0	Initial average radius of drop	m
R_c	Coagulation radius	m
R_c	Radius of cyclone	m
R_{cr}	Critical radius	m
R_i	Factors of resistance (components of resistance tensor) along principal axes of ellipsoid	m
R_i	Radius of *i*-th particles	m
R_{ij}	Components of resistance tensor	m

$R_i^{(s)}$	Specific mole rate of heterogeneous chemical reaction with formation of *i*-th component	mole·m^{-2}·s^{-1}
$R_i^{(v)}$	Specific mole rate of homogeneous chemical reaction with formation of *i*-th component	mole·m^{-2}·s^{-1}
R_m	Minimal radius of drops	m
R_{ms}	Minimal radius of drops settling with Stokesian velocity	m
R_s	Impede factor of membrane	
R_z	Radius of cell	m
Re	Reynolds number	
R	Dimensionless radius of cylinder capture section	
$\boldsymbol{R}$	Resistance tensor (Translation tensor)	m
s	Specific entropy	J·kg^{-1} K^{-1}
s	Specific surface	m^{-1}
s	Relative distance between particles	
s	Sedimentation factor	s
s	Random displacement	m
s	Supersaturation degree	
s_{cr}	Critical supersaturation degree	
S	Entropy	J·K^{-1}
S	Area	m^2
S	Surface	
S	Stokes number	
S	Spread factor	N·m^{-1}
S_A	Parameter of molecular interaction	
S_{av}	Average area of interface	m^2
S$_{cr}$	Critical Stokes number	
S_E	Parameter of electrohydrodynamic interaction	
S_f	Total area of microchannel sections	m^2
S_i	Dimensionless parameter	
S_m	Dimensionless parameter	
S$_m$	Minimal Stokes number	
S_R	Parameter of electrostatic interaction	
Sc	Shmidt number	
St	Strouhal number	
t	Time	s
t_b	Absorbent residence time on absorber plate	s
t_{br}	Characteristic time of Brownian coagulations	s

t_e	Residence time in separation-contact element	s
t_{ik}	Maxwell stress tensor	N·m^{-2}
t_{in}	Characteristic time of inertial coagulation	s
t_k	Characteristic time of drop coagulation (coalescence)	s
$\bar{t}_l$	Average life time of drops in turbulent flow	s
t_m	Characteristic time of drops mass exchange with gas	s
t_{mono}	Characteristic time of coagulation (coalescence) in monodisperse emulsion	s
t_{poly}	Characteristic time of drop coagulation (coalescence) in polydisperse emulsion	s
t_r	Time of drop relaxation in turbulent flow	m·s^{-1}
t_t	Characteristic time of drop turbulent coagulation	s
t_v	Characteristic time of velocity profile development in channel	s
$t_{s\varphi}$, $t_{e\varphi}$, $t_{e\varphi 1}$	Correction factors for hydrodynamic moments	
$\boldsymbol{t}$	Stress	N·m^{-2}
T	Absolute temperature	K
T	Characteristic time	s
T	Period of turbulent pulsations	s
T_G	Temperature of gas	K
T_L	Temperature of liquid	K
T_c	Critical temperature	K
$T_{cr}^{(k)}$	Temperature of condensation beginning	K
T_r	Reduced temperature	
T_t	Temperature of dew-point	K
$\boldsymbol{T}_e$	Moment caused by particle own motion	N·m
$\boldsymbol{T}_s$	Moment caused by Stokesion flow around particle	N·m
$\boldsymbol{T}$	Stress tensor	N·m^{-2}
$\boldsymbol{T}$	Moment vector	N·m
u	Velocity component	m·s^{-1}
u_{cr}	Critical velocity	m·s^{-1}

u_d	Dynamic velocity of gas	$m \cdot s^{-1}$
u_s	Stokesian velocity	$m \cdot s^{-1}$
u_s	Velocity of particle cross drift in turbulent flow	$m \cdot s^{-1}$
$\bar{u}$	Average velocity	$m \cdot s^{-1}$
u_e	Gas velocity in separation-contact element	$m \cdot s^{-1}$
u_i^n	Normal velocity component of ***i***-th phase	$m \cdot s^{-1}$
u_m	Drop velocity near the wall in turbulent flow	$m \cdot s^{-1}$
u_{max}	Maximal velocity	$m \cdot s^{-1}$
u_λ	Velocity of turbulent pulsation of scale λ	$m \cdot s^{-1}$
$\boldsymbol{u}$	Velocity vector, mean-flow-rate velocity vector	$m \cdot s^{-1}$
$\boldsymbol{u}^*$	Mean-mole velocity vector	$m \cdot s^{-1}$
$\boldsymbol{u}_{st}$	Stokesian velocity	$m \cdot s^{-1}$
$\boldsymbol{u}_{sh}$	Velocity of shear flow	$m \cdot s^{-1}$
U	Characteristic velocity	$m \cdot s^{-1}$
U_e	Rate of filtration through porous medium	$m \cdot s^{-1}$
U_G	Velocity of motion of interface border	$m \cdot s^{-1}$
U_s	Sedimentation velocity	$m \cdot s^{-1}$
v	Velocity component	$m \cdot s^{-1}$
v	Specific volume	$m^3\ kg^{-1}$
v	Dimensionless velocity	
$\boldsymbol{v}_i$	Mobility of particles of ***i***-th solution component	$mole \cdot s \cdot kg^{-1}$
v_i	Mobility factor of a body along ***i***-th principal axis	$s \cdot kg^{-1}$
v_φ	Tangential component of velocity in cyclone	$m \cdot s^{-1}$
v_z	Longitudinal component of velocity in cyclone	$m \cdot s^{-1}$
V	Volume	m^3
V	Mole fraction of gas phase	
V	Electromotive force (emf)	V
V	Total potential energy of interaction between two particles	J
$\boldsymbol{V}$	Mobility tensor	$s \cdot kg^{-1}$
V_A^S	Potential of molecular attraction force between two spherical particles	J
V_A^P	Potential of molecular attraction force between two infinite parallel planes	$J \cdot m^{-2}$

V_{av}	Average volume of drops	m^3
V_{cr}	Critical volume	m^3
V_d	Volume of drop	m^3
V_e	Volume of eluent	m^3
V_i	Mole concentration of *i*-th component	$mole{\cdot}m^{-3}$
V_i	Potential of *i*-th particle surface	J
V_k	Volume of germ	m^3
V_{mol}	Volume of molecule	m^3
V_R^S	Potential of electrostatic repulsion force between two particles	J
V_t	Volume of particle	m^3
V_v	Volume of voids between particles of permeable medium	m^3
w	Velocity component	$m{\cdot}s^{-1}$
w	Specific work	$J{\cdot}kg^{-1}$
$\boldsymbol{w_i}$	Velocity of *i*-th phase relative medium as a whole	$m{\cdot}s^{-1}$
W	Volume concentration (volume content)	m^3/m^3
W	Work of drop done on the change of volume in a unit time	W
W	Energy of one mole	J
W	Stability factor	
W_0	Volume concentration of drops at the entrance of separator	m^3/m^3
W_1	Volume concentration of drops at the exit of separator	m^3/m^3
We	Weber number	
We_{cr}	Critical Weber number	
x_{cr}	Critical distance from top end of the string up to the point of liquid film detachment	m
x_i	Mole fraction of *i*-th component of liquid phase	
x_{Ir}	Mole fraction of hydrate inhibitore in solution	
x_M	Mole fraction of methanol in hydrate inhibitore	
x_{wr}	Mole fraction of water in solution	
$\boldsymbol{x}$	Radius-vector of point $P(x, y, z)$	
X	Thermodynamic force	
X_L	Length at which the flowing jet reaches wall	m
X^{z-}	Anion with charge z	

y_i	Mole fraction of ***i***-th gas phase component	
y_M	Mole fraction of methanol vapor in gas	
z	Compressibility of gas	
Z	Dimensionless parameter	
z_m	Dimensionless minimal radius	
z_i	Charge of ion of ***i***-th component	
α	Thermal diffusivity	$m^2 \cdot s^{-1}$
α	Thermal expansion factor	K^{-1}
α	Heat exchange factor	$W \cdot m^{-2} \cdot K^{-1}$
α	Dimensionless parameter	
α	Effective section	
α	Condensation factor	
α	Correction multiplier on microchannel curvature of porous medium	
α	Mass fraction of glycol in absorbent solution	
α	Slope of inclined wall	
β	Volume expansion factor	$Pa^{-1} \cdot s^{-1}$
β	Dimensionless parameter	
β	Coalescence parameter	s^{-1}
β	Design parameter of atomizer	
β_1	Asymmetry square of distribution	
β_2	Excess of distribution	
β_{ij}	Collisions frequency of particles ***i*** and ***j***	s^{-1}
γ	Activity factor	
γ	Dimensionless parameter of repulsion force energy	
γ_I	Activity factor of inhibitor	
γ_w	Activity factor of water	
γ_φ	Dimensionless parameter of cyclone	
$\dot{\gamma}$	Shear rate	s^{-1}
$\bar{\dot{\gamma}}$	Dimensionless shear rate	
Γ	Hamaker constant	J
Γ	Surface concentration of surfactant	$mole \cdot m^{-2}$
Γ_∞	Limiting surface concentration of surfactant	$mole \cdot m^{-2}$
δ	Thickness of gap between two spherical particles	m
δ	Thickness of a boundary layer	m
δ_v	Thickness of viscous boundary layer	m
δ_f	Thickness of liquid film	m

δ_D	Thickness of diffusion boundary layer	m
Δ	Dimensionless thickness of gap between two spherical particles	
Δ_i	Dimensionless parameter	
Δ_k	Capillary length	m
Δy_i	Difference between mole fractions of *i*-th component at the interface and in gas bulk flow	
$\Delta\rho$	Difference of densities of bordering phases	$kg{\cdot}m^{-3}$
$\Delta\varphi_{om}$	Ohmic drop of potential	B
ε	Dielectric permittivity	$C{\cdot}V^{-1}{\cdot}m^{-1}$
ε	Void fraction of porous medium (porosity)	
ε	Dimensionless parameter	
ε_0	Dielectric permittivity in vacuum	$C{\cdot}V^{-1}{\cdot}m^{-1}$
ε_0	Specific energy dissipation of turbulent flow	$J{\cdot}kg^{-1}{\cdot}s^{-1}$
ε_{cr}	Critical specific energy dissipation of turbulent flow	$J{\cdot}kg^{-1}{\cdot}s^{-1}$
ε_r	Relative dielectric permittivity	
ε_{ij}	Components of strain rate tensor	$m{\cdot}s^{-2}$
ε_v	Void fraction of mesh layer	
ζ	ζ-potential	V
ζ	Vertical perturbation of interface	m
ζ	Dimensionless variable	
η	Dimensionless variable	
η	Separation efficiency, coefficient of effectiveness (CE)	
η_f	Capture efficiency of filter	
η_G	Effectiveness coefficient of mesh droplet capture	
η_h	Effectiveness coefficient of horizontal separator	
η_i	Mole fraction of *i*-th component	
η_k	Effectiveness coefficient of horizontal separator with regard to coagulation of drops	
η_s	Effectiveness coefficient of separator with string droplet capture	
η_t	Dehydration factor	
η_v	Effectiveness coefficient of vertical separator	
η_z	Effectiveness coefficient of cyclone	
Θ	Velocity divergence	

θ	Fraction of surface occupied by molecules of adsorbed substance	
θ	Dimensionless temperature	
λ	Heat conductivity factor	$W \cdot m^{-1} \cdot K^{-1}$
λ	Particle resistance factor	
λ	Scale of turbulent pulsation	m
λ	Ablation factor	
λ	Wave length	m
λ	Correction to minimal radius of drop on condensation growth of drops	
λ_0	Inner scale of turbulence	m
λ_D	Thickness of electric double layer	m
λ_G	Heat conductivity factor of gas	$W \cdot m^{-1} \cdot K^{-1}$
λ_h	Ablation factor of horizontal separator or settler	
λ_v	Ablation factor of vertical separator or settler	
λ_L	London wave length	Å
Λ	Mole conductivity	$S \cdot m^2 \cdot mole^{-1}$
Λ	Dimensionless parameter	
μ	Dynamic viscosity factor	Pa·c
μ	Chemical potential	$J \cdot mole^{-1}$ or $J \cdot kg^{-1}$
$\mu_i^{(0)}$	Chemical potential of pure *i*-th component	$J \cdot mole^{-1}$
$\bar{\mu}$	Ratio of viscosities of internal and external liquids	
ν	Kinematic viscosity factor	$m^2 \cdot s^{-1}$
ν	Stoichiometric factor	
ν_{ki}	Stoichiometric factor of *k*-th component in *j*-th reaction	
ν_+, ν_-	Number of ions	
ξ	Degree of completeness of reaction	$mole \cdot m^{-3}$
ξ	Dimensionless variable, dimensionless parameter	
ξ_i	Dimensionless parameter	
Ξ	Osmotic factor	
π	Pressure drop in reverse osmosis	Pa
π	Dimensionless parameter	
π_0	Osmotic pressure	Pa
Π_i	Mass percentage of *i*-th component	
$\mathbf{\Pi}$	Viscous stress tensor	$N \cdot m^{-2}$
χ	Debye reverse radius	m^{-1}
χ	Dimensionless parameter	
χ	Ratio of drop charges	