

*Emmanuel G. Sinaiski and Eugeniγ J. Lapiga*

## **Separation of Multiphase, Multicomponent Systems**



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*Emmanuil G. Sinaiski*  
*and Eugeny J. Lapiga*  
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Multicomponent Systems**

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#### Cover

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 (reverse osmosis), and mass exchange of particles, drops, and bubbles with the ambient media. For charged solutions, consideration is given to processes in electrolytic cells, electro dialysis, the structure of electrical double layers, electrokinetic phenomena, and electroosmosis.

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. Chap-

ter 8 (devoted to non-charged suspensions) provides an introduction to the microhydrodynamics 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	$\text{m}\cdot\text{s}^{-1}$
$a_i$	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)	$\text{m}^{-1}$
$a_t$	Radius of particle	m
$A$	Dimensionless parameter	
$A^*$	Reduced gas constant	$\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
$A_{cyl}$	Parameter of stream function at flow around cylinder	
$A_i$	Chemical affinity of reaction	$\text{J}\cdot\text{mole}^{-1}$
$A_i$	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 $\nu$ -th order	$\text{mole}^{1-\nu}\cdot\text{m}^{3\nu-2}\cdot\text{s}^{-1}$
$B_i$	Henry constant of $i$ -th component	Pa
$Bo$	Bond number	
$c$	Specific heat capacity	$\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
$c$	Wave velocity	$\text{m}\cdot\text{s}^{-1}$

$c_{cap}$	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	$\text{J}\cdot\text{mole}^{-1}$
$E$	Dimensionless parameter	
$E_{cr}$	Critical strength of electric field	$\text{W}\cdot\text{m}^{-1}$
$E_{cyl}$	Capture efficiency of particles by cylinder	
$E_n$	Normal component of electric field strength	$\text{W}\cdot\text{m}^{-1}$
$E_s$	Capture efficiency of particles by sphere	
$f$	Friction factor	$\text{kg}\cdot\text{s}^{-1}$
$f$	Resistance factor	
$f(W)$	Hinderness factor	
$F$	Stability factor	
$f_i$	Molar density of free energy	$\text{J}\cdot\text{mole}^{-1}$
$f_i$	Fugacity of $i$ -th component	Pa
$f_k$	Dimensionless parameter of $k$ -th component of electric force of interaction between two charged particles	
$f_k^0$	Dimensionless parameter of $k$ -th component of electric force of interaction between two far-spaced charged particles	
$f_k^1$	Dimensionless parameter of $k$ -th component of electric force of interaction between two far-spaced charged particles, found with greater accuracy	
$\tilde{f}_k$	Dimensionless parameter of $k$ -th component of electric force of interaction between two touching charged particles	
$f_{ij}$	Components of friction tensor	$\text{kg}\cdot\text{s}^{-1}$
$f_{sr}, f_{s0}, f_{er}, f_{e0}, f_{e01}$	Correction factors of hydrodynamic forces	
$f(D)$	Distribution of drops over diameters at jet disintegration	
$f(V)$	Breakage frequency of drop of volume $V$	$\text{m}^{-3}\cdot\text{s}^{-1}$
$f$	Density of mass force	$\text{N}\cdot\text{m}^{-3}$
$f$	Friction tensor	$\text{kg}\cdot\text{s}^{-1}$
$f_E$	Density of electric force	$\text{N}\cdot\text{m}^{-3}$
$f^r$	Rotation friction tensor	$\text{m}^2\cdot\text{kg}\cdot\text{s}$
$F$	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
$F_\tau$	Tangential component of force	N
$F_{th}$	Thermodynamic force	N
$F_v$	Viscous friction force	N
$F_w$	Resistance force	N
$\mathbf{F}$	Force	N
$\mathbf{F}_a$	Molecular attraction force	N
$\mathbf{F}_\alpha^s$	Molecular attraction force between two spherical particles	N
$\mathbf{F}_e$	Force induced by particle own motion	N
$\tilde{\mathbf{F}}_i$	Electric force acting on $i$ -th resting charged particle	N
$\mathbf{F}_n$	Normal to particle surface force component	
$F_R^s$	Electrostatic repulsion force between two spherical particles	N
$\mathbf{F}_s$	Stokes force	N
Fr	Froude number	
$g_{eff}$	Effective gravity acceleration at wave motion	$m \cdot s^{-2}$
$G$	Free energy (Gibbs energy)	J
$G$	Absolute value of vorticity vector	$m \cdot s^{-2}$
$G$	Dimensionless parameter	
$G$	Mass flow rate	$kg \cdot s^{-1}$
$G$	Capture (collision) section	$m^2$
$G(t)$	Random force	N
Gr	Grashoff number	
$h$	Specific enthalpy	$J \cdot kg^{-1}$
$h$	Half the channel height	m
$h$	Distance between particle centre and wall	m
$h$	Hydrodynamic resistance factor	$kg \cdot s^{-1}$
$h$	Dimensionless vorticity	
$h$	Distance between mash layers	m
$h^0$	Factor of hydrodynamic resistance at motion of non-hindered (free) particle	$kg \cdot s^{-1}$

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

$L$	Mole fraction of liquid phase	
$L$	Work of friction forces	J
$L$	Work done on a unit mass of gas	$\text{J}\cdot\text{kg}^{-1}$
$L_0$	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	$\text{m}^{3k-3}$
$\hat{m}_k$	The dimensionless moment of $k$ -th order	
$M$	Molecular mass	$\text{kg}\cdot\text{mole}^{-1}$
$\bar{M}$	Average molecular mass	$\text{kg}\cdot\text{mole}^{-1}$
$M$	Mach number	
$Me^{z+}$	Metal cation of charge $z$	
$n$	Number of moles	
$n$	Numerical concentration	$\text{m}^{-3}$
$n$	Number of absorbent recirculations in separation-contact element	
$\mathbf{n}$	Vector of a normal	
$n(R, t, P)$	Distribution of drops over radiuses	$\text{m}^{-4}$
$n(m, t, P)$	Distribution of bubbles over mass	$\text{kg}^{-1}\cdot\text{m}^3$
$n(V, t, P)$	Distribution of drops over volumes	$\text{m}^{-6}$
$n_d(D)$	Distribution of drops over diameters behind atomizer	$\text{m}^{-4}$
$n_i$	Components of normal vector	
$n_i$	Number of moles of $i$ -th component	mole
$nm^3$	Cubic metre of gas under normal conditions	$\text{m}^3$
$N$	Number of moles	mole

$N$	Numerical concentration of particles	$\text{m}^{-3}$
$N$	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	$\text{m}^{-3}$
$N_e$	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 $t$	$\text{s}^{-1}$
$Nu_D$	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
$p_\infty$	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
$p_\sigma$	Capillary pressure	Pa
$\mathbf{p}$	Unit vector	
$P$	Point of volume	
$P$	Probability of particle displacement	
$P(V, \omega)$	Probability of drop formation	
$\mathbf{P}_{ji}$	Intensity of momentum exchange between $j$ -th and $i$ -th phases	$\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-2}$
$Pe_D$	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	$C \cdot m^{-2}$
$q$	Heat flux	$W \cdot m^{-2}$
$q_i$	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	$J \cdot K \Gamma^{-1}$
$Q_i$	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	$\text{mole}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$
$R_i^{(v)}$	Specific mole rate of homogeneous chemical reaction with formation of $i$ -th component	$\text{mole}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$
$R_m$	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	
$\mathbf{R}$	Resistance tensor (Translation tensor)	m
$s$	Specific entropy	$\text{J}\cdot\text{kg}^{-1}\text{K}^{-1}$
$s$	Specific surface	$\text{m}^{-1}$
$s$	Relative distance between particles	
$s$	Sedimentation factor	s
$s$	Random displacement	m
$s$	Supersaturation degree	
$s_{cr}$	Critical supersaturation degree	
$S$	Entropy	$\text{J}\cdot\text{K}^{-1}$
$S$	Area	$\text{m}^2$
$S$	Surface	
$S$	Stokes number	
$S$	Spread factor	$\text{N}\cdot\text{m}^{-1}$
$S_A$	Parameter of molecular interaction	
$S_{av}$	Average area of interface	$\text{m}^2$
$S_{cr}$	Critical Stokes number	
$S_E$	Parameter of electrohydrodynamic interaction	
$S_f$	Total area of microchannel sections	$\text{m}^2$
$S_i$	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	$\text{N}\cdot\text{m}^{-2}$
$t_{in}$	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	$\text{m}\cdot\text{s}^{-1}$
$t_t$	Characteristic time of drop turbulent coagulation	s
$t_v$	Characteristic time of velocity profile development in channel	s
$t_{s\phi}, t_{e\phi}, t_{e\phi 1}$	Correction factors for hydrodynamic moments	
$\mathbf{t}$	Stress	$\text{N}\cdot\text{m}^{-2}$
$T$	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
$\mathbf{T}_e$	Moment caused by particle own motion	$\text{N}\cdot\text{m}$
$\mathbf{T}_s$	Moment caused by Stokesion flow around particle	$\text{N}\cdot\text{m}$
$\mathbf{T}$	Stress tensor	$\text{N}\cdot\text{m}^{-2}$
$\mathbf{T}$	Moment vector	$\text{N}\cdot\text{m}$
$u$	Velocity component	$\text{m}\cdot\text{s}^{-1}$
$u_{cr}$	Critical velocity	$\text{m}\cdot\text{s}^{-1}$

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

$V_{av}$	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	$\text{mole}\cdot\text{m}^{-3}$
$V_i$	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	$\text{m}\cdot\text{s}^{-1}$
$w$	Specific work	$\text{J}\cdot\text{kg}^{-1}$
$w_i$	Velocity of $i$ -th phase relative medium as a whole	$\text{m}\cdot\text{s}^{-1}$
$W$	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 inhibitor in solution	
$x_M$	Mole fraction of methanol in hydrate inhibitor	
$x_{wr}$	Mole fraction of water in solution	
$\mathbf{x}$	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 $z$	

$\gamma_i$	Mole fraction of $i$ -th gas phase component	
$\gamma_M$	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	
$\alpha$	Thermal diffusivity	$\text{m}^2 \cdot \text{s}^{-1}$
$\alpha$	Thermal expansion factor	$\text{K}^{-1}$
$\alpha$	Heat exchange factor	$\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$
$\alpha$	Dimensionless parameter	
$\alpha$	Effective section	
$\alpha$	Condensation factor	
$\alpha$	Correction multiplier on microchannel curvature of porous medium	
$\alpha$	Mass fraction of glycol in absorbent solution	
$\alpha$	Slope of inclined wall	
$\beta$	Volume expansion factor	$\text{Pa}^{-1} \cdot \text{s}^{-1}$
$\beta$	Dimensionless parameter	
$\beta$	Coalescence parameter	$\text{s}^{-1}$
$\beta$	Design parameter of atomizer	
$\beta_1$	Asymmetry square of distribution	
$\beta_2$	Excess of distribution	
$\beta_{ij}$	Collisions frequency of particles $i$ and $j$	$\text{s}^{-1}$
$\gamma$	Activity factor	
$\gamma$	Dimensionless parameter of repulsion force energy	
$\gamma_1$	Activity factor of inhibitor	
$\gamma_w$	Activity factor of water	
$\gamma_\varphi$	Dimensionless parameter of cyclone	
$\dot{\gamma}$	Shear rate	$\text{s}^{-1}$
$\bar{\gamma}$	Dimensionless shear rate	
$\Gamma$	Hamaker constant	J
$\Gamma$	Surface concentration of surfactant	$\text{mole} \cdot \text{m}^{-2}$
$\Gamma_\infty$	Limiting surface concentration of surfactant	$\text{mole} \cdot \text{m}^{-2}$
$\delta$	Thickness of gap between two spherical particles	m
$\delta$	Thickness of a boundary layer	m
$\delta_v$	Thickness of viscous boundary layer	m
$\delta_f$	Thickness of liquid film	m

$\delta_D$	Thickness of diffusion boundary layer	m
$\Delta$	Dimensionless thickness of gap between two spherical particles	
$\Delta_i$	Dimensionless parameter	
$\Delta_k$	Capillary length	m
$\Delta y_i$	Difference between mole fractions of $i$ -th component at the interface and in gas bulk flow	
$\Delta\rho$	Difference of densities of bordering phases	$\text{kg}\cdot\text{m}^{-3}$
$\Delta\varphi_{om}$	Ohmic drop of potential	B
$\varepsilon$	Dielectric permittivity	$\text{C}\cdot\text{V}^{-1}\cdot\text{m}^{-1}$
$\varepsilon$	Void fraction of porous medium (porosity)	
$\varepsilon$	Dimensionless parameter	
$\varepsilon_0$	Dielectric permittivity in vacuum	$\text{C}\cdot\text{V}^{-1}\cdot\text{m}^{-1}$
$\varepsilon_0$	Specific energy dissipation of turbulent flow	$\text{J}\cdot\text{kg}^{-1}\cdot\text{s}^{-1}$
$\varepsilon_{cr}$	Critical specific energy dissipation of turbulent flow	$\text{J}\cdot\text{kg}^{-1}\cdot\text{s}^{-1}$
$\varepsilon_r$	Relative dielectric permittivity	
$\varepsilon_{ij}$	Components of strain rate tensor	$\text{m}\cdot\text{s}^{-2}$
$\varepsilon_v$	Void fraction of mesh layer	
$\zeta$	$\zeta$ -potential	V
$\zeta$	Vertical perturbation of interface	m
$\zeta$	Dimensionless variable	
$\eta$	Dimensionless variable	
$\eta$	Separation efficiency, coefficient of effectiveness (CE)	
$\eta_f$	Capture efficiency of filter	
$\eta_G$	Effectiveness coefficient of mesh droplet capture	
$\eta_h$	Effectiveness coefficient of horizontal separator	
$\eta_i$	Mole fraction of $i$ -th component	
$\eta_k$	Effectiveness coefficient of horizontal separator with regard to coagulation of drops	
$\eta_s$	Effectiveness coefficient of separator with string droplet capture	
$\eta_t$	Dehydration factor	
$\eta_v$	Effectiveness coefficient of vertical separator	
$\eta_z$	Effectiveness coefficient of cyclone	
$\Theta$	Velocity divergence	

$\theta$	Fraction of surface occupied by molecules of adsorbed substance	
$\theta$	Dimensionless temperature	
$\lambda$	Heat conductivity factor	$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
$\lambda$	Particle resistance factor	
$\lambda$	Scale of turbulent pulsation	m
$\lambda$	Ablation factor	
$\lambda$	Wave length	m
$\lambda$	Correction to minimal radius of drop on condensation growth of drops	
$\lambda_0$	Inner scale of turbulence	m
$\lambda_D$	Thickness of electric double layer	m
$\lambda_G$	Heat conductivity factor of gas	$\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
$\lambda_h$	Ablation factor of horizontal separator or settler	
$\lambda_v$	Ablation factor of vertical separator or settler	
$\lambda_L$	London wave length	$\text{\AA}$
$\Lambda$	Mole conductivity	$\text{S}\cdot\text{m}^2\cdot\text{mole}^{-1}$
$\Lambda$	Dimensionless parameter	
$\mu$	Dynamic viscosity factor	Pa·c
$\mu$	Chemical potential	$\text{J}\cdot\text{mole}^{-1}$ or $\text{J}\cdot\text{kg}^{-1}$
$\mu_i^{(0)}$	Chemical potential of pure $i$ -th component	$\text{J}\cdot\text{mole}^{-1}$
$\bar{\mu}$	Ratio of viscosities of internal and external liquids	
$\nu$	Kinematic viscosity factor	$\text{m}^2\cdot\text{s}^{-1}$
$\nu$	Stoichiometric factor	
$\nu_{ki}$	Stoichiometric factor of $k$ -th component in $j$ -th reaction	
$\nu_+, \nu_-$	Number of ions	
$\xi$	Degree of completeness of reaction	$\text{mole}\cdot\text{m}^{-3}$
$\xi$	Dimensionless variable, dimensionless parameter	
$\xi_i$	Dimensionless parameter	
$\Xi$	Osmotic factor	
$\pi$	Pressure drop in reverse osmosis	Pa
$\pi$	Dimensionless parameter	
$\pi_0$	Osmotic pressure	Pa
$\Pi_i$	Mass percentage of $i$ -th component	
$\Pi$	Viscous stress tensor	$\text{N}\cdot\text{m}^{-2}$
$\chi$	Debye reverse radius	$\text{m}^{-1}$
$\chi$	Dimensionless parameter	
$\chi$	Ratio of drop charges	