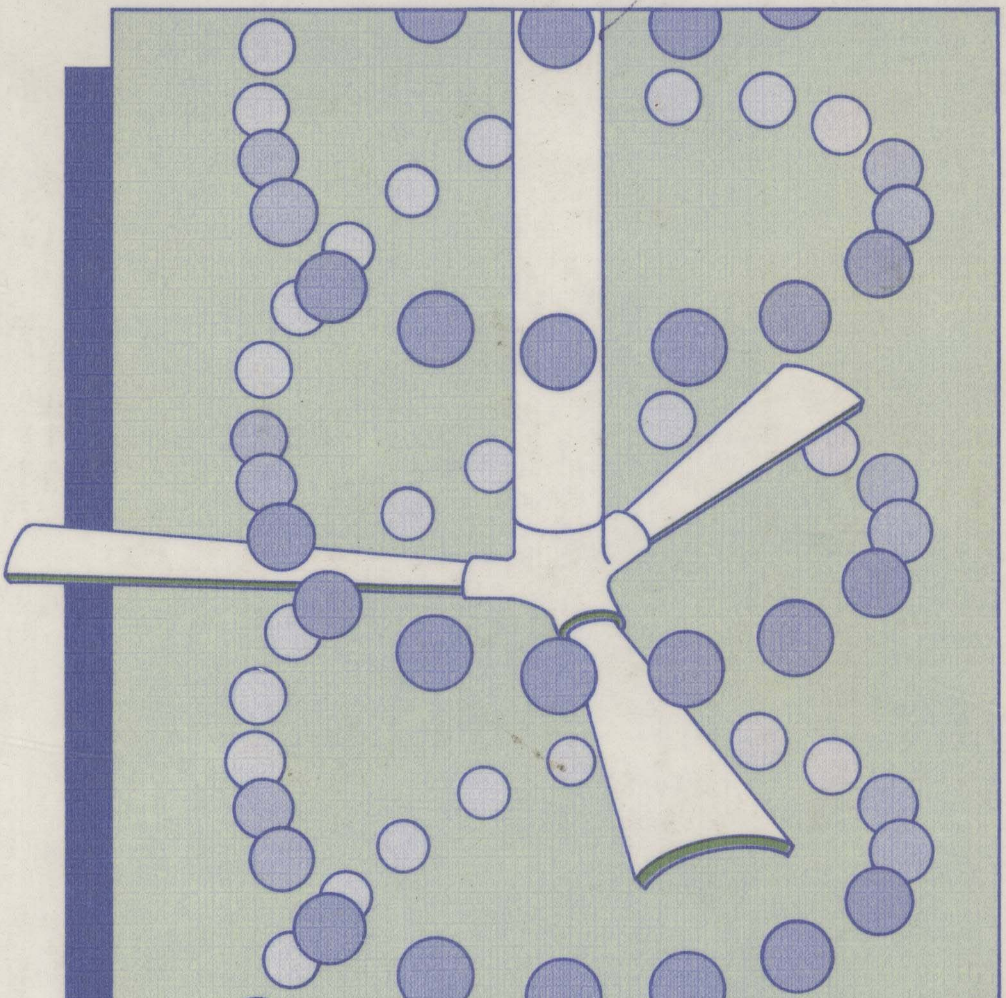
Mixing 8



Eighth European Conference on

Mixing

Institution of Chemical Engineers, Rugby, UK

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A three–day symposium organised by the Institution of Chemical Engineers and the Fluid Mixing Subject Group on behalf of the Working Party on Mixing of the European Federation of Chemical Engineers (EFCE) and held at the University of Cambridge, 21–23 September 1994.

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Preface

In September 1974 the first of the European Mixing Conferences was organised by BHRA and held in Churchill College, here in Cambridge. We mark the twentieth anniversary by returning for the Eighth Conference in a series that is now recognised as a prime forum for the reporting of progress in this field, with the published Proceedings having a valued reputation as a source of frequently cited articles that is available worldwide.

On that first occasion just eighteen papers were presented — the organisers had also included centrifugal separation in the programme since there was some concern that mixing alone would not attract enough interest. Twenty years on one of the most difficult tasks in arranging the Conference has been to select from the flood of work offered. The range of the interests of individual participants is so wide that Parallel Lecture Sessions would have been a much less satisfactory format that the extended Poster Presentations we have chosen. Although this has inevitably brought disappointment to some would-be lecturers, and indeed difficulties of funding for others, we hope that the greater opportunities for personal contact will be valued and that as oral and poster presentations receive the same treatment in the Proceedings this will reassure participants of the value placed on their contributions.

Mixing has always been an interdisciplinary subject with applications ranging from microprocesses to atmospheric circulation. It has traditionally been regarded as an empirical technology. Practical difficulties were often associated with the engineering aspects of power transmission and there was frequently little understanding of mixing process requirements. With the refining of objectives a more fundamental view has emerged. The Conference Programme reflects the familiarity that today's mixing technologists are likely to have with theories of turbulence, their realisation of the importance of scale in mixing processes, consciousness of the complications that can arise in multiphase systems and the wide current awareness of the potential — and sometimes limitations — of computational fluid mechanics.

I would like to express on behalf of my colleagues on the Organising Committee our gratitude to the European Federation of Chemical Engineers Working Party on Fluid Mixing for allowing the IChemE, in association with the Fluid Mixing Subject Group of the Institution, to organise this Conference, to the authors for offering their work for presentation on this occasion and to both Corresponding Members and Members of the Programme Committee for the work that has been done in preparing the event.

John M. Smith
(Chairman)

Recommended Standard Terminology and Nomenclature for Mixing

This nomenclature is split into the following sections:

- General terms;
- Geometry;
- Fluid properties;
- Dynamics;
- Statistics and measures of mixing;
- Dimensionless groups;
- Subscripts and superscripts;
- Symbols.

Each section contains a glossary of terms and definitions followed by an alphabetical list of recommended symbols. Common usage is followed wherever possible, whilst duplication of symbols is minimized.

General terms

Laminar mixing — reduction of scale of segregation or striation thickness (see below) by laminar flow deformation (cutting, folding, shearing and stretching) with no turbulence or random motion.

Turbulent mixing — reduction of scale of segregation (see below) by random turbulent motion.

Micro-mixing — mixing on a scale smaller than the minimum eddy size, or minimum striation thickness (see below) by molecular diffusion.

Macro-mixing — mixing on a scale greater than the minimum eddy size or minimum striation thickness, by laminar or turbulent motion.

Minimum eddy size — length scale below which molecular diffusion is more significant than mixing by turbulent eddies.

Striation thickness — average distance between adjacent interfaces of materials to be mixed by a laminar mechanism.

Blending — mixing of miscible liquids (of different densities, viscosities, etc).

Dispersion — an immiscible phase (gas, liquid or solid) distributed throughout a fluid in the form of small bubbles, droplets or particles.

Suspension or slurry — a dispersion in liquid of solid particles which may or may not settle out in the absence of agitation or flow.

Paste — a non-Newtonian dispersion of solid particles in high concentration in a liquid.

Froth — a dispersion of gas bubbles in liquid which separates in the absence of agitation and bubble generation.

Foam — a dispersion of gas bubbles in liquid with high volume fraction of gas, which remains stable for a prolonged period in the absence of agitation and bubble generation.

Geometry

Agitator — a rotating mixing element in a vessel (generally mounted on central, axial shaft).

Anchor — an agitator with vertical blades contoured to the shape of the vessel, with close clearance from the wall (see Figure 11).

Angled agitator — agitator with shaft angled to the vessel axis.

Attritor — stirred bead mill.

Baffle — vertical plate, etc, arranged in a vessel to prevent gross liquid swirl and surface vortexing (see Figure 1).

Ball mill — rotating drum containing heavy balls (or rods) falling on material to mix and grind it (for powder/liquid) (Figure 6).

Bead mill — vessel containing beads to transmit force to dispersion (powder/liquid) (Figure 10).

Calander — machine for mixing between rolls.

Clearance — gap between anchor blade or ribbon and vessel wall; or distance between propeller, turbine or paddle centre line (at agitator axis) and vessel bottom.

Concave blade — agitator blade curved in vertical plane, concave to flow (Figure 1).

Convex blade — agitator blade curved in vertical plane, convex to flow.

Disc turbine — turbine with blades (flat, pitched, concave, etc) mounted around disc, projecting above and below disc, and not extending to axis (Figure 14).

Disperser — high speed rotating disc, often with sawtooth rim (for dispersing powder in liquid for creating emulsions, etc).

Draught tube — vertical tube, $D <$ tube diameter $< T$, mounted concentric with agitator to promote circulation (usually with propeller or screw).

Emulsifier — high energy device using flow energy, ultrasonics, etc, to create fine dispersions.

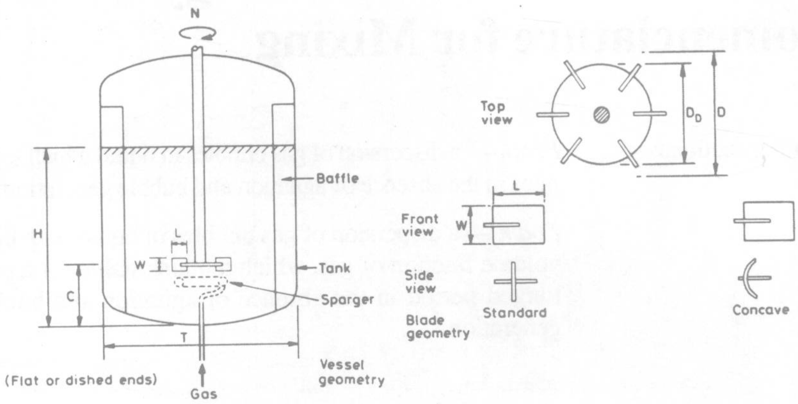

Figure 1—*Vessel geometry*

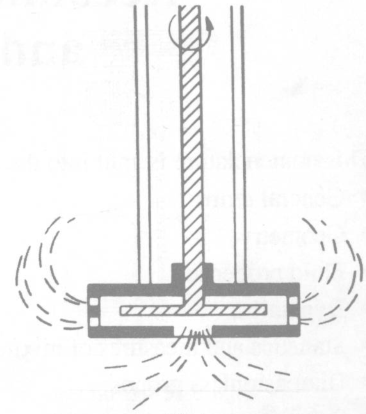

Figure 2—*High-shear mixer*

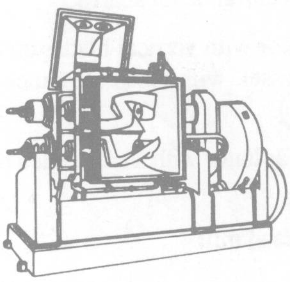

Figure 3—*Double-arm z-blade mixer*

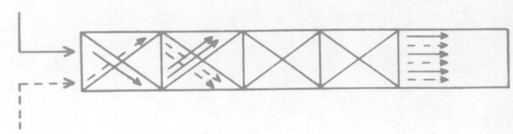

Figure 4—*In-line mixer*

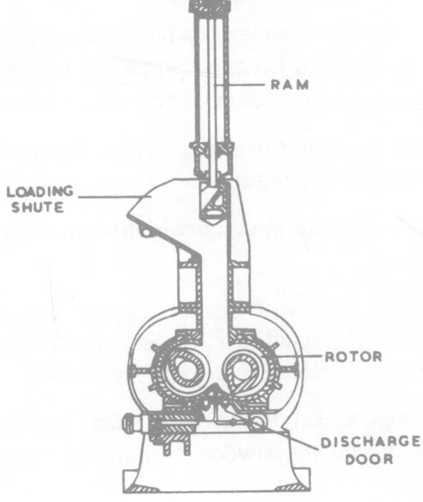

Figure 5—*Internal (Banbury) mixer*

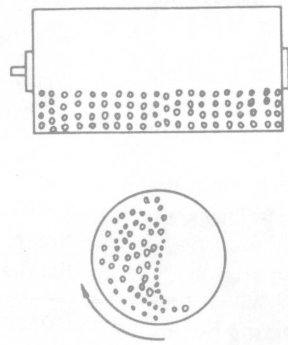

Figure 6—*Ball mill*

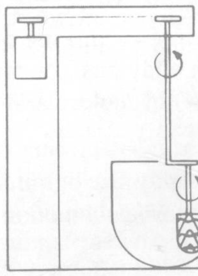

Figure 7—*Planetary mixer*

Figure 8—*Orbiting screw*

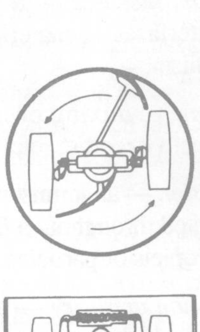

Figure 9—*Muller*

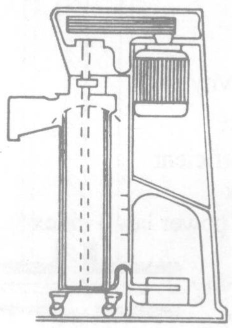

Figure 10—*Bead mill*

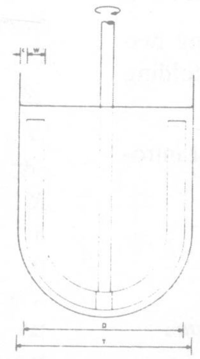

Figure 11—*Anchor agitator*

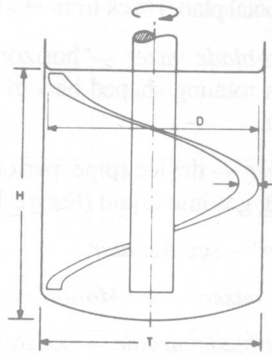

Figure 12—*Helical ribbon stirrer (only one of two blades is shown)*

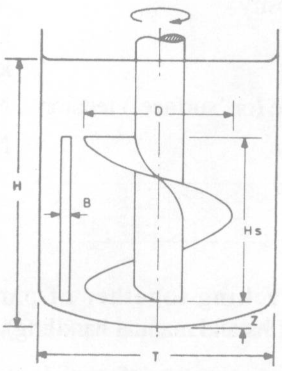

Figure 13—*Helical screw stirrer with three baffles at 120°*

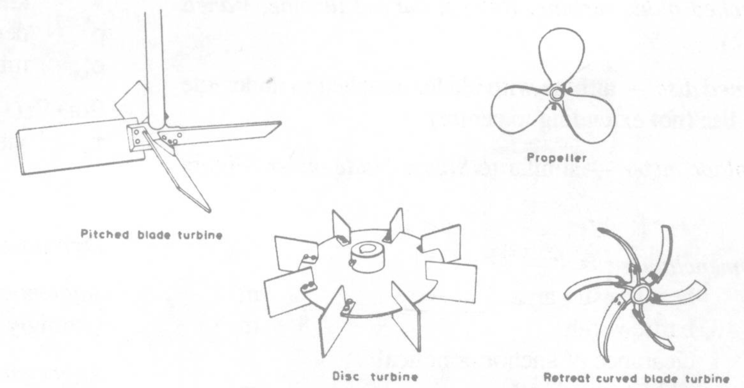

Figure 14—*Types of turbine*

Extruder — one or two screws rotating in close clearance housing. Pumps and mixes by laminar shear.

Flat-blade turbine — Turbine with vertical blades attached directly to shaft.

Helical ribbon — helical ribbon attached remotely to vertical rotating shaft, to give vertical flow near vessel walls (generally for laminar mixing) (Figure 12). Can have second ribbon for opposite flow near vessel axis.

Helical screw — screw flights directly on rotating shaft, giving vertical flow near vessel axis (often used with draught tube). Can be twin intermeshing screws (generally for laminar mixing) (Figure 13).

High-shear mixer — radial flow impeller surrounded by close-clearance stator, giving very high shear within stator with some circulation around vessel (often for liquid/liquid or solid/liquid dispersion) (Figure 2).

Impeller — see *Agitator*.

Internal mixer — close-clearance single or twin rotors (usually cams) in chamber, giving high shear for paste mixing (Figure 5).

In-line mixer — motionless or rotating mixing elements incorporated into tubular flow device (Figure 4).

Jet mixer — gas or liquid jets arranged in a tube or vessel to provide (generally turbulent) mixing energy.

Motionless mixer — an in-line mixer in which mixing is produced by flow past fixed stationary elements.

Muller — heavy rollers (and scrapers), often spring-loaded, rotating at low speed in a mixing vessel (for pastes or powder/liquid) (Figure 9).

Off-centre agitator — agitator with centre not on axis of vessel.

Orbital screw — see *Planetary mixer* (and Figure 8).

Paddle — slow moving flat blade agitator of diameter > ½ vessel diameter, giving predominantly tangential flow.

Pitched-blade turbine — turbine with blades at angle to the vertical (Figure 14) (specify upflow or downflow).

Planetary mixer — mixing element (beater, screw, dough hook) rotating on its own axis which also rotates around the vessel axis (for high viscosities and pastes) (Figure 7).

Propeller — agitator shaped like marine propeller, giving mainly axial flow (Figure 14).

Retreat-curved turbine — turbine with blades curved (in horizontal plane) back from rotation direction (Figure 14).

Sigma-blade mixer — horizontal shafts carrying two contra-rotating shaped bars giving cutting and folding action.

Sparger — device (pipe, perforated ring, etc) for introducing gas into liquid (Figure 1).

Stirrer — see *Agitator*.

Static mixer — see *Motionless mixer*.

Swept-blade turbine — see *Retreat-curved turbine*.

Turbine — radial flow agitator with blade diameter ≤ ½ vessel diameter (see *Disc turbine*, *Flat-blade turbine*, *Pitched-blade turbine*, *Retreat-curved turbine*, *Vaned disc*).

Vaned disc — turbine with blades attached to underside of disc (not extending to centre).

Z-blade mixer — similar to *Sigma-blade mixer* (Figure 3).

Nomenclature

A_H	heat transfer area	m^2
B	baffle width	m
c	clearance of anchor or helical ribbon from wall	m
c_B	clearance of baffle from wall	m
D	agitator diameter	m
D_c	diameter of coil	m
D_{sh}	shaft diameter	m
D_t	diameter of tube	m
H_L	height of liquid from bottom of vessel	m
H	height of total vessel contents from bottom of vessel	m
l_{sh}	effective shaft length (agitator centre to bearing)	m
L	length of agitator blade (perpendicular to shaft)	m
n	number of blades on agitator	—
p	pitch of screw, ribbon or propeller	m
T	vessel diameter	m
V_L	volume of liquid in vessel	m^3
V	total volume of vessel contents	m^3
W	width of agitator blade (parallel to shaft)	m
C	distance of turbine or paddle centre line (at agitator centre) from bottom of vessel	m
α	pitch angle of blade to vertical (specify upflow or downflow)	—
x, y, z	linear coordinates	—
r, θ, z	cylindrical coordinates	—

Fluid properties

Nomenclature

C_p	specific heat	J/kg K
$\mathscr{D}$	molecular diffusivity	m^2/s
$\mathscr{D}_H$	thermal diffusivity	m^3/s
$\mathscr{H}_t$	Henry's Law coefficient	N/m^2
K	consistency index	Ns^n/m^2
n	flow behaviour ('power law') index	—
θ	temperature	K
κ or λ	thermal conductivity	W/m K
μ	dynamic viscosity	Ns/m^2
μ_a	apparent viscosity	Ns/m^2
μ_E	extensional viscosity	Ns/m^2
ν	kinematic viscosity	m^2/s
ρ	density	kg/m^3
ρ_M	mixture density	kg/m^3
$\sigma_{GL}, \sigma_{LL}, \sigma_{LS}$	interface (or 'surface') tension	N/m
τ_y	yield stress	N/m^2

Dynamics

Agglomeration — attaching together of particles (strongly enough to withstand manual handling).

Aggregation — attaching together of particles by relatively weak forces.

Coagulation — attaching together of droplets (eg, emulsion) by short range attractive forces.

Coalescence — merging together of bubbles or droplets to form larger ones.

Flocculation — attaching together of particles suspended in liquid to form loose structures (flocs).

Flooding — overloading of agitator blades by gas such that agitator power consumption is reduced to a minimum.

Wetting — displacement of gas (or vapour) from a solid surface by a liquid.

Circulation time — time interval between successive passages of a fluid element past a fixed point.

Mixing time — time taken to mix from a given initial state to a prescribed final state of mixture quality.

Residence time — time spent by an element of fluid between entry to and exit from the mixer, etc.

Nomenclature

a	interface area per unit volume of dispersion	m^{-1}
C	concentration	kg/m^3, $kgmole/m^3$ m^3/m^3, etc
$\overline{C}$	space-averaged concentration	"

$\overline{C}$	time-averaged concentration	"
C'	fluctuating component of concentration	"
C^*	equilibrium concentration	"
C_D	drag coefficient	—
d	bubble, droplet, particle diameter	m
$\overline{d}$	arithmetic mean of d	m
$\overline{d}_{SV}$	surface-volume mean of d	m
$\mathscr{D}_E$	eddy diffusivity	m^2/s
f	frequency	s^{-1}
F	force	N
g	gravitational acceleration	m/s^2
h	film heat transfer coefficient, process side	W/m K
k	reaction rate constant	s^{-1}, $m^3\ mol^{-1} s^{-1}$, etc
k_T	turbulence kinetic energy	J/kg
k_s	shear rate constant	rev^{-1}
k_G	gas 'film' mass transfer coefficient	m/s
k_L	liquid 'film' mass transfer coefficient	m/s
K_G	overall mass transfer coefficient referred to gas side	m/s
K_L	overall mass transfer coefficient referred to liquid side	m/s
M	torque	Nm
N	agitator speed	rev/s
N_{JS}	agitator speed to just suspend particles off vessel bottom (or surface)	rev/s
N_{CH}	agitator speed for complete homogeneity of suspension	rev/s
N_F	agitator speed for 'flooding' of blades by gas	rev/s
N_{CD}	agitator speed for complete dispersion (of gas throughout vessel)	rev/s
P	power	W
q	heat transfer rate	W
Q	volumetric flow rate	m^3/s
Q_G	volumetric gas inlet rate	m^3/s
Q_p	agitator pumping rate	m^3/s
t	time	s
t_c	circulation time	s
t_M	mixing time	s
t_R	residence time	s
U	overall heat transfer coefficient	W/m K
v	linear velocity	m/s
v_s	superficial velocity	m/s
v_{tf}	terminal falling velocity	m/s
v_{tr}	terminal rise velocity	m/s
γ	shear strain	—
$\dot{\gamma}$	shear rate	s^{-1}
$\bar{\dot{\gamma}}$	average shear rate	s^{-1}
$\varepsilon_G, \varepsilon_L, \varepsilon_S$	volume fraction of dispersed phase	—
ε_T	turbulence energy dissipation rate	W/kg
λ_T	turbulence length scale	m
τ	shear stress	N/m^2
ω	angular velocity	rad/s

Statistics and measures of mixing

Intensity of segregation — a measure of the difference in concentration between neighbouring clumps of fluid,

$$= \frac{\overline{C_A'^2}}{\overline{C}_A(1-\overline{C}_A)}$$

Scale of segregation — a measure of the average distance between 'clumps' of the same component in a mixture.

Scale of scrutiny — length of volume scale at which mixing is measured.

Striation thickness — average distance between adjacent interfaces of materials to be mixed by a laminar mechanism.

Nomenclature

I_s	intensity of segregation	—
L_s	scale of segregation	m
R	correlation coefficient of concentrations	
S or σ	standard deviation	—
S^2 or σ^2	variance	—
δ	striation thickness	m

Dimensionless groups

Ar	Archimedes number	$\frac{L^3 g \Delta\rho}{v^2 \rho}$
Fl	Flow number	$\frac{Q}{ND^3}$
Fr	Froude number	$\frac{N^2 D}{g}$ or $\frac{v^2}{gH}$
Ne	Newton number — see Power number	
Nu	Nusselt number	$\frac{hd}{\kappa}$, etc
Pe	Peclet number	$\frac{V_s D_t}{\mathscr{D}_E}$ or $\frac{C_p \rho_V D_t}{\kappa}$
Po	Power number	$\frac{P}{\rho N^3 D^5}$
Pr	Prandt number	$\frac{\mu C_p}{\kappa}$
Re	Reynolds number	$\frac{ND^2\rho}{\mu}$ or $\frac{v D_t \rho}{\mu}$
Sc	Schmidt number	$\frac{\mu}{\rho \mathscr{D}}$
Sh	Sherwood number	$\frac{k_L d}{\mathscr{D}}$, etc

We	Weber number	$\frac{N^2 D^3 \rho}{\sigma_{GL}}$, etc or $\frac{\rho v^2 d}{\sigma_{GL}}$, etc

Subscripts

b	bubble
B	bulk
c	continuous
C	circulation
d	dispersed phase
f	final
g	gassed
G	gas
i	initial, inlet
I	interface
L	liquid
M	mixture, mixing
o	outlet
p	particle
S	solid
T	total
u	ungassed

Superscripts

—	space average
′	fluctuating component
~	time average
*	equilibrium

Symbols

a	interface area per unit volume of dispersion	m^{-1}
A_H	heat transfer area	m^2
Ar	Archimedes number	$\frac{L^3 g \Delta\rho}{v^2 \rho}$
B	baffle width	m
c	clearance of anchor or helical ribbon from wall	m
c_B	clearance of baffle from wall	m
C	distance of turbine or paddle centre line (at agitator centre) from bottom of vessel	m
C	concentration kg/m^3, $kgmole/m^3$, m^3/m^3, etc	
$\overline{C}$	space-averaged concentration	"
C	time-averaged concentration	"
C'	fluctuating component of concentration	"
C^*	equilibrium concentration	"
C_D	drag coefficient	—
C_p	specific heat	J/kg K
$\mathscr{D}$	molecular diffusivity	m^2/s
$\mathscr{D}_H$	thermal diffusivity	m^3/s
$\mathscr{D}_E$	eddy diffusivity	m^2/s
d	bubble, droplet, particle diameter	m
$\overline{d}$	arithmetic mean of d	m
$\overline{d}_{SV}$	surface-volume mean of d	m
D	agitator diameter	m
D_c	diameter of coil	m
D_{sh}	shaft diameter	m
D_t	diameter of tube	m
f	frequency	s^{-1}
F	force	N
Fl	Flow number	$\frac{Q}{N D^3}$
Fr	Froude number	$\frac{N^2 D}{g}$ or $\frac{v^2}{gH}$
g	gravitational acceleration	m/s^2
h	film heat transfer coefficient, process side	W/m K
H	height of total vessel contents from bottom of vessel	m
H_L	height of liquid from bottom of vessel	m
$\mathscr{H}$	Henry's Law coefficient	N/m^2, etc
I_s	intensity of segregation	—
k	reaction rate constant	s^{-1}, $m^3\,mol^{-1}\,s^{-1}$, etc
K	consistency index	Ns^n/m^2
k_G	gas 'film' mass transfer coefficient	m/s
k_L	liquid 'film' mass transfer coefficient	m/s
k_s	shear rate constant	rev^{-1}
k_T	turbulence kinetic energy	J/kg
K_G	overall mass transfer coefficient referred to gas side	m/s
K_L	overall mass transfer coefficient referred to liquid side	m/s
l_{sh}	effective shaft length (agitator centre to bearing)	m
L	length of agitator blade (perpendicular to shaft)	m
L_s	scale of segregation	m
M	torque	m
n	number of blades on agitator	—
n	flow behaviour ('power law') index	—
N	agitator speed	rev/s
N_{CD}	agitator speed for complete dispersion (of gas throughout vessel)	rev/s
N_{CH}	agitator speed for complete homogeneity of suspension	rev/s
N_F	agitator speed for 'flooding' of blades by gas	rev/s
N_{JS}	agitator speed to just suspend particles off vessel bottom (or surface)	rev/s
Ne	Newton number — see Power number	
Nu	Nusselt number	$\frac{hd}{\kappa}$, etc
p	pitch or screw, ribbon of propeller	m
q	heat transfer rate	W

Q	volumetric flow rate		m^3/s
Q_G	volumetric gas inlet rate		m^3/s
Q_p	agitator pumping rate		m^3/s
Pe	Peclet number	$\frac{V_s D_t}{\mathscr{D}_E}$ or $\frac{C_p \rho_V D_t}{\kappa}$	
Pr	Prandtl number	$\frac{\mu C_p}{\kappa}$	
Po	Power number	$\frac{P}{\rho N^3 D^5}$	
R	correlation coefficient of concentrations		
Re	Reynolds number	$\frac{N D^2 \rho}{\mu}$ or $\frac{v D_t \rho}{\mu}$	
S or σ	standard deviation		
Sc	Schmidt number	$\frac{\mu}{\rho \mathscr{D}}$	
Sh	Sherwood number	$\frac{k_L d}{\mathscr{D}}$, etc	
t	time		s
t_c	circulation time		s
t_M	mixing time		s
t_R	residence time		s
T	vessel diameter		m
U	overall heat transfer coefficient		W/m K
v	linear velocity		m/s
v_s	superficial velocity		m/s
v_{tf}	terminal falling velocity		m/s
v_{tr}	terminal rise velocity		m/s
V_L	volume of liquid in vessel		m^3
V	total volume of vessel contents		m^3
W	width of agitator blade (parallel to shaft)		m
We	Weber number	$\frac{N^2 D^3 \rho}{\sigma_{GL}}$, etc or $\frac{\rho v^2 d}{\sigma_{GL}}$, etc	
α	pitch angle of blade to vertical (specify upflow or downflow)		—
γ	shear strain		—
$\dot{\gamma}$	shear rate		s^{-1}
$\bar{\dot{\gamma}}$	average shear rate		s^{-1}
δ	striation thickness		m
ε_G, ε_L, ε_S	volume fraction of dispersed phase		—
ε_T	turbulence energy dissipation rate		W/m^3
θ	temperature		K
κ or λ	thermal conductivity		W/m K
λ_T	turbulence length scale		m
μ	dynamic viscosity		Ns/m
μ_a	apparent viscosity		"
μ_E	extensional viscosity		"
ν	kinematic viscosity		m^2/s
ρ	density		kg/m^3
ρ_M	mixture density		kg/m^3
σ_{GL}, σ_{LL}, σ_{LS}	interface (or 'surface') tension		N/m
τ_y	yield stress		N/m^2
τ	shear stress		N/m^2
ω	angular velocity		rad/s

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