External liquid solid mass transfer for solid particles transported in a milli-channel within a gas–liquid segmented flow

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HIGHLIGHTS

- L–S external mass transfer has been investigated for G–L–S slurry Taylor flow.
- Mass transfer coefficients appear similar to stirred tanks and slurry bubble columns.
- There is a little impact of flow orientation on mass transfer coefficient.
- Predictive Sherwood correlations have been derived.
- A CHER can combine good transfers to quasi-ideal plug flow for all phases.

GRAPHICAL ABSTRACT
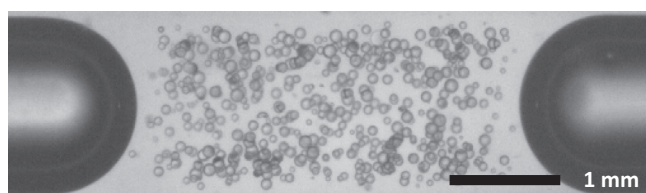
ABSTRACT

This article focuses on the measurement of external liquid–solid mass transfer coefficient for micro-particles (d_P = 40–200 μm) transported in a gas–liquid Taylor flow. The particles are kept in motion due to the secondary vortices present in the liquid slugs of these segmented flows. Acidic ion exchange particles and dilute sodium hydroxide solutions are used to perform ion exchange and neutralisation under external mass transfer limitations. Concentration profiles are monitored along the reactor with 4 conductivity cells which provides accurate mass transfer coefficients for each experiment. Two phase velocity (2.5–28 cm/s), mean particle size (100–160 μm), solid loading (5–18 g/L), reactor orientation (vertical down flow-horizontal) and liquid phase nature (Sc = 790–2300) were investigated. In that experimental window, it was found that the solid charge and the flow direction have a small influence on the L–S mass transfer even though the direction of the flow influences particle distribution in the liquid slug. Similar mass transfer coefficients and dependencies on the two phase velocities and liquid properties were found. Increasing the two-phase velocity leads first to increase the mass transfer coefficient. Then at highest velocities (u_{TP} > 20 cm/s), a much lower impact is observed and the mass transfer coefficient tends to stabilize. A first correlation form for the L–S Sherwood number in "slurry Taylor" flow is proposed for both flow orientations. These findings are used in a second part to illustrate the high potentialities of this advanced structured flow in comparison with other conventional reactors using suspended particles like stirred tank and bubble column reactors. The G–L–S "slurry Taylor" offers compelling advantages combining excellent overall external mass transfer (G–L and L–S) and almost ideal plug flow behaviour for the three phases and very good heat transfer capacities.

1. Introduction

Multiphase reactions and especially three phase gas–liquid–solid (G–L–S) reactions play an important role in the chemical,

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Symbols

Abbreviations

B	bubble
exp.	experimental
H	horizontal
G	gas phase
I	inert phase
L	liquid phase
P	particle
S	solid phase
susp.	L–S suspension
theo.	theoretical
TP	two phase
V	vertical

Roman

$A_{exch.}$	surface area for wall heat exchange [m²]
a_{GL}	gas–liquid interface specific surface area [m_{GL}^2/m_R^{-3}]
a_{LS}	liquid–solid interface specific surface area [$m_{LS}^2 \, m_R^{-3}$]
a_S	solid particle geometrical specific surface area [m^{-1}]
Ca	capillary number ($\mu_L \cdot u_b/\sigma_L$) [–]
C_{Na+}	sodium ion concentration in the liquid phase [mol L^{-1}]
$C_{Na+,su}$	sodium ion concentration at the solid surface [mol L^{-1}]
$C_{NaOH,0}$	initial sodium hydroxide concentration at the reactor entrance [mol L^{-1}]
d_P	particle diameter [m]
$d_{P,S}$	Sauter particle mean diameter [m]
d_T	internal tube or reactor diameter [m]
$D_{m,L \, Na+}$	diffusivity of sodium ions in the liquid mixture [m² s^{-1}]
e_W	reactor wall thickness [m]
f	friction factor [–]
F_{Na+}	molar flux of Na$^+$ ions [mol s^{-1}]
g	gravitational acceleration [m s^{-2}]
h	column or reactor height [m]
h_{ext}	wall convective heat transfer coefficient (utility side) [W/m²/K]
h_{int}	wall convective heat transfer coefficient (process side) [W/m²/K]
k_L	G–L mass transfer coefficient [m s^{-1}]
k_La	G–L mass transfer coefficient [s^{-1}]
K_{OV}	overall volumetric mass transfer coefficient [s^{-1}]
k_S	L–S external mass transfer coefficient [m s^{-1}]
L_{slug}	slug length, measured in the channel center between two bubble noses [m]
$n_{IE,0}$	initial molar amount of ion exchange sites [mol]
$n_{NaOH,0}$	initial molar amount of sodium hydroxide ions [mol]
N_{Na+}	normalized molar flux of Na$^+$ ions [mol s^{-1} m^{-2}]
P	pressure [Pa]
P	power consumption [W]
Pe_L	liquid Péclet number ($u_{TP} \cdot d_T/D_{ax}$ for Taylor flow) [–]
$Q_{aqu.}$	volumetric flow rate of the aqueous suspension, before mixing with NaOH solution and formation of Taylor flow [m³ s^{-1}]

Q_{inert}	volumetric flow rate of inert phase (here gas) [m³ s^{-1}]
Q_{NaOH}	volumetric flow rate of sodium hydroxide solution entering the junction [m³ s^{-1}]
Q_L	volumetric flow rate of liquid phase [m³ s^{-1}]
$Q_{susp.}$	volumetric flow rate of L–S suspension ($Q_{susp.} = Q_{NaOH} + Q_{aq.}$) [m³ s^{-1}]
Re_{TP}	Reynolds number based on flow velocity ($Re_I = \rho_L u_{TP} d_T/\mu_L$) [–]
Re_p	particulate Reynolds number based on relative slip velocity ($Re_P = \rho_L \cdot u_R \cdot d_p/\mu_L$) [–]
$Re_{p,I}$	particulate Reynolds number based on energy dissipation rate ($Re_{p,I} = \bar{\varepsilon} \cdot dp^4/v^3)^{1/n}$ with n = 2, 3 respectively for laminar and turbulent flows [–]
$Re_{p,II}$	particulate Reynolds number based on flow velocity ($Re_{p,II} = \rho_L \cdot u_{TP} \cdot d_p/\mu_L$) [–]
S_{LS}	liquid–solid interface [m²]
S_T	channel cross section [m²]
Sc_L	Schmidt number ($\mu_L/(\rho_L \cdot D_{Na+})$) [–]
Sh	Sherwood number ($k_S \cdot d_P/D_{Na+}$) [–]
U	overall wall heat transfer coefficient [W/m²/K]
u_b	bubble velocity [m s^{-1}]
u_R	relative mean slip velocity between solid particles and the liquid flow [m s^{-1}]
u_{TP}	2-phase velocity (($Q_{susp.} + Q_{inert})/S_T$) [m s^{-1}]
$u_{v,G}$	superficial gas velocity [m s^{-1}]
$u_{v,L}$	superficial liquid velocity [m s^{-1}]
V_L	liquid volume [m³]
V_{LS}	liquid–solid suspension volume [m³]
V_R	reactor volume [m³]
$w_{surf.}$	mass fraction of surfactant [–]
x_{H_2O}	molar fraction of water [–]
z	position or length [–]

Greek

β_L	liquid phase hold-up for the liquid solid suspension only ($m_L^3/(m_L^3 + m_S^3)$) [–]
ΔP	pressure drop [Pa]
$\Delta \rho$	relative difference in density between solid particles and liquid phase [kg m^{-3}]
$\tilde{\varepsilon}$	energy dissipation rate per unit volume of reactor [W m$_R^3$]
$\bar{\varepsilon}$	energy dissipation rate per unit mass of liquid [W kg$_L^{-1}$]
ε_G	gas hold up (per reactor volume) [–]
$\varepsilon_{S,1}$	solid hold up (per liquid volume) [–]
$\varepsilon_{S,2}$	solid hold up (per volume of G–L–S mixture) [–]
μ	dynamic viscosity [Pa s]
v	kinematic viscosity [m² s^{-1}]
ρ	density [kg m^{-3}]
τ	residence time in reactor [s]
X_{Na+}	sodium ion conversion [%]
ω_{cat} or ω_S	catalyst or solid loading [kg$_S$/m$_{L+S}^3$]

petrochemical or pharmaceutical industries. In the particular case of heterogeneously catalyzed reactions, the use of a solid suspension appears often the best trade off between easiness of solid catalyst handling, process complexity, flexibility and reactor performance. Fine powders provide good external surface area for heat and mass transfers and enhanced internal transfers. Moreover, introducing or replacing catalyst particles in a continuous way, appears easier for regeneration of fast deactivating catalysts than in other technologies with fixed catalyst structures. Usual three phase G–L–S reactors using suspension catalysts are bubble columns, stirred tank reactors and fluidized or ebullated beds [1–4]. These reactors are generally characterized by good mass and heat transfer capacities, low power requirements and high flexibility. However they also promote a high degree of back-mixing which can be a drawback for reactions with selectivity issues and when very high conversions are required. For applications which require the use of suspension catalysis (e.g. deactivation issue, need for a high internal mass transfer) and when the intrinsic reaction kinetics demand a plug flow behaviour and good external mass transfer abilities, no industrial technology appears able to answer both demands simultaneously.