Chemical Engineering Journal 308 (2017) 669–682

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

A factorial approach to understanding the effect of inner geometry of baffled meso-scale tubes on solids suspension and axial dispersion in continuous, oscillatory liquid–solid plug flows

Louisa N. Ejim [a], Stephanie Yerdelen [b], Thomas McGlone [b], Iyke Onyemelukwe [a], Blair Johnston [b], Alastair J. Florence [b,*], Nuno M. Reis [a,*]

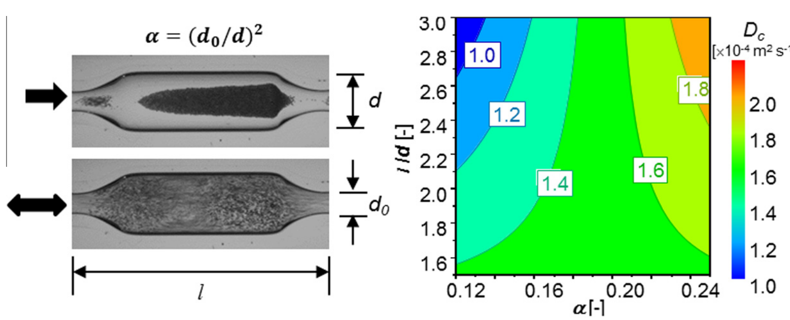
[a] EPSRC Centre for Innovative Manufacturing in Continuous Manufacturing and Crystallisation c/o Department of Chemical Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK

[b] EPSRC Centre for Innovative Manufacturing in Continuous Manufacturing and Crystallisation c/o Strathclyde Institute of Pharmacy and Biomedical Sciences, University of Strathclyde, Technology and Innovation Centre, 99 George Street, Glasgow G1 1RD, UK

HIGHLIGHTS

- The effect of inner geometry of meso-scale OFRs on axial dispersion was studied.
- The impact on batch suspension and continuous liquid–solid flows was studied.
- The effect of d_o, α, l and baffle shape was evaluated with a 2×2 factorial design.
- Continuous liquid–solid flow modelled with plug flow with axial dispersion model.
- Smooth-edged constrictions produced sharper solids RTDs.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 18 May 2016
Received in revised form 2 September 2016
Accepted 3 September 2016
Available online 6 September 2016

Keywords:
Oscillatory flow
Meso-scale reactor
Smooth periodic constrictions
Design of experiment
Solid-liquid flow
Plug flow

ABSTRACT

Oscillatory flow reactors (OFRs) are a new generation of tubular mixing and reaction equipment uniquely capable of combining continuous near plug flow with homogeneous particle suspension, yet the design of OFRs for liquid–solid and multi-phase flow processes relies on rules established during the past two decades from single, liquid-phase studies. A Design of Experiment (DoE) approach was herein implemented for establishing the relationship between four key geometrical parameters of the inner tube baffles and both the suspension of particles and the axial dispersion for liquid–solid continuous flows in 10 mm internal diameter (d) meso-scale tubes with periodic baffles. The parameters evaluated were the orifice open diameter, $d_o = 0.35d$–$0.50d$; the open cross section, $\alpha = 0.12d$–$0.25d$, constriction spacing, $l = 1.5d$–$3.0d$, and baffle shape (sharp vs smooth edged). A total of ten tubes were tested, five consisting of smooth periodic constrictions (SPC) and the other five of sharp edged periodic constrictions (SEPC) according to a complete 2×2 factorial design with 1 central point. Each tube was experimentally evaluated via optical imaging of suspended monodispersed polyvinyl chloride (PVC) particles. Both SPC and SEPC meso-tubes were capable of delivering a near plug flow behaviour and the values of axial dispersion coefficient (D_c) estimated for the solids were in the range of 1.0–2.2×10^{-4} m^2 s^{-1}. In contrast, the minimum (critical) fluid oscillation conditions required for full suspension of particles varied significantly, in general with the SPC tubes requiring up to 50% lower amplitude for full particles suspension. Overall, α revealed the dominant parameter in controlling solids backmixing, and the inner tube geometry requiring the lowest energy input for homogenous particle suspension and minimum D_c (i.e. sharpest residence

* Corresponding authors.
E-mail addresses: alastair.florence@strath.ac.uk (A.J. Florence), n.m.reis@lboro.ac.uk (N.M. Reis).

http://dx.doi.org/10.1016/j.cej.2016.09.013
1385-8947/

Notation

A	cross sectional area of tube (m^2)
C	concentration of particles (g mL^{-1})
C_d	discharge coefficient (dimensionless)
C_D	drag coefficient (dimensionless)
C_o	initial concentration of PVC particles (g mL^{-1})
$C_{out}(t)$	outlet concentration of PVC at time t (g mL^{-1})
d	inner tube diameter (m)
D_c	axial dispersion coefficient (m^2 s^{-1})
d_o	inner orifice diameter (m)
d_p	diameter of PVC particles (m)
$E(t)$	exit age distribution function
$E(\theta)$	normalised exit age distribution function
f	oscillation frequency (Hz)
g	acceleration of gravity (m s^{-2})
$F(\theta)$	normalised RTD cumulative distribution function
$F(\infty)$	cumulative normalised particle concentration
I	intensity of the light emerging out of the optical box
I_0	intensity of incident light beam entering the optical box
l	baffle spacing (m)
l/d	length to diameter ratio
L	axial position of the test section relative to the tube washout inlet (m)
l_p	light path distance (m)
N	number of baffles (dimensionless)
P/V	power density (W m^{-3})
Q	volumetric flowrate (m^3 s^{-1})
R	cross-correlation coefficient
t	time (s)
t_m	axial dispersion model mean residence time (s)
$\bar{t}$	experimental mean residence time (s)
u	mean superficial flow velocity (m s^{-1})
u_m	volume-weighted mean settling velocity of particles (m s^{-1})
u_p	maximum steady state settling velocity of particles (m s^{-1})
$u(t)_{max}$	maximum oscillation fluid velocity (m s^{-1})
V	inner volume of the tube (m^3)
ν	kinematic viscosity of the fluid (m^2 s^{-1})
$W(t)$	RTD wash out function
$W(\infty)$	cumulative fraction of particles
x	axial position (m)
x_o	oscillation amplitude (m)
$x_{o,crit}$	critical amplitude of suspension (m)
z	dimensionless length (x/L)

Dimensionless groups

D	dimensionless axial dispersion number, $D = D_c/uL$
Re_n	net Reynolds number
Re_o	oscillatory Reynolds number
St	Strouhal number

Greek Letters

ε	wavelength-dependent molar absorptivity coefficient (M^{-1} cm^{-1})
θ	dimensionless time, $\theta = t/\bar{t}$
ρ_f	density of fluid (kg m^{-3})
ρ_p	density of particles (kg m^{-3})
ρ_m	density of PVC-water mixture (kg m^{-3})
μ	viscosity of fluid (Pa.s)
τ	mean hydraulic time (s)
α	open cross sectional area (%)
ω	angular frequency (Hz)
φ	velocity ratio (dimensionless)

time distribution) presented a $l/d = 3$, $d_o = 0.35d$, $\alpha = 12\%$ and SPC design. This study is believed to support the future design of optimised meso-scale OFR systems for continuous screening and manufacturing of value-added liquid–solid and multi-phase systems, such as catalytic and crystallisation processes.

1. Introduction

Oscillatory flow reactors (OFRs) are a new generation of mixing equipment capable of delivering plug flow behaviour decoupled from the net flow [1] for applications in chemical and biological systems. Several key applications have been explored as a result of their unique ability to accommodate slow reactions in a reactor of length to diameter ratio a magnitude lower than conventional tubular plug flow reactors. The plug flow behaviour in OFRs results from effective flow separation around the edge of periodically spaced orifice baffles, which promote the formation of vortices by interacting with the periodic, oscillatory fluid. This yields secondary mixing in the tube, resulting in radial velocities of the same order of magnitude as the input axial velocities [2]. Subjecting OFRs to a net flow with a superimposed reversing oscillatory component of the correct magnitude, leads to efficient controllable fluid mixing, enhanced heat and mass transfer, good particle suspension and reduced shear [3]. The need for small scale continuous manufacturing platforms and scalable continuous screening devices has led to a relatively recent development in OFR technology to down-scaling the reactor to meso-scale [3], which can be broadly defined as internal diameter, d in the range of 1–10 mm. meso-scale OFRs are becoming considerably attractive for continuous catalytic and pharmaceutical manufacturing owing to their small volume and ability to cope with multiphase flows including particles and operate at low flow rates with reduced feed-stock materials and waste. Nonetheless, currently the design of OFRs relies on "rule of thumb" concepts established in the past two or three decades based on single, liquid-phase dispersion [4] and mixing [5] studies which are actually paramount to establish the relationship between the inner baffled-tube geometry and solids flow, especially in Meso-scale OFRs.

The fluid mechanics in OFRs depend on several key geometrical parameters such as the baffle spacing (l), orifice diameter (d_0) and open cross sectional area (α), however the relationship between these geometrical parameters and continuous particles suspension/flow has not been yet established in literature. Baffle spacing has a significant effect on the behaviour of fluid as it determines the growth extent of generated eddies [5]; the vortices formed are unable to mix across the entire inter-baffle region if l/d is too small. Instead, eddies generated are distorted as a result of interaction with the baffles, therefore restraining the growth of vortices