Chemical Engineering Research and Design xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

Flow studies in an in-line Silverson 150/250 high shear mixer using PIV

C.J.U. Espinoza[a,b], M.J.H. Simmons[a], F. Alberini[a,*], O. Mihailova[b], D. Rothman[c], A.J. Kowalski[b]

[a] School of Chemical Engineering, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK
[b] Unilever R&D, Port Sunlight Laboratory, Bebington, Wirral CH63 3JW, UK
[c] Silverson Machines Ltd., Chesham, Buckinghamshire HP5 1PQ, UK

ARTICLE INFO

Article history:
Received 31 October 2017
Received in revised form 3 January 2018
Accepted 12 January 2018
Available online xxx

Keywords:
Rotor–stator mixer
High shear mixer
Flow number
PIV
Fluid mechanics
Silverson

ABSTRACT

Angle resolved 2-D PIV measurements were taken of the flow inside an in-line Silverson 150/250 high shear mixer, facilitated by a custom built transparent poly methyl methacrylate mixing head. Water was used as the working fluid in the turbulent regime (120,000 < Re < 420,000) and measurements were taken in a field of view encompassing one quarter of the whole mixing head. The effect of the presence of an additional externally driven flow from a pump, and back pressure using an outlet control valve, were examined. The results show that the dominant flow pattern can either be radial or tangential with the former being driven by the external flow at high flow rates and the latter at increasing rotor speeds. Increasing the back pressure promoted tangential flow. Detailed measurements were made of the influence of these parameters upon the mixer flow pattern and calculation of flow number from 2-D PIV data; the latter are strongly influenced by the geometry of the mixer and pipework.

1. Introduction

High shear mixers (HSM), or 'rotor–stator' mixers (RSM), are widely used in industrial processes such as dispersion, emulsification and liquid–liquid homogenisation because of their capability to impose high levels of shear and energy dissipation rates (three orders of magnitude greater than a mechanically stirred vessel) on a relatively small volume of fluid. They are used in the cosmetics, food, home and personal care and pharmaceutical industries for the manufacture of e.g. mayonnaise, detergents, shampoo and conditioner (Zhang et al., 2012) and can be operated in batch, semi-continuous or continuous (in-line) modes. They are also classified as colloid mills, axial and radial discharge RSMs and toothed devices; and existing manufacturers include Ross, Chemineer, IKA work, Siefer, Rayneri and Silverson (Utomo, 2009).

HSMs have a mixing head which consists of a high speed rotor (moving mixing element with a typical tip speed range of 10–50 m s^{-1}) and a stator (fixed mixing element) which are in close proximity to each other (Atiemo-Obeng and Calabrese, 2004), with a rotor–stator (R–S) gap ranging from 100 to 3000 μm (Karbstein and Schubert, 1995). The operating principle of a HSM involves drawing the fluid axially into the R–S gap; subjecting it to high tangential velocity gradients and turbulence (shear rates ranging from 20,000 to 100,000 s^{-1}); and eventually expelling it radially through the stator holes in the form of jets (Utomo et al., 2009; Zhang et al., 2012). HSMs are manufactured in different sizes and geometries to suit a given application.

Regardless of the ubiquity of these devices, publications detailing aspects of their design and basis of operation have only become available over the last decade. Thus, previous

* Corresponding author.
E-mail addresses: CJE002@bham.ac.uk (C.J.U. Espinoza), F.Alberini@bham.ac.uk (F. Alberini).
https://doi.org/10.1016/j.cherd.2018.01.028

Nomenclature

Symbols

B	rotor blade width, m
D	filled volume diameter, m
D_h	stator hole diameter, m
$D_{ps,inner}$	primary stator inner diameter, m
$D_{ps,outer}$	primary stator outer diameter, m
$D_{r,i}$	inner rotor diameter, m
$D_{r,o}$	outer rotor diameter, m
$D_{ss,inner}$	secondary stator inner diameter, m
$D_{ss,outer}$	secondary stator outer diameter, m
L_{IA}	side length of interrogation area, m
L_p	side length of interrogation area, pixels
$\dot{m}$	mass flow rate, $kg\,h^{-1}$
N	rotor speed, rps
N_Q	flow number, dimensionless
P_1	point coordinates (m, m)
P_2	point coordinates (m, m)
$Q_{fit,integrated}$	calculated volumetric flow rate from a fitted function, $m^3\,s^{-1}$
$Q_{measured}$	measured volumetric flow rate using a flow meter, $m^3\,s^{-1}$
Q_{plug}	calculated volumetric flow rate using plug flow approximation, $m^3\,s^{-1}$
Q_{surf}	calculated surface flow rate, $m^2\,s^{-1}$
Q_T	total volumetric flow rate, $m^3\,s^{-1}$
r	arbitrary radial distance in cylindrical coordinates, m
R	filled volume radius, m
r, θ, z	radial, tangential and axial directions in cylindrical coordinates, m
S	magnification, dimensionless
S_r	row separation distance, m
$\bar{U}$	mean velocity, $m\,s^{-1}$
U	instantaneous velocity, $m\,s^{-1}$
U_{hole}	stator hole velocity, $m\,s^{-1}$
U_{max}	maximum velocity, $m\,s^{-1}$
U_r	radial component of velocity in cylindrical coordinates, $m\,s^{-1}$
U_{rms}	root mean square (RMS) velocity, $m\,s^{-1}$
U_{tip}	rotor tip speed, $m\,s^{-1}$
U_x	x-component of velocity in Cartesian coordinates, $m\,s^{-1}$
U_y	y-component of velocity in Cartesian coordinates, $m\,s^{-1}$
U_θ	tangential component of velocity in cylindrical coordinates, $m\,s^{-1}$
x, y, z	directions in Cartesian coordinates, m
z	arbitrary axial distance in cylindrical coordinates, m
Z	stator thickness, m

Greek letters

Δt	time delay between image pairs, s
θ	tangential angle, radians
μ	fluid viscosity, Pa s
ρ	fluid density, $kg\,m^{-3}$

Dimensionless groups

$Re = \frac{\rho N D_{r,o}^2}{\mu}$	Reynolds number, dimensionless

Abbreviations

PO	pump only
PS	pump and Silverson
SO	Silverson only
VFO	valve fully open
VPC	valve partially closed

selection of operating parameters has relied on operator experience and trial-and-error (Mortensen et al., 2017). Existing studies for both batch and in-line HSMs focus on the development of scaling rules and features of the turbulence within the mixing head. The majority of studies have either been purely experimental, focussing on droplet break-up (Carrillo De Hert and Rodgers, 2017; Hall et al., 2011; James et al., 2017a; Rodgers and Cooke, 2012; Rueger and Calabrese, 2013a,b; Shi et al., 2013), measurement of power consumption (Cooke et al., 2012; James et al., 2017b; Kowalski et al., 2011; Padron, 2001), or flow visualisation studies using techniques such as Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV) (Mortensen et al., 2011, 2017; Utomo et al., 2008) to study the effects of processing parameters such as pump and rotor settings as well as the influence of stator geometries. Some published work on numerical simulations have employed computational fluid dynamics (CFD) (Håkansson and Innings, 2017; Utomo et al., 2009), with the most recent work focussing on validation of CFD simulations via experiments (Jasińska et al., 2013, 2015; Qin et al., 2017; Utomo et al., 2008; Xu et al., 2013; Zhang et al., 2017).

Despite the above efforts, the number of published studies remains low and their generic applicability are limited due to the plethora of factors that needs to be considered to characterise fluid flow behaviour such as: mixer specifications, processing conditions, rotor and stator geometries as well as the mixing mechanisms and applications. Generic scale-up rules do not exist and indeed Mortensen et al. (2011) stated that: “a general characterisation of rotor–stator mixer performance by simple mechanistic models does not seem realistic”. The implication is that robust and validated CFD based models are a necessary tool for the practising engineer.

There is an increasing industrial interest in switching from batch to in-line operation of HSMs because of its economic edge in terms of larger throughput and continuous operation (Qin et al., 2017). However, the lack of theoretical knowledge, even more than for batch operated HSMs, makes their design and application even more challenging (Håkansson and Innings, 2017). Some recent studies on pilot-scale in-line HSMs by Xu et al. (2013), Zhang et al. (2017) and Qin et al. (2017) follow the above approach of validating CFD models. They have all collectively evaluated, both numerically and theoretically, parameters such as hydrodynamics (flow pattern) and power consumption in a FLUKO® mixer that are critical in emulsification processes. These parameters allow the characterisation of breakup mechanisms and calculation of energy dissipated in the mixing head.

In this study, angle resolved 2-D PIV measurements are carried out to characterise the flow field inside a custom built, pilot-scale, in-line Silverson 150/250 HSM, using water as the working fluid (single phase flow). The effects of process parameters such as rotor speed, external pump flow rate and back pressure were investigated. The velocity fields are analysed to determine overall flow structures as well as flows near