Chemical Engineering Science 173 (2017) 570–577

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Numerical and experimental analysis of Fluid Phase Resonance mixers

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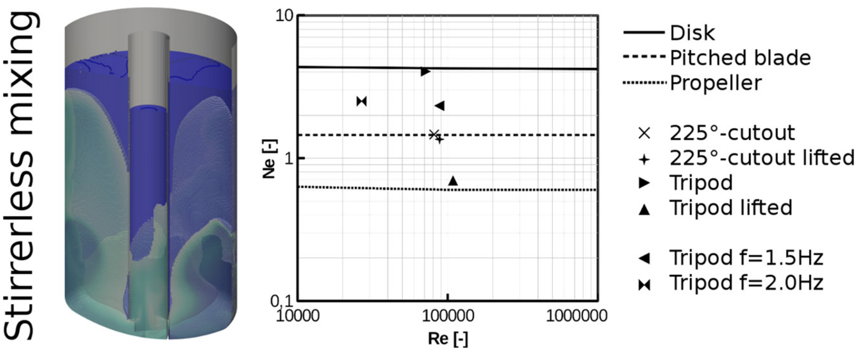
HIGHLIGHTS

- The new mixing technology "Fluid Phase Resonance mixing" is investigated.
- CFD simulations (verified by measurements) are used to optimise the process.
- Mixing time, mixing quality, and power consumption are determined.
- One best configuration is identified.
- Best configuration is as efficient as propeller stirrer.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 21 November 2016
Received in revised form 22 May 2017
Accepted 8 August 2017
Available online 9 August 2017

Keywords:
Mixing vessel
Fluid Phase Resonance mixing
Oscillating flow
Geometry optimisation
Stirred vessel
Computational Fluid Dynamics

ABSTRACT

Fluid Phase Resonance (FPR) mixers are investigated by means of Computational Fluid Dynamics (CFD) and Laser Doppler Anemometry (LDA). In FPR mixers, a pipe is immersed centrally into a liquid contained in a vessel. Two air cushions are produced above the liquid outside and inside the pipe. The latter is periodically pressurised so that the liquid in the central pipe and the vessel is oscillating, providing good flow conditions for mixing. Starting with a basic geometry, further configurations are developed and simulated with CFD to optimise the mixing quality. Results for two simulations are validated by LDA. Comparing velocity, turbulent kinetic energy, mixing quality, mixing time, and Newton number, the influence of geometry and oscillation frequency is investigated. The mixers are compared to standard stirred vessels by Newton numbers. It is found that FPR mixers can be as efficient as propeller stirrers.

1. Introduction

Fluid Phase Resonance (FPR) mixing is a technology based on works by Ostrovsky and Abiev (1998). This technology usually benefits from an enhanced boundary layer renewal in oscillating fluid motion due to the Richardson-effect (Richardson and Tyler, 1929). Since then, several research projects were investigating possible applications. For example, the principle was used to improve the efficiency of processes as diverse as filtration (Pflieger et al., 2009), electrolysis (Moreno Mañas, 2012), and mass exchange in bubble columns (Hussein, 2004). The present work does not make use of the boundary layer renewal, but deals with the application of low frequency pressure oscillations in a typical a range of 1 1/s to 5 1/s for liquid mixing processes. In Fig. 1 the principle is illustrated, showing one half of an axisymmetric mixing vessel cross-section. The vessel is filled with liquid in which a central pipe is immersed to a certain level. Thus, two gas cushions are forming above the liquid. At the upper end of the central pipe a drive is attached, generating harmonically oscillating pressure in the gas cushion inside the pipe, which in turn causes the liquid phase inside the pipe and the vessel to move periodically up and down. This movement is not necessarily only oscillating in vertical direc-

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http://dx.doi.org/10.1016/j.ces.2017.08.012
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Nomenclature

Latin symbols

A_{inlet}	inlet area [m^2]
c_i	concentration in *i*-th cell [–]
c_{target}	concentration of homogeneous mixture [–]
d_{pi}	pipe diameter [m]
d_v	vessel diameter [m]
f	drive frequency [s^{-1}]
h_c	cutout height [m]
h_f	filling height [m]
h_{pi}	pipe height [m]
h_v	vessel height [m]
k	turbulent kinetic energy [$m^2\ s^{-2}$]
M_{rel}	relative mixing quality [–]
n	number of cells [–]
Ne	Newton number [–]
P	power consumption [$kg\ m^2\ s^{-3}$]
p	pressure [$kg\ m^{-1}\ s^{-2}$]
r	radius [m]
Re	Reynolds number [–]
t	time [s]
t_0	start time [s]
U	velocity [$m\ s^{-1}$]
U_{eff}	effective velocity [$m\ s^{-1}$]
$U_{i,max/min,turb}$	max./min. velocity in direction *i* with turbulent fluctuation [$m\ s^{-1}$]
U_{max}	maximum velocity [$m\ s^{-1}$]
$\overline{u'}$	turbulent velocity fluctuation [$m\ s^{-1}$]
V_i	volume of *i*-th cell [m^3]
$\dot{V}_{max}$	maximum volume flow rate [$m^3\ s^{-1}$]

Greek symbols

ϵ	turbulent dissipation rate [$m^2\ s^{-3}$]
ν	kinematic viscosity [$m^2\ s^{-1}$]
ν_t	turbulent kinematic viscosity [$m^2\ s^{-1}$]
ρ	density [$kg\ m^{-3}$]
σ	surface tension [$kg\ s^{-2}$]
ψ	compressibility [$s^2\ m^{-2}$]
ω	turbulent frequency [s^{-1}]

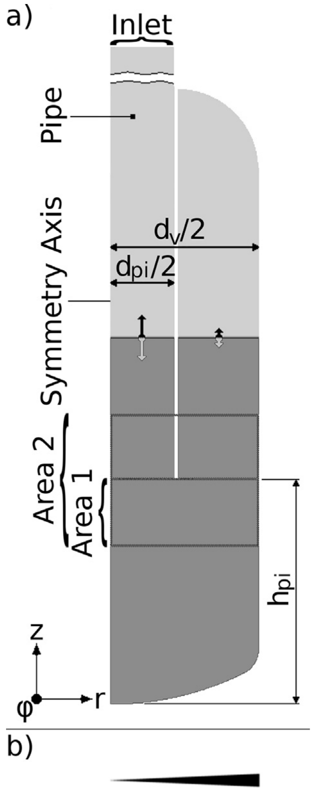

Fig. 1. Geometry and computational domain of the basic configuration; (a) front view; liquid phase is represented as dark grey, gas phase as light grey; measurement areas are shown for radial (Area 1) and axial (Area 2) velocity components; (b) top view.

tion, but also a circulation through all the liquid might be induced, which can be used for mixing purposes. The name Fluid Phase Resonance Mixing is derived from the principle: There are two fluid phases, e.g. water and air, which form an oscillating system with a certain resonance frequency. If the drive frequency matches the resonance frequency, the movement of the liquid will be the most intense compared to other frequencies. The system's resonance frequency depends on a wide range of parameters, e.g. vessel and pipe diameter and their ratio, filling height, volume of the gas cushions, liquid viscosity, pipe exit height above bottom, pipe exit geometry, and whether the outer gas cushion is open to the atmosphere or not.

Advantages of FPR mixing are, first of all, that there are no moving parts inside the vessel and that the immersed pipe may be made of a wide range of materials, e. g. glass or PTFE, to prevent corrosion due to aggressive media. Explosion prevention might also be better than with standard stirred vessels. Due to its simplicity the apparatus is quite cheap and easy to clean.

An experimental optimization of such a vessel geometry with regard to mixing quality and mixing time is rather cumbersome, wherefore CFD was applied for this purpose. A CFD simulation is initially done for a simple basic geometry (Fig. 1). The results are validated by measurements with Laser Doppler Anemometry (LDA). Based on conclusions from this basic geometry, four different central pipe configurations are created (Fig. 2). Further simulations are done for these four configurations and for one of these configurations three different drive frequencies around the system's resonance frequency are simulated. One of these simulations is also validated with LDA measurements. The mixing behaviour of the FPR mixers is analysed by simulating tracer dispersion. Furthermore, the power consumption is calculated and compared with standard stirred vessels.

2. Vessel geometry and process parameters

A vessel with a torispherical shaped bottom of diameter d_v = 0.45 m and height h_v = 1.1 m is used for the investigations. The coordinate system is defined with its origin at the lowest point of the vessel, the *z*-axis, i.e. the vertical axis, along the vessels centre line, and the *r*-axis pointing in radial direction. In the basic configuration (Fig. 1), the central pipe diameter d_{pi} is 0.20 m and its height above the bottom, i.e. clearance between the vessel bottom and the central pipe exit, h_{pi} is 0.335 m. With a filling height of h_f = 0.55 m, the filling height to diameter ratio is 1.2. The maximum air volume flow $\dot{V}_{max}$ of the drive is 0.012 m^3/s and its frequency f is 2.0 1/s.