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Static mixers: Mechanisms, applications, and characterization methods – A review

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A B S T R A C T

Static mixers and multifunctional heat exchangers/reactors (MHE/R) are qualified as efficient receptacles for processes including physical or chemical transformations accompanied by heat transfer due to their high productivity and reduced energy expenditures. The present work reviews recent conceptual and technological innovations in passive static mixers and continuous in-line reactors. Current industrial applications are discussed from a process intensification perspective, focusing on mixing and mass transfer performance. Typical experimental techniques employed to characterize and quantify the mixing process are explored. The work is complemented by a review of mixing fundamentals, knowledge of which allows the development of theoretical models crucial for the analysis of experimental data, like the chemical probe mixing assessment method. Considering the development of continuous flow equipment in numerous processes, advances in this field will certainly be of increasing interest to the scientific and industrial communities.

Keywords: Process intensification; Passive mixing; Static mixer; Continuous multifunctional heat exchanger/reactor; Mixing assessment

1. Introduction

Static mixers and multifunctional heat exchangers/reactors (MHE/R) are being increasingly incorporated in process industries for their mixing and heat transfer capabilities. Process intensification is a chemical engineering purpose that consists in seeking processes with higher productivity, safer operating conditions, reduced waste production, and lower energy consumption. New applications are being explored and new on-line exchanger/reactor designs are being developed offering several advantages compared to batch processing and mechanically stirred vessels. The small space requirement, low equipment operation and maintenance costs, sharp residence time distribution, improved selectivity through intensified mixing and isothermal operation, byproduct reduction, and enhanced safety are the main features that have promoted the use of these devices in chemical, pharmaceutical, food processing, polymer synthesis, pulp and paper, paint and resin, water treatment, and petrochemical industries (Anxionnaz et al., 2008; Bayat et al., 2012; Ferrouillat et al., 2006a,b; Shi et al., 2011; Thakur et al., 2003).

Characterizing mixing in industrial processes is an important issue for various economic and environmental considerations (Anxionnaz et al., 2008; Lobry et al., 2011; Stankiewicz and Moulijn, 2000) since it governs byproduct effluents and consequently process efficiency. In addition, due to the wide range of applications of mixers and micro-structured mixers, such as homogenization, chemical reaction, dispersion and emulsification, and heating or cooling processes, the mixing efficiency in these devices is a decisive criterion for overall process performance. Indeed, mixing affects various process parameters including heat and mass transfer rates, process operating time, cost and safety, as well as product quality.

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To describe the mixing mechanism, Fournier et al. (1996a) and Baldyga and Bourne (1999) introduced macromixing, mesomixing and micromixing as three parallel mixing stages of different scales. Macromixing concerns homogeneity at the reactor scale and is generally described by the residence-time-distribution (RTD) method (Castelain et al., 1997; Habchi et al., 2009a; Villermaux, 1986) as a signature of velocity field uniformity. At the intermediate scale, mesomixing reflects the coarse-scale turbulent exchange between the fresh feed and its surroundings governed by turbulent fluctuations, so it is characterized by the RMS of velocity fluctuations or the turbulent kinetic energy (TKE) (Habchi et al., 2010), and the length scale of these fluctuations. When the fluid aggregates are reduced in size by the turbulent cascade to the Kolmogorov scale, micromixing starts by engulfment in the smallest vortices; it is then achieved in the viscous-convective subrange by laminar stretching and folding, associated with thickness reduction by striation, up to molecular diffusion at sub-Batchelor scales that rapidly dissipates the concentration variances (Batchelor, 1953). The turbulence micro-scales are directly related to the turbulence energy dissipation rate ε (Hinze, 1955; Lemenand et al., 2005; Streiff et al., 1997). In this sense, the Kolmogorov scale is a key parameter for the selectivity of chemical reactions in the turbulent regime, since the limiting mechanism of the whole mixing process occurs at the smaller turbulence scale, hence governing species contact at the molecular scale, (Baldyga and Bourne, 1988, 1989, 1999; Baldyga and Pohorecki, 1995; Falk and Commenge, 2010; Guichardon and Falk, 2000; Komori et al., 1991; Villermaux, 1986).

Qualitative investigation of the mixing process using optical techniques can give valuable information on the flow hydrodynamics. However, understanding and quantifying the mixing mechanism is essential in designing industrial processes involving fast reactions that can present characteristic reaction times smaller than the characteristic mixing time. This fundamental property of the turbulent field (Wallace, 2009) can be determined by classical velocimetry methods such as laser Doppler anemometry, particle image velocimetry, or hot-wire anemometry, all of which give access, in three-dimensional space, to the contributions of the turbulent energy dissipation rate. Alternative methods to characterize mixing based on observations of a chemical system have been recently developed, especially by Baldyga and Bourne (1990), Bourne et al. (1992a,b), and Fournier et al. (1996a): Villermaux–Dushman reactions or the iodide/iodate method (Baldyga and Bourne, 1989; Durandal et al., 2006; Dushman, 1904; Guichardon and Falk, 2000; Guichardon et al., 2000; Mohand Kaci, 2007; Oates and Harvey, 2006; Wheat and Posner, 2009). These techniques, called “chemical probe methods”, are based on the competition between mixing and well known chemical kinetics by the straightforward observation of reaction selectivity through monitoring the secondary product concentrations. Under optimal conditions, the slowest reaction time is equal to the mixing time. From the knowledge of the mechanism, kinetics, and stoichiometry of the chemical reaction, the local turbulent energy dissipation rate can readily be derived from the measured selectivity by using phenomenological mixing models (Bourne et al., 1992a; Fournier et al., 1996a; Guichardon and Falk, 2000).

The following sections present an overview of static mixers and multifunctional heat exchangers/reactors, their applications and mixing capabilities. Then mixing fundamentals and experimental techniques developed for its assessment are reviewed. The iodide/iodate method based on the concept presented above is then detailed and the adaptive procedure and mixing models are discussed. The final section includes concluding remarks on static mixers, their present state and future opportunities, with comments on the mixing characterization techniques presented.

2. Static mixers for industrial processes

2.1. *Distributive mixing in static mixers*

A static mixer can be a hollow tube or channel with a specific geometrical construction that influences the flow structure in a manner to promote secondary transverse flows that enhance mass and heat transfer in the cross-section. Another type of static mixer concept is the insert-type configuration in which the typical design is a series of identical, stationary inserts, called *elements*, and that can be installed in pipes, channels, or ducts. The purpose of the elements is to redistribute the fluid in the directions transverse to the main flow, these are the radial and tangential directions. Static mixers divide and redistribute streamlines in a sequential fashion using only the pumping energy of the flowing fluid.

The inserts can be tailored and optimized for particular applications and flow regimes. Commercial designs typically use standard values for the various parameters that provide high performance throughout the range of possible applications.

Static mixers were not widely used in the process industry before the 1970s, although some patents are much older. A patent dating to 1874 describes a single-element, multilayer motionless mixer used to mix gaseous fuel with air (Sutherland, 1874); An early French patent used staged/helical elements to promote mixing in a tube (Les Consommateurs de Petrole, 1931), and another shows a multi-element design for blending solids (Bakker, 1949). In the early 1950s, staged elements designed to promote heat transfer were patented (Lynn, 1958). Since then, major petrochemical companies made development efforts and presumably used their own designs, before any commercialization (Stearns, 1953; Tollar, 1966; Veasey, 1968).

There are more than 2000 U.S. patents and 8000 literature articles describing motionless mixers and their applications (Thakur et al., 2003). Nowadays, static mixers have become standard equipment in the process industry. They are used in continuous processes as an alternative to conventional agitation since similar and sometimes better performance can be achieved with lower cost. Motionless mixers typically exhibit lower energy consumption and reduced maintenance requirements because they do not include moving parts. They require smaller space, lower equipment cost, and no power except pumping. They can provide homogenization of feed streams with a minimum residence time and can be manufactured from most materials of construction so as to meet various standards and to adapt with harsh working conditions.

However, stirred vessels remain powerful tools in process industry and find vast applications especially for processing highly viscous products (Aubin and Xuereb, 2006; Cabaret et al., 2007). Numerous recent studies investigate their hydrodynamics with Newtonian as well as rheologically complex fluids (Alliet-Gaubert et al., 2006; Aubin et al., 2000, 2001; Fangary et al., 2000; Torré et al., 2007). New impeller and mixing vessel configurations and innovative operating methods are