Chemical Engineering Science 137 (2015) 837–851

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Enhancement of mixing by different baffle arrays in cavity flows

Baiping Xu [a], Tangqing Kuang [b], Huiwen Yu [a], Meigui Wang [a], Lih-Sheng Turng [c,*]

[a] Technology Development Center for Polymer Processing Engineering of Guangdong Colleges and Universities, Guangdong Industry Technical College, Guangzhou 510300, PR China
[b] School of Mechanical & Electrical Engineering of East China Jiaotong University, Nanchang 330013, PR China
[c] Polymer Engineering Center, University of Wisconsin–Madison, Madison, WI 53706, USA

HIGHLIGHTS

- Mixing in a cavity channel with different baffle arrays was investigated using FVM.
- Lagrangian particle tracking calculations were performed to evaluate mixing.
- Mixing is highly dependent on the baffle arrangement and the characteristic length.

ARTICLE INFO

Article history:
Received 26 April 2015
Received in revised form
25 July 2015
Accepted 1 August 2015
Available online 8 August 2015

Keywords:
Mixing
Modeling
Single screw extruder
Finite volume method
Particle tracking

ABSTRACT

Four different types of baffle arrays were inserted in an unwound channel of a single screw extruder to generate chaotic mixing. The periodic unit of the flow channel was modeled as a dynamic system of complex cavity flow. The finite volume method was used to solve the three-dimensional flow of a purely viscous non-Newtonian fluid obeying the power-law constitutive model. Lagrangian particle calculations along with statistical methods were performed by a fourth-order Runge–Kutta scheme. The effect of the baffle's array mode and characteristic length on the mixing kinematics was investigated numerically. Poincaré sections and period points were applied to reveal the different patterns and sizes of the KAM tori. Distributive mixing was visualized by the evolution of passive tracer particles initially located at different positions. The variance index and residence time distribution (RTD) were used to evaluate the statistical results. Compared with case B, where two baffles were arranged side by side in each baffled zone, the staggered alternative modes in cases C and D, where only one baffle was used in each baffled zone, surprisingly produced better mixing. Moreover, the characteristic length was also one of the key factors that influenced the mixing. When the characteristic length equaled 10 mm, case C had better mixing than case D, whereas, when the characteristic length equaled 7.5 mm, the result was reversed and case D_2 had the best mixing, while no obvious KAM islands or period tori were found.

1. Introduction

Mixing of highly viscous fluid is an important part of many industrial processes, such as polymer blending, food processing, and microfluidic technology, where laminar flow dominates mixing processes and no turbulence can be used to enhance mixing due to the vanishing Reynold's number. One of the most used models is the mixing in cavities. This type of model is related to the mixing in single extruders. Extruders with simple conveying screw elements have poor mixing capabilities despite a number of significant advantages such as better pressure generating capabilities, lower purchase costs, lower operating costs, and the possibility of direct extrusion when compared with twin screw extruders. Many efforts have been made to improve the mixing capabilities of extruders by introducing complex geometrical configurations into the screw channel. Some typical structures such as cavity transfer mixers, pin-barrel extruders, and different types of pin mixers are commonly used to meet practical mixing requirements (Baiping et al., 2014). However, all of these configurations were derived from practical experience, without the direction of advanced research. How to design a novel configuration to achieve more efficient mixing is of critical importance and has been attracting more attention recently.

A famous paper cast deep insight into the nature of mixing and opened up a new avenue toward perfect mixing. In this paper from the early 1980s, chaotic advection was first proposed when stretching and folding were introduced as the cause of the random motion of fluid particles (Aref, 1984). Afterwards, numerous studies followed that showed that the quality of mixing depends on the system

* Corresponding author.
E-mail address: turng@engr.wisc.edu (L.-S. Turng).

http://dx.doi.org/10.1016/j.ces.2015.08.001
0009-2509/

parameters being carefully tuned (Anderson et al., 2000; Aref, 2002; Galaktionov et al., 2002; Jiajun et al., 2009). Among all of the geometries used to generate chaotic mixing, cavity flow was of particular interest in the physical model of mixing and became one of the typical examples (Jana et al., 1994; Kang and Kwon, 2004; Sundararajan and Stroock, 2012). A great deal of research has been done on different cavity flows to find proper ways of introducing chaotic advection to improve mixing effectiveness. Most of them have focused on two dimensional periodic flows (Hwang and Kwon, 2000; Vikhansky, 2002; Hwang et al., 2004, 2005; Chen and Stremler, 2009). In general, chaotic regions coexist with regular islands, which are determined by different mixing protocols. Therefore, stable and unstable manifolds of hyperbolic periodic points are regarded as the engines of chaotic transport (Chella and Ottino, 1985; Ottino et al., 1992; Jana et al., 1994; Kim and Kwon, 1996a, 1996b).

On the other hand, in order to select better mixing flows, there are many ways to compute and assess mixing, although none of them are commonly accepted. Various techniques from mathematics to physics have been tried; i.e., Poincaré maps, periodic point analysis, tracer stretching distributions, and so on (Ottino et al., 1992; Jana et al., 1994; Kim and Kwon, 1996a, 1996b). Recently, Eulerian indicators (EIs) were developed to predict mixing characteristics based directly on Eulerian velocity fields without calculating particle trajectories (Sturman and Wiggins, 2009; McIlhany et al., 2011). This method came from the theory of Linked Twist maps (LTMs). On the other hand, the Lagrangian particle method (LPM) is a popular computational tool for analyzing mixing where the trajectories of the particles are traced throughout the flow domain by integrating the velocity equations. Compared with EIs, LPM can obtain the details of mixing although it requires lengthy numerical computations and is time-consuming. The spatial distribution of a group of particles can be characterized in a variety of ways, which include tracer patterns, bin counting, nearest-neighbor distances, and correlation coefficients (Wang and Manas-Zloczower, 2003; Phelps and Tucker, 2006). The combination of LPM and bin counting can directly result in the application of entropy measure, which has recently gained popularity after works published by Latora, and Baranger, Wang et al., and Kang and Kwon (Latora and Baranger, 1999; Wang and Manas-Zloczower, 2003; Kang and Kwon, 2004; Fodor and Kaufman, 2011). The Shannon entropy is a rigorous measurement of mixing, disorder, or lack of information, and is convenient to connect to complete spatial randomness. However, its value depends on the scale of observation; i.e., the number of bins meshing the flow domain and the number of particles one bin contains initially. The finite time dynamic theory was developed to feature local transport information like the Lagrangian coherent

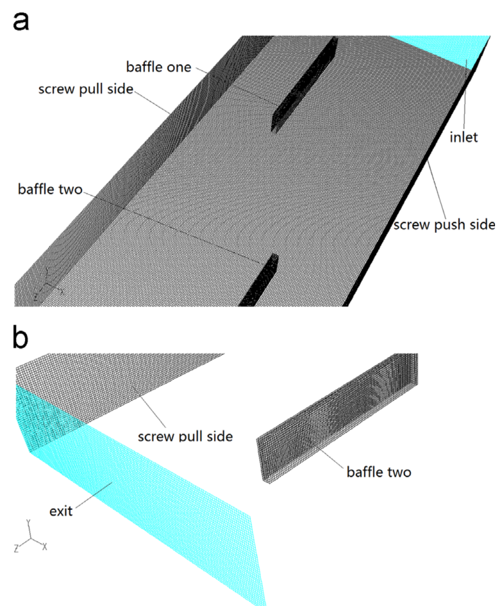

Fig. 2. Flow domain meshing with hexahedron grids for case C: (a) local view near inlet and (b) local view near exit.

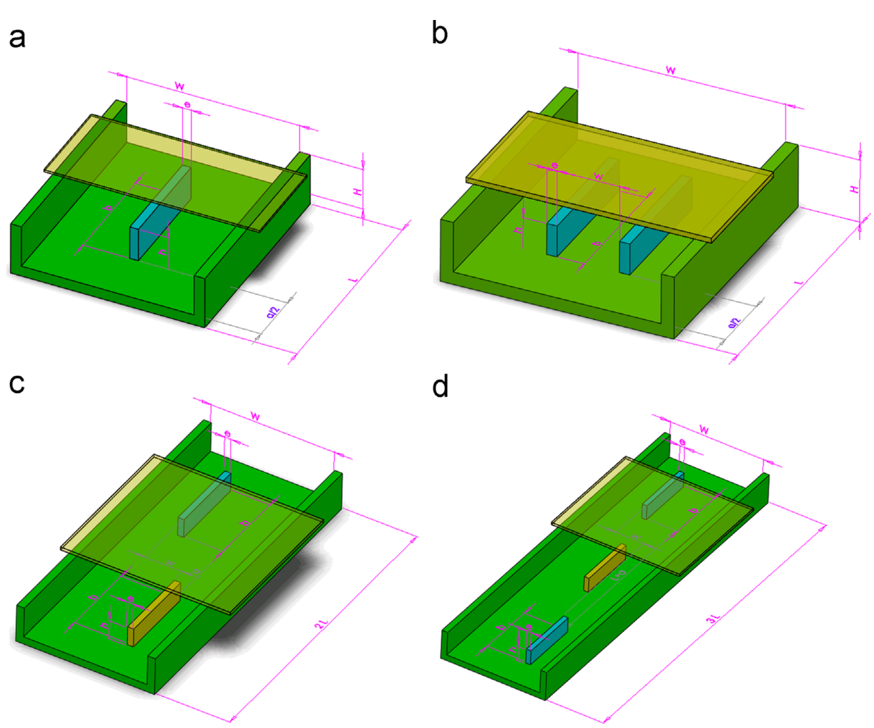

Fig. 1. Geometry of the unwound channel of a single screw extruder with different baffle arrays: (a) case A, (b) case B, (c) case C, and (d) case D.