Noise-Induced Stability Analysis of a Capillary Flow Microreactor with Mixing by Radial Diffusion of Laminar Flow Profiles

Pratap R. Patnaik, Department of Chemical Engineering, Gharda Institute of Technology, Maharashtra, India

ABSTRACT

To overcome the problem of fluid mixing in capillary tubes, the induction of radial diffusion of laminar flow profiles (RDLFP) was proposed recently, together with a mathematical. Since, under realistic conditions, continuous flow capillary reactors are influenced by noise in the feed streams, the stability of such a reactor for a system of three liquids was analyzed through its largest Lyapunov exponents. Simulations showed that although the aim of RDLFP is to improve mixing, poorly mixed microreactors are more robust to the inflex of noise than well-mixed tubes. Therefore, these contrasting requirements have to be balanced to decide the best operating conditions. Multi-component noise in multi-fluid systems can also induce stochastic resonance, which may either enhance or reduce stability. Thus, it is important and useful to filter the noise judiciously to promote reactor stability.

Keywords: Capillary Microreactor, Continuous Flow, Lyapunov Exponent, Mixing, Noise Inflow, Stability, Three Feed Streams

INTRODUCTION

With increasing realization of their benefits, microreactors are being preferred over larger conventional reactors (called macroreactors here) for many chemical and biological reactions. High-throughput screening (Steger et al., 2004), multiplexed bioanalyses (Moser et al., 2006), studies of single molecules (Li et al., 2006), DNA detection and polymerase chain reaction (Giordano et al., 2001), cellular biosensors (Lv et al., 2002) and integration of DNA analysis with separation methods such as capillary electrophoresis (Zhang & Yeung, 1998) illustrate the variety of situations where microreactors score over macroreactors.

The benefits of microreactors are enhanced by designing and operating these reactors so as to favor (i) easy and reproducible mixing, (ii) low evaporation losses, (iii) rapid transport rates...
and (iv) simple interfacing with sensitive and informative analytical tools (Okhonin et al., 2008). These requirements may be met by carrying out the reactions in nanoliter volumes of reaction mixtures contained in microfabricated wells (Moeller et al., 2008), oil droplets (Kim et al., 2013) or capillary tubes (Jovanovic et al., 2012). Each method has specific advantages and limitations. Wells and droplets require precise microprinting instrumentation for accurate mixing of reactants, and both are difficult to interface with separation methods, thus limiting them largely to in situ applications. These two methods also require either noisy fluorophore-quencher systems or rare fluorogenic substrates (Okhonin et al., 2008).

Contrasted with microwells and microdroplets, capillary microreactors readily meet the requirements low evaporation and facile analytical interfacing. Evaporation is low because of the extremely small liquid-air interface at the capillary surface. A major challenge of capillary microreactors, however, is the generation of good, easy and reproducible mixing of the reactants. Mixing is an inherent problem because the flow in capillary microreactors is predominantly laminar (Wirth, 2008). Two methods have been proposed to promote good mixing: electokinetic diffusion and longitudinal diffusion through radial interfaces between separately injected plugs of reactants. The former is based on the differential velocities of different liquids in an electric field applied at the ends of the capillary (Sanders et al., 2005), but this method becomes impractical for buffers and for multi-reactant systems. Longitudinal diffusion, on the contrary, does not depend on an external agent; it is based on diffusion through radial interfaces between separately injected plugs of liquid. However, this method too has practical difficulties because the total length of a succession of plugs can be several millimeters, and thus require several hours to mix intimately.

Okhonin and coworkers (2005) suggested the introduction of radial diffusion of laminar flow profiles (RDLFP) as a feasible method to promote mixing inside a capillary. The method is described in detail in their work. Briefly, reactant solutions are injected into the capillary under pressure as a series of consecutive plugs, each longer than the diameter of the capillary tube. The reactants mix predominantly by radial diffusion since longitudinal diffusion in laminar flow is negligible. Moreover, owing to the narrow diameter of the capillary, radial diffusion is fast. Okhonin et al. (2005) proposed a mathematical model, presented later, for RDLFP. Some limitations of this model were removed by them later (Okhonin et al., 2008), resulting in a more refined and realistic model that forms the basis of the present work.

Under realistic conditions, many open systems are under the influence of “noise” from their environments. This noise can seriously undermine the performances of both microreactors (Fletcher et al., 2003) and larger reactors (Lopez et al., 2012). While excessive noise can destabilize a microreactor (Patnaik, 2008a) and even drive it toward chaotic behavior, “intelligently” controlled noise can enhance the performance beyond what is possible in the complete absence of noise. This has been discussed previously (Patnaik, 2010) and again here for the present problem, for which it is relevant because it is difficult to maintain exact control of the sizes of a rapid succession of small plugs of liquid.

If noise can change significantly the stability of a microreactor, it is useful to know when and how the stability features change. One salient feature that can change is the nature of mixing of two or more reactants, and this in turn has a significant effect on the reaction system. Direct methods to determine reactor stability include (i) computing the complete solution of the mathematical model, (ii) determining how the eigenvalues vary, and (iii) plotting the Poincare diagram of key variables that characterize the microreactor. All three methods are, however, complex and time-consuming. So an easier method was employed by Patnaik (2008b, 2012) by calculating the Lyapunov exponents of the variables of interest. In fact, not all the Lyapunov exponents need be known; only the largest exponent suffices to indicate reactor stability; this is
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