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Review

A review of the Residence Time Distribution (RTD) applications in solid unit operations

Yijie Gao, Fernando J. Muzzio, Marianthi G. Ierapetritou *

Department of Chemical and Biochemical Engineering, Rutgers, The State University of New Jersey, 98 Brett Road, Piscataway, NJ 08854, USA

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ABSTRACT

This review traces current applications of the residence time theory in various solid unit operations. Besides reviewing recent experimental and simulation studies in the literature, some common modeling and tracer detection techniques applied in continuous flow systems are also considered. We attempt to clarify and emphasize the influence of the residence time profile on the unit performance, which is the key in system design and performance improvement of practical unit operations. The development of predictive modeling is also an important goal in the long-term development of the residence time theory.

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Contents

1. Introduction

In chemical engineering and related fields, the Residence Time Distribution (RTD) is defined as the probability distribution of time that solid or fluid materials stay inside one or more unit operations in a continuous flow system. It is a crucial index in understanding the material flow profile, and is widely used in many industrial processes, such as the continuous manufacturing of chemicals, plastics, polymers, food, catalysts, and pharmaceutical products. In order to achieve satisfactory output from a specific unit operation, raw materials are designed to stay inside the unit under specific operating conditions for a specified period of time. This residence time information is usually compared with the time necessary to complete the reaction

* Corresponding author. Tel.: +1 732 445 2971; fax: +1 732 445 2581.
E-mail address: marianth@soemail.rutgers.edu (M.G. Ierapetritou).

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or process within the same unit operation. For example, in continuous powder mixing processes, powder is mixed in a continuous mixer. The local mixing rate coupled with the time the powder stays inside the mixer determines the unit performance. If the time required for local mixing is longer than the actual residence time powder stays in the system, the process cannot provide a complete mixture, and it fails its designed purpose [1]. In other words, the performance of any continuous unit operation is determined by the competition of the two sub-processes: a batch process or reaction superimposed by an axial flow. Therefore, the characterization of the RTD in different continuous unit operations is the first step in the design, improvement, and scale-up of many manufacturing processes in the chemical engineering industry.

The research on the RTD in chemical engineering fields has focused on the influence of operation conditions, materials, and the unit geometry on the RTD profile, the improvement of measurement methods, and the improvement of predictive modeling on different processes and units. Most studies investigated continuous unit operations by using the RTD; few extended to the correlation between the RTD and the reaction or process performance, which is usually case-sensitive. For example, a continuous polymer foaming process was studied in an extruder [2], where the thermal decomposition rate of chemical blowing agent was compared with the RTD to investigate the optimization of the foam density; a chemical-looping combustor was investigated in both continuous and batch mode, in which the RTD was used to develop a model for predicting the mass-based reaction rate constant for char conversion [3]; the production of polypropylene was characterized in a horizontal stirred bed reaction by considering the RTDs of catalyst and polymer separately, which strongly depend on the temporal catalyst activity [4]; the emulsification process in polymer mixing was studied in a twin-screw continuous extruder, where the RTD and the morphology profile of the mixture was examined simultaneously in one pulse test [5]; the Cr(VI) reduction in wastewater treatment was investigated in an electrochemical tubular reactor by applying CFD and velocity profile, where the performance was coupled with the axial flow rate [6].

Due to the wide scope of the RTD issue, every year a large number of papers have been published using this conception in a host of disciplines. A previous review by Nauman [7] summarized the theoretical development history of the RTD since the beginning of the last century, especially for continuous fluid systems. Some developments have occurred since the previous review that will be covered in this paper. Moreover, this review mainly profiles the applications of the RTD theory in characterizing solid chemical engineering unit operations. Also, this review differs from the previous one in that it emphasizes coupling the RTD with the unit performance of specific unit operations. This paper is organized in the following manner. Section 2 illustrates different modeling work of the RTD in these applications, followed by a discussion on general RTD measurement methods in Section 3. In Section 4, recent applications of the RTD in solid continuous flow and manufacturing systems are described in details. Our goal in this review paper is to bring together the recent applications of the RTD theory across a wide range of studies in the chemical engineering fields, and contribute to the performance investigation of versatile continuous unit operations.

2. RTD modeling

2.1. CSTR and PFR series

Modern RTD theory originally developed from continuous fluid systems [8]. Early fluid reactor models assumed plug flow in a tubular-shape reactor (PFR), or perfect mixing in continuous stirred tank reactors (CSTR). These conceptions represent two extreme RTD profiles in the reactor. In practical continuous flow systems, experimental RTD profiles are usually between the two extremes. To describe the non-idealness of the RTD profile, different combinations of CSTR and PFR were introduced in modeling practical cases. CSTR in a series model is one commonly used model [3,9–11]:

$$\tau = NV_0/F \tag{1}$$

$$E(\theta) = \frac{N(N\theta)^{N-1}}{(N-1)!}\exp(-N\theta) \tag{2}$$

where τ is the mean residence time (MRT), N the number of CSTR tanks, V_0 the volume of each tank, and F the volumetric flow rate. $E(\theta)$ represents the dimensionless RTD and $\theta = t/\tau$ the dimensionless time. As a one-parameter model, the idealness of the RTD is represented by the number of CSTR tanks used (Fig. 1). Large number of tanks indicates a PFR-like reactor ($N \to \infty$), and a small number leads to a CSTR-like reactor ($N = 1$). Two modifications were reported: the tanks in series were followed by a PFR element in case of the RTD rise part delay when axial dispersion is significantly limited [2,12]; backward flux was introduced among the CSTR tanks to capture the long tail in the RTD profiles [4,13]. In the second modification, large backward flux indicates fast material exchange between adjacent tanks. The long tail profile can also be modeled by a dead zone volume cross-flowing with the CSTR element [14–16]. Notice that the fraction of the dead zone element represents the degree of non-idealness of the continuous flow system. Amador et al. [17] reported a resistance network model that can be considered as parallel connections of a series of PFR elements [18], thus also belonging to this kind of model.

2.2. Axial dispersion model

Despite the combination of CSTR and PFR elements, the axial dispersion model is an efficient alternative to generalize the conception of the RTD to most non-ideal reactors. The differential equation representing the axial dispersion process of a tracer in the flow system, or the Fokker–Planck equation (FPE), is expressed as a global 1D equation:

$$\frac{\partial c}{\partial t} = E\frac{\partial^2 c}{\partial z^2} - v_z\frac{\partial c}{\partial z} \tag{3}$$

where c is the concentration of a component in the system, v_z is the global axial velocity, and E denotes the dispersion coefficient in solid systems, or the diffusion coefficient in fluid systems, respectively. The variables t and z represent time and axial distance from the tracer injection point. The advantage of the FPE is the clear physical meaning of its parameters, where v_z and E indicates the combination of the axial transport and the superimposed axial dispersion in this model. There have been many industrial studies on the RTD directly using the FPE [13,19–23]. Based on previous literature [24,25], Sherritt et al. [26] summarized various FPE solutions under different boundary conditions in a rotary drum. For example, Vashisth and Nigam [27] applied the solution based on error function to analyze single-phase laminar flow through a straight tube. The most widely used solution of the RTD was developed by Taylor [28] with open–open boundaries:

$$E(\theta) = \frac{1}{2\sqrt{\pi\theta/Pe}}\exp\left\{-\frac{Pe(1-\theta)^2}{4\theta}\right\} \tag{4}$$

where $\theta = t/\tau$ is the dimensionless time, τ is the mean residence time (MRT); $Pe = v_z l/E$ represents the Peclet number, and l is the distance between injection and detection points. This solution was applied in the fitting of experimental RTD data in various systems [1,9,29–31]. Although some of the reported systems were not single phase or

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