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RESIDENCE TIME DISTRIBUTION (RTD) IN OPERATING PLANT: A REVIEW

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ABSTRACT

Radiotracer technology is a technique of radioactive injection into the system and the detection is done using radiation detector. It is also a tool for investigating and solving plant process problems namely process malfunctions and mechanical damages. Radiotracer is the most preferred stimulus response techniques in the industries due to its non-invasive application and on line monitoring capabilities, which avoid shut down of the plant. Radiotracer techniques have many advantages, such as high detection sensitivity, in-situ detection, availability of a wide range of compatible radiotracers for different phases, rapid response and high reliability and accuracy of the results. The residence time distribution (RTD) is one of the important parameters that can provide information on the characteristics or hydrodynamics of the nuclear reactor. In this paper, the overall review is presented in brief regarding radiotracer technology in plant operation.

Keywords: Detection, nuclear reactor, plant operation, radiotracer technology, residence time distribution (RTD)

INTRODUCTION

The RTD is one of the important parameters that can provide information on the characteristics or hydrodynamics of the process plant or reactor. The RTD, which was first developed by Danckwerts (1953) have been widely utilised to diagnose possible system malfunctions, such as bypassing, leakage, blockage, channelling, fouling and backmixing, as well as to help estimate the quality of mixing. Radiotracers technique uses a radioactive source and scintillation detectors to accurately detect plant production anomalies (IAEA, 2001; IAEA, 2008). Radioactive tracing is often the only fine-scale and non-intrusive yet efficient technique for characterising the flows of phases in vessels (Behin and Aghajari, 2008)). Radiotracer technology also assists industries in satisfying the critical need for production efficiency. The greatest benefit of radiotracer technology over the conventional methods is that the investigation can be carried out on-stream and without disrupting the operating process of the plant. Hence, any expensive downtime is avoided and the convenience of direct measurement results in substantial economic benefits and investigating costs.

Nevertheless, although the technology is applicable across a broad industrial spectrum, Hills (2001), Furman et al. (2011), Pant et al. (2001) and Pant et al. (2002) stated that the relevant target areas for radiotracer applications are defined and that the most appropriate target beneficiaries of radiotracer applications include the mineral processing sectors, petroleum and petrochemical industries and wastewater treatment plants. An investigation of many major industrial applications, including fluidised beds, sugar crystallisers, trickle bed reactors, cement rotary kilns, wastewater treatment units and inter-well communications in oil fields, can be performed by injecting a radiotracer at the inlet of the system and monitoring it at the outlet. The data output can be treated and analysed to investigate the behaviour of the system.

Knowledge of the liquid RTD allows accurate modelling of the system and aids in designing an optimised vessel or maintaining a desired flow and to diagnose operational inefficiencies. The RTD is often measured using a stimulus–response technique, in which a specific quantity of tracer is introduced at the system inlet as a short duration pulse or a step function, and the tracer concentration at the output is recorded over time (IAEA, 2001). To diagnose operational inefficiencies and to characterise the newly design equipment, it is important to understand vessel hydrodynamics, which may be studied by interpreting the vessel RTD.

RESIDENCE TIME DISTRIBUTION

The RTD which is synonymic with the exit age distribution density function E(t) is a probability distribution function that describes the amount of time a fluid element spends inside a reactor. It helps in troubleshooting of reactors and characterizes the macroscopic mixing and flow within the reactors. If an impulse of tracer is injected at the inlet of a system at time t equals to 0 and its concentration is measured as a function of time at the outlet, then E(t) representing the probability for a tracer element to have a residence time between the time interval (t, t+dt) and is defined as follows:

$$E_i(t) = \frac{C_i(t)}{\int_0^\infty C_i(t)\,\mathrm{d}t},$$

such that

$$\int_0^\infty E_i(t)\,\mathrm{d}t = 1, \tag{1}$$

The experimental mean residence time (MRT) of the system was calculated by the difference of first moments of outlet and inlet response curves. Mathematical expression for the first moment in discrete form can be written as follows:

$$\text{First moment} = \frac{\sum_i t_i C_i \Delta t_i}{\sum_i C_i \Delta t_i}, \tag{2}$$

The variance of the standard deviation of the RTD was calculated using:

$$\sigma^2 = \int_0^\infty \left(t - t_{\mathrm{m}}\right)^2 E(t)\,\mathrm{d}t\,. \tag{3}$$

Thus, MRT, τ, is then

$$\tau = \int_0^\infty tE(t)dt \tag{4}$$

However, the theoretical MRT is the ratio of the vessel volume, V, to the volumetric flow rate, Q:

$$\mathrm{MRT}_{theory} = \frac{V}{Q} \tag{5}$$

Thus, the relative difference between theoretical and experimental residence time or dead zone is:

$$V_{dead}\,(\%) = \frac{\mathrm{MRT}_{theory} - \tau}{\mathrm{MRT}_{theory}}\, x\, 100 \tag{6}$$

Conventionally, the RTD can be described by various models, for example, continuous stirred tank reactor (CSTR) with exchange volumes, CSTR with a dead zone, CSTR with a bypass, and so forth. However these models contain many parameters like mean residence time, volume of the dead zone, the exchange flow rate, the bypass flow rate, etc., that can be varied to fit the experimental data. Nevertheless, the models mentioned above do not consider the flow field within the reactor, which results into non-ideal behaviour in the first place.

The International Atomic Energy Agency (IAEA) (2008) has newly developed six (6) mathematical models to analyse the experimentally obtained radiotracer curves. These RTD models are the axial dispersed plug flow model, the axial dispersed plug flow with exchange model, the perfect mixers in series model, the perfect mixers in series with exchange model, the perfect mixers in parallel model, and the perfect mixers with recycle model. Mathematical RTD models can provide theoretical information or describe the hydrodynamic behaviour of the reactor used to obtain experimental data. Table 1 shows the parameters for each of the models. The total flow rate is denoted as Q, J is the number of mixers in primary flow, J_2 is the number of mixers in secondary flow, V is the volume of the fluid, and Q is the volumetric flow rate. The second series of mixers is denoted as J_2, with a volume of V_2 and a volumetric flow rate of Q_2. MRT or τ is mean residence time in the primary flow whereas τ_2 is MRT in secondary flow. Pe is peclet number whereas K is ratio of V_1 to V_2. The curve with the best fit is chosen based on the minimum value of the square of the difference between experimental data and the model (IAEA, 2008). The sum of the squares of the differences between the model and the data is minimised and fulfilled the following equation:

$$RMS = \left[\frac{1}{N_T}\int_0^{\infty}\left[E_{exp}(\theta) - E_m\ (\theta, N)\right]^2 d\theta\right]^{1/2} = Minimum \tag{7}$$

where N_T is the number of data points, $E_{exp}(\theta)$ is the experimentally measured curve, and $E_m\,(\theta, N)$ is the simulated model.

Table 1: Optimized parameters for each model

Models	**Optimized Parameters**				
[I] axial dispersed plug flow model	τ	Pe			
[II] axial dispersed plug flow with exchange model	τ	Pe	N	J	
[III] perfect mixers in series model	τ	J			
[IV] perfect mixers in series with exchange model	τ	J	t_m	K	
[V] perfect mixers in parallel model	τ1	J1	τ2	J2	Q1/Q
[VI] perfect mixers with recycle model	τ1	J1	τ2	J2	Q1/Qr

The treatment of the data involves background correction, radioactive decay correction, starting point correction, filtering, and data extrapolation. Figure 1 shows the principle of RTD by Stegowski and Furman (2004).

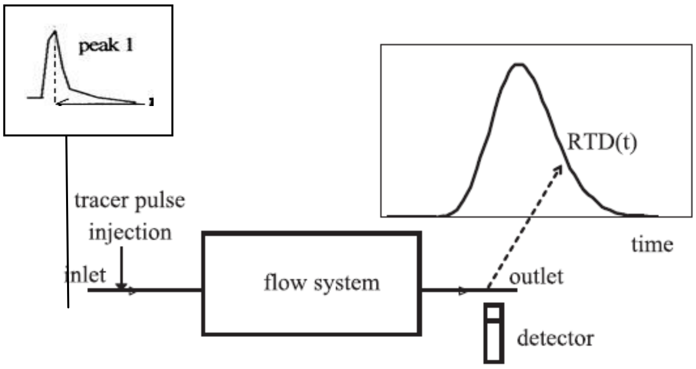

Figure1: Principle measurement of RTD by Stegowski and Furman (2004)

The results obtained from radiotracer experiments are in the form of counts per second (cps) versus time. The curves obtained are then normalized into RTD curves before translating them to MRT curves. The MRT curve was obtained by integrating the area under the curves of the RTD curve as shown in Figure 2. The pre-treatment of data was made prior to plotting the RTD curves as described by IAEA (2001).

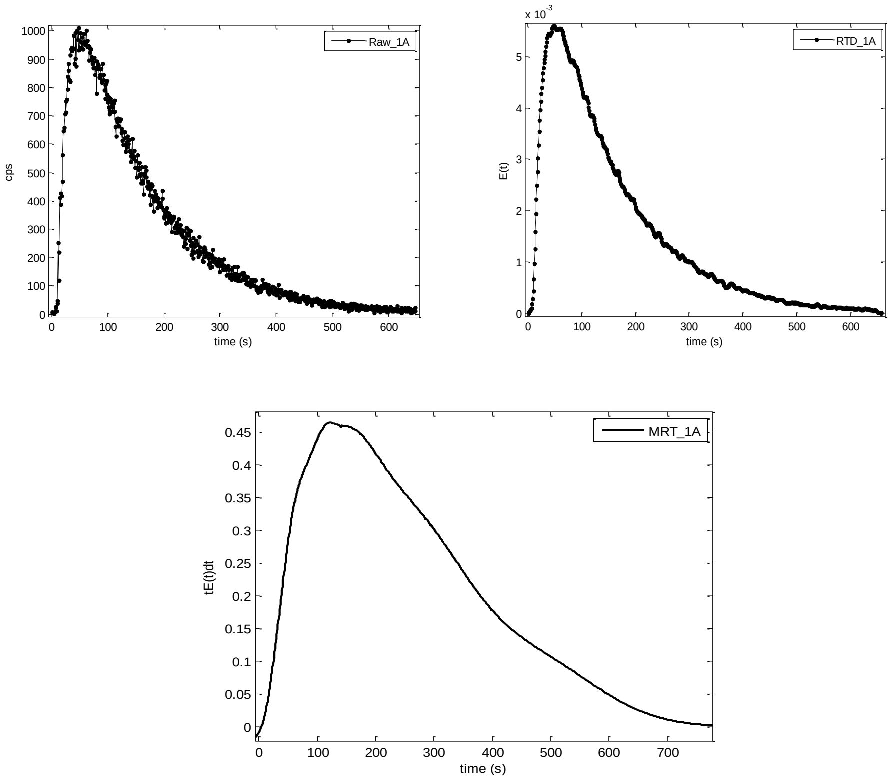

Figure 2: Determination of mean residence time (MRT)

CASE STUDIES

Sugiharto et al. (2009) determined the RTD and the system flow rate in a 24 inches multiphase flow hydrocarbon transmission pipeline containing approximately 95% water, 3% crude oil, 2% gas and negligible solid material. Radiotracer sources I-13 and Na-24 were used independently for the measurement of the RTD in hydrocarbons and water, respectively. The authors discovered that the tanks in series model best described the RTD of the system and the water moved faster than the hydrocarbon even though the density of water is higher. This might be water is more dominant in the transmission line and the movement of crude oil is slowed due to friction with gas at the top layer and friction at the water–crude oil interface. Moreover, Behin and Aghajari (2008) studied the RTD measurement in a pilot-scale oil–water separator operated by Drood oil of the Iranian Offshore Oil Company (IOOC) located in Kharg Island using 5 mCi of I-131 and 4 mCi of I-131 as iodobenzene for the aqueous and organic phase, respectively. They reported that the experimental results were in a good agreement using the model of perfect mixing tanks in series with a dead zone to describe the liquid behaviour. Therefore, it is concluded that tanks in series models suite with the multiphase flow profile.

The next case studies, which were conducted by Pant et al. (2009a) indicate the superiority of radiotracer technology in hostile industrial environments. Pant et al. (2009a) conducted an RTD study in a pilot and an industrialised fluid catalytic cracking unit (FCCU) using an intrinsic tracer. The lanthanum-140 and sodium-24 tracers were obtained from the catalyst sample. The tracers were characterised using neutron activation analysis to investigate the degree of axial mixing and radial distribution in the riser section of the FCCUs and to determine the residence time distribution of the catalyst. According to Pant et al., the axial dispersion model (ADM) is the best model to describe material flow in a tabular reactor, such as FCCU, because this model can describe one-dimensional convection and dispersion in a pipe.

Moreover, Pant et al. (2009b) measured the RTD of coal particles in a pilot-scale fluidised bed gasifier (FBG). These researcher ssuccessfully used 100 g of each lanthanum-140- and gold-198-labelled coal particles or 100 g of lanthanum-140- and gold-198-labelled coal particles 50 g of each at very high temperature, 1000°C, as the radiotracer source. They represented the behaviour of the coal particles that flow from the bottom of the gasifier with tanks in series model. The results revealed that there was a good degree of mixing and that only a small fraction of the feed material by passed and short-circuited from the bottom of the gasifier. This was also the first report of the use of radiotracers in an FBG in India and proved the superiority of radiotracer techniques in the energy industry. Pant and Yelgoankar (2002) investigated the RTD in servotherm special oil as the heat transfer medium (HTM) in two identical aniline production reactors, one of which was the reference reactor. These researchers used Br-82 as para-dibromo benzeneas the radioactive source. The output from the RTD indicated the presence of undesired parallel flow streams in the shell-side of the abnormal reactor due to a 60% fouling of the reactor. The data were treated prior to any RTD analysis to ensure that only the specified radioactive material was analysed. The authors implemented tanks in series model to simulate the results and detected the presence of several anomalies in the reactor, which were mainly fouling/scaling or dead volume. Due to the large amount of fouling in the reactor and the possibility of the occurrence of parallel streams in the shell-side of the reactor, they implemented a model of tanks-in-series with two parallel streams to represent the RTD curve that was obtained from the radiotracer experiments. The results showed the ability of the radiotracer technology to highlight the percentage of abnormalities that were present in the processing plant accurately, which was impossible to achieve with other conventional methods.

CONCLUSIONS

The development of radiotracer technology and a principle of radiotracer technology in residence time distribution (RTD) applications are reviewed. A description of the data analysis is explained and mathematical models that were used in radiotracer applications are also presented. The provided case studies indicated the versatility and feasibility of radiotracer technology in numerous industrial applications. Radiotracer technology has many advantages over conventional tracers; these include its high detection sensitivity, physico-chemical compatibility, in-situ detection and limited memory effect. Radiotracer technology also assists industries in satisfying the critical need for production efficiency through the identification of process malfunctions and anomalies, as well as mechanical damage in the plant. Although radioisotopes have been used to solve a number of industry problems for over 50 years, research and development of the technology continues unchallenged. The greatest benefit of radiotracer technology over the conventional methods is that the investigation can be carried out on-stream and without disrupting the operating process of the plant. Hence, any expensive downtime is avoided and the convenience of direct measurement results in substantial economic benefits and investigating costs.

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