

Engineering: Residence Time Distribution II



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In my previous column (CEREAL FOODS WORLD, July-August 2008), I began a discussion of the concept of a residence time distribution, that is the distribution of times that “particles” experience within a reaction vessel, for example an extruder, preconditioner, or any cooking/sterilization process. This column will continue my explanation of this tool frequently used to “see” what’s going on in a process.

Consider a simple continuous cooking process. Imagine running an experiment to determine the residence time distribution at two flow rates. The residence time distribution is obtained by

injecting some sort of tracer (say a color or a radioactive material) as a pulse at the inlet of the system. Selecting a suitable tracer is not as trivial as it seems and will be discussed at a later date. We then sample the discharge from the process at various times. We might, for the two different flow rates, get a result similar to the results presented in Figure 1. The higher flow rate is twice the lower flow rate.

The differences in residence time and residence time distribution are immediately obvious. As expected, the residence time for the lower flow rate is significantly longer, as illustrated in Figure 1 by the shift of the tracer concentration peak to the right. In fact the average residence time for the lower flow rate is ex-

actly twice that of the higher flow rate. The second observation is that the width of the peak is wider at the lower feed rate. Most observers would say, “The distribution of residence times is wider for the lower flow rate.” Is this correct?

Remember that these residence time distribution curves are really a type of probability density curve, or the area under any segment of the curve represents the probability (the fraction of total material) of some material being resident in the process for the time length of that segment. Let us reconsider the way we look at this data.

Probability density curves, for example a normal probability curve, are always drawn in a dimensionless form. The dimensionless form is chosen so that that the total area under the curve is unity, meaning that the probability of all possible events is only unity. Without yet going into the mathematical details of how that is done with tracer versus time curves, let me present the results of this action in Figure 2.

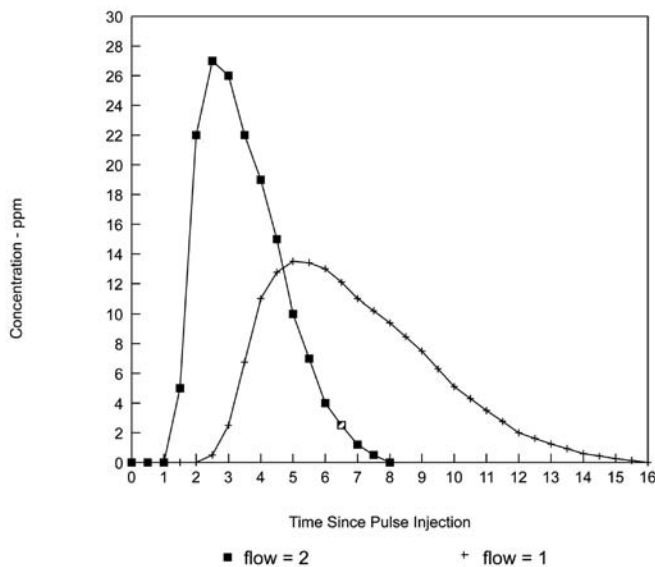


Fig 1. Outlet Tracer Concentration vs. Time

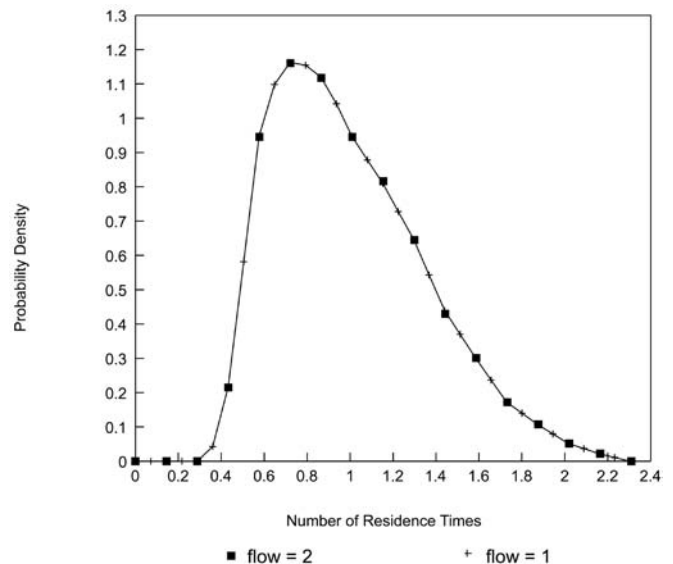


Fig 2. Probability Density vs. Number of Residence Times

Now, can one say that the distribution of residence times is really wider for the lower flow rate? In fact, when present in this form, the deviation of residence times, expressed as a fraction of mean residence time, is identical for both flow rates. The mixing of the tracer material, or as some might say, the dispersion (which is like a diffusivity) of the material, is identical for both conditions. Like a “regular” probability density function, such as a normal distribution, the curve is described by two parameters, a mean, and a standard deviation. The area under the curve between two times is the probability that material (the fraction of total material) will reside in the process between the two times. The only reason the residence time distribution seems wider at

lower flow rates is that the material has a longer time to disperse than at the higher flow rate. In fact, one sees this kind of behavior observed for many processes, such as laminar flow through a pipe, or much of the published data on extruders where the flow rate, screw configuration, and/or screw speeds are changed.

I contend that there is no real difference in the “quality” of the residence time distribution for either case. I can illustrate this with a simple thought experiment. Suppose the process is trying to accomplish a simple, temperature-dependent chemical reaction. The goal of a commercial process, independent of the feed (production) rate, is to produce the identical product that has the same extent of reaction at any feed rate. If I reduce the feed rate through the process, which increases the residence time, I have to reduce the temperature of the process to obtain the same extent of reaction as obtained at the higher flow rate. It’s somewhat difficult to prove mathematically, but the fact that the dispersion of residence times is the same at any flow rate, the net effect is that at the same average extent of the reaction, the distribution of extents of reaction within the product will remain the same. In other words, from both practical and real points of view, there is no difference in process result at difference feed rates. Therefore, there is no difference in the “quality” of the residence time distribution at either flow rate.

Looking at the data this way allows one to make more generalizations about the behavior of processes. For example, when one looks at the residence time distribution data for twin screw

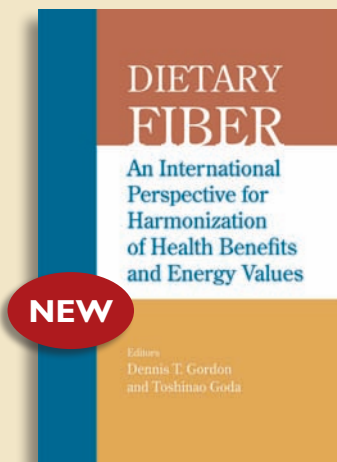
extruders, one can say the process exhibits a dead time of about 60% of the mean residence time, independent of the screw speed, feed rate, and screw configuration being studied. If one looks at the raw data, the results are considerably more difficult to interpret. Another example may be observed when looking at the residence time distribution data for preconditioners (see example, Levine et al., *CEREAL FOODS WORLD*, April 2002, pp 142–148). If one plots the data for the raw residence time distribution for various designs of preconditioners, one might conclude that the “quality” of the residence time distribution is highly dependent on such variables as feed rate and preconditioner design, but when looking at the data in dimensionless form, one finds that the results can be compressed into one set of curves.

To summarize, before anyone can make any real sense of residence time distribution, one must look at the data in the form of a dimensionless probability distribution function. In fact, there is much food literature where this is not done.

In my next column, I will discuss how one actually gets the tracer versus time curve and how one analyzes the data to obtain the mean and standard deviation of the distribution.

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