A First Course on Kinetics and Reaction Engineering

Unit 29. Multiple Reactor Networks

Overview

Unit 29 considers systems where two or more reactors are somehow connected and function together in the processing of a feed stream. There are two reasons for considering these types of reactor networks. First, one might be called upon to perform reaction engineering tasks on a real system that uses such a network of reactors. One common example is a reactor network wherein multiple CSTRs are connected in series. This configuration is sometimes referred to as a cascade of CSTRs, and the greater the number of CSTRs in series, the more the cascade as a whole behaves like a PFR. A less obvious reason for considering reactor networks is that one might attempt to model a single real world (non-ideal) reactor using a network of ideal reactors. The resulting model would be empirical in nature, but nonetheless it would be useful if it proved to accurately predict the performance of the real world reactor.

Learning Objectives

Upon completion of this unit, you should be able to define, in words, the following terms:

- CSTR cascade
- series network
- parallel network

Upon completion of this unit, you should be able to perform the following specific tasks and be able to recognize when they are needed and apply them correctly in the course of a more complex analysis:

- Cite reasons for using multiple reactors instead of a single reactor
- Explain, on physical grounds, the advantages of using a cascade of CSTRs over using a single CSTR
- State that in the limit where the number of CSTRs in a cascade approaches infinity, the performance of the cascade of CSTRs approaches the performance of a PFR
- List the reasons why an infinite cascade of CSTRs, while similar in performance to a PFR, might not perform exactly the same as a PFR
- State the equivalence of two PFRs in series to a single PFR with their combined volume
- State that mixing streams of unequal conversion is usually detrimental to the performance of a reactor network
- Quantitatively analyze the performance of a reactor network

Information

Up to this point in the course, we have only considered single reactors. A chemical process can use more than one reactor, either by design or when the capacity of an existing facility needs to be increased. Alternatively, a single real world reactor might not conform to the assumptions of one of the three ideal reactor types, but it might be accurately modeled *as if* it consisted of two or more reactors. For example, a packed bed reactor might have the packing poorly distributed so that some of the fluid flows through large voids rapidly without contacting much of the packing while the remainder flows through portions of the bed that are more densely packed. This reactor would not conform to an ideal PFR model, but it might be accurately represented by two PFRs operating in parallel where one of the PFRs in the model represented the part of the bed with large voids and the other represented the more densely packed part. In either case, it is clear the a reaction engineer needs to be able to analyze networks of reactors where the reactors may be of the same or of different types and they may be connected in a number of different ways.

The most common configurations of multiple reactors are series networks of reactors and parallel networks of reactors, as illustrated in Figure 29.1. The analysis of any one of the reactors in a network is no different from the analysis of a single reactor. After all, it makes no difference in the analysis of a reactor whether the feed to that reactor is coming from a storage tank somewhere in the chemical plant or from the outlet of another reactor. Similarly, it makes no difference in the reactor analysis whether the product stream is sent to a distillation tower elsewhere in the chemical plant or to another reactor.

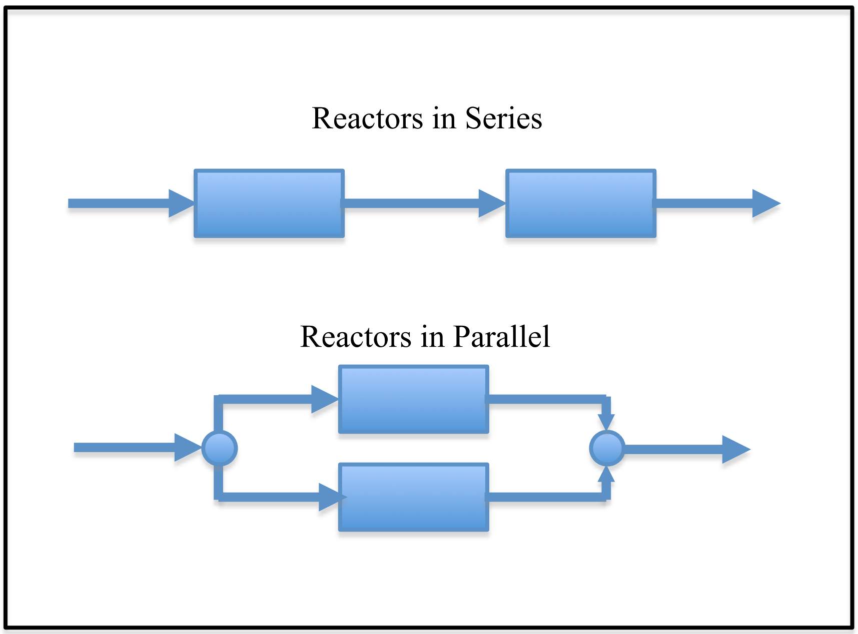

Figure 29.1 Reactors connected (top) in series and (bottom) in parallel.

While the equations used to analyze a reactor in a network are no different from the equations used to analyze a single reactor, solving the design equations can be different. For example, consider two reactors connected in series. It can happen that after the design equations for the first reactor are set up, it is not possible to solve them. (For example, it could be that the overall conversion is known, but not the conversion in just the first reactor.) In such cases, the design equations for the second reactor must also be set up, with the inlet flows and temperature being set equal to the outlet values from the first reactor. It might not be possible to solve the design equations for the second reactor by themselves, either. If that's the case, then the design equations for both reactors would all have to be solved simultaneously.

Again, there is no difference in setting up the design equations for each reactor from setting the equations up for a single reactor. However, it is necessary to recognize which flow streams are equal to each other (such as the outlet from the first series reactor equaling the inlet to the second series reactor), and to recognize that the equations may become coupled so that they all must be solved simultaneously. It is good practice to number or otherwise distinguish each stream in the process and then use those stream designators as the design equations are written. This is illustrated in the examples that accompany this unit.

As already noted, there are different reasons why a reactor network might be used instead of a single reactor. One possibility is expanding the capacity of an existing chemical plant. If the company decides to substantially increase the amount of material they are processing, the existing reactor may not be able to accommodate the increase. (Increasing the flow rate to process more reactant will lower the residence time, and that generally will lower the conversion, offsetting the increased flow.) It would make sense to continue using the existing reactor and add a second reactor to the process rather than eliminating the existing reactor and replacing it with a single, larger reactor. In other cases, multiple reactors might be part of the original design. An example is the use of PFRs where it is necessary to heat or cool. We've already seen that the most practical way to add heat transfer area to a PFR is to use tubes with smaller diameter. It is quite common to use a large number of reactor tubes arranged in parallel, with a single shell surrounding all the tubes to provide heat transfer.

One could envision situations where it might make sense to use two different kinds of reactor in a network, too. For example, consider an autocatalytic reaction such as cell growth. If one wanted to use a plug flow reactor for cell growth, the feed stream would always need to contain cells and substrate. However, if a small CSTR was installed in series ahead of the PFR, only substrate would need to be supplied in the feed. As long as cells are growing in the CSTR, the substrate would mix with those growing cells, and the feed to the PFR would contain both cells and substrate.

It is sometimes advantageous to design a reactor network with multiple CSTRs connected in series. This configuration is sometimes referred to as a cascade of CSTRs. This particular configuration can offer a significant advantage over a single CSTR. Recall that in a CSTR, the feed is immediately diluted to the final composition and temperature, and all reaction occurs at those final conditions. Since the reactant concentration at the final conditions is typically small, and since the rate of reaction becomes small (and eventually zero) as the reactant concentration decreases, this means that in a single CSTR, the reaction usually occurs at a low rate. That, in turn, means that a large reactor volume will be required.

If two smaller CSTRs are used instead of one large CSTR, better performance will be possible. At equal conversions, the reaction rate in the last reactor of the series will be the same as the reaction rate in the single CSTR (for adiabatic operation). This is true because at equal overall conversions the final composition and adiabatic temperature rise will be the same; if the composition and temperature are the same, then the rate is the same. The key point, however, is that in the ***first*** of the series CSTRs, the rate of reaction will be higher, because the reactant concentration will be higher. In this way, the total volume required to accomplish the overall conversion would be smaller than in the single reactor because a part of the conversion would be taking place at a higher rate.

You might be thinking that if the reaction is exothermic and the reactor operates adiabatically, then the increase in temperature (and its tendency to increase the rate) will predominate over the decrease in reactant concentration (and its tendency to decrease the rate). A simple qualitative analysis will show that there will be a critical conversion, and a corresponding critical space time, where the rate reaches a maximum. If one were judicious in selecting the relative volumes of the two reactors in series, the first could be designed so that it operated at the critical space time where the reaction rate was at its maximum value. Then the second CSTR in series would be sized so that the desired overall conversion is achieved.

In fact, if one adds more and more CSTRs in series, making them smaller and smaller so that the total reactor volume remains the same, as the number of CSTRs approaches infinity, the cascade of CSTRs approaches the performance of a PFR. Each CSTR would be like a differential volume within the PFR. In fact, the behavior will not be exactly equal to a PFR in situations where the PFR has a significant pressure drop or in situations where the heat transfer area per reactor volume of the CSTRs does not exactly equal that of the PFR. Still, the behavior of a large number of CSTRs in series will be very, very similar to the behavior of a PFR. In a real design exercise, one would likely analyze CSTR cascades with a different number of reactors (say from one to five) and perform an economic analysis to determine the optimum number of reactors to use.

In a sense, a cascade of CSTRs is a sort of augmented ideal reactor. For a small number of CSTRs in series, the cascade displays performance that is somewhere between that of a single CSTR and a single PFR. Thus, in situations where neither of the ideal reactor types is perfectly suited to the reactions taking place, a CSTR cascade might offer better performance.

There are a couple of things to be aware of when setting up a network of reactors. First, there is no difference (from a performance perspective) between two PFRs in series and one PFR of the same diameter with a volume equal to the two in series. If you think about it, as long as there isn't any heating, cooling or mixing in of additional fluid between the two series reactors, the fluid doesn't "know" that one reactor ended and the next started. It's like hooking two pieces of pipe together, effectively they become one longer piece of pipe. Second, if parallel reactors are used, one should avoid mixing streams of unequal conversion; this effectively undoes some of the reaction that has taken place because after mixing the effective conversion of the mixed stream will be lower than that in the stream with the higher conversion before mixing.