

REACTR: An Industrial Chemical Reactor Dynamic Simulation Computer Program

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Abstract:

REACTR is a computer program designed to simulate the conduct of a chemical reaction in an industrial chemical reactor. REACTR calculates the temperature and chemical concentration profile of the reaction as a function of time. REACTR can simulate reactions governed by first-order, second-order, and consecutive first-order kinetics. It can simulate batch, semi-batch, and continuous reactor operation modes. Further, it can simulate any combination of kinetic model and operation mode under isothermal, adiabatic, or nonisothermal operating conditions. REACTR was evaluated with an extensive validation program, and it provided exceptionally accurate results for all of the validation test problems. A primary use for REACTR is to identify unsafe operating conditions where a run-away reaction might be expected to occur. REACTR also may be used to explore the effect of some process variables on the course of the reaction. The identification of multiple steady states and oscillation in CSTR systems by REACTR simulations shows that the program is capable of producing emergent properties that extend beyond its design. Chemists may find REACTR to be an especially useful tool for learning some important principles of chemical engineering.

Introduction

The science of organic chemistry has made remarkable progress in the synthesis of complex molecules during the past several decades. Organic synthesis programs in the pharmaceutical industry target molecules with specific biological activities with the objective of developing commercial products for the treatment of human and animal diseases.

Recent developments in combinatorial chemistry and related parallel synthesis methodologies and automated high-throughput screening techniques have enabled the identification of very large numbers of potential drug candidates. The rapid identification of active compounds has allowed the pharmaceutical industry to develop new products at an accelerated rate.

The high-throughput synthetic methods provide a means for the preparation of new compounds in milligram quantities. New product development, however, requires gram to kilogram quantities of material. The study of the methodology for the preparation of new chemical entities on a manufacturing scale constitutes the chemical science known as chemical process development.

The initial chemistry focus in the development of a new pharmaceutical product is the identification of a suitable

synthetic route. Several different synthetic routes may be identified to prepare a target molecule, and different reagents may be used to achieve a particular molecular transformation within a given synthetic route. These combinations of syntheses routes and reagents are studied in the route identification phase of process development, and the product of this research is a laboratory process for the preparation of the target molecule on a scale ranging from several hundred milligrams to several grams.

Once a synthetic route and its associated reagents are identified, the individual chemical steps of the synthesis are studied with the objective of understanding the details of each reaction. The reaction mechanism may be studied if it is not already well understood, and the fundamental parameters that affect the performance of the reaction are identified. This synthesis development phase of process development provides the fundamental information required for scale-up of the chemical reaction.

The transition from the synthesis of a compound on a gram scale in the laboratory to the synthesis of that compound on a multikilogram scale in a chemical plant constitutes the essential focus of the scale-up phase of chemical process development.

The development of chemical processes for the synthesis of organic molecules on a large scale involves the use of organic chemistry, physical chemistry, and chemical engineering principles. Three of the major issues addressed during the development of a new chemical manufacturing process are economics, safety, and scalability.

Economics eventually drives all commercial activities, and the development of the lowest-cost chemical process is essential for business success. The cost of goods for a chemical product is governed by the cost of the raw materials, the cost of the equipment used for the production, the cost of labor to conduct the production, and the yields of the individual steps in the synthetic route. These cost drivers provide a clear direction for the initial phases of route identification and synthesis development. Organic chemists usually conduct these early phases of process development.

Process safety is essential to the success of the chemical process as it provides for the well-being of personnel and for the preservation of the means of production. Process safety is related in an obvious way to the inherent toxicological and physicochemical properties of the reagents and solvents used in the process.

The safe operation of a process also is intimately related to the thermokinetic profile of the reaction. The control of reaction rate and the corresponding heat-generation rate are

pivotal to the prevention of unsafe, run-away reactions.¹ Proper control of the reaction temperature also influences the reaction product distribution and ensures that product of the required purity and quality is produced. These are issues that constitute, in part, the scalability of a process.

Process scalability also derives from the physical properties of the reaction mixture and the isolated reaction products. The selection of equipment appropriate for processing the reaction materials also is an important aspect of ensuring the scalability of a process. Chemical engineers typically address safety and scalability issues during the later phase of process development.

Process development excellence necessarily derives from the collaborative work of chemists and chemical engineers. Successful collaboration between these two disciplines requires that each understand the fundamental principles of the other. Chemical engineers often have varying exposures to organic chemistry during their education and work experience. Academic physical chemistry is usually the initial means by which chemists can relate to chemical engineering. Chemists also have varying exposure to the principles of chemical engineering in their industrial experience.

We sought to enhance the effectiveness of process development in our organization by providing a tool for organic chemists to facilitate their understanding of chemical engineering as it relates to the scale-up of a chemical reaction. This tool, a computer program called REACTR, assembles and integrates basic kinetic and thermodynamic equations from physical chemistry and chemical engineering for easy understanding and use by the organic chemist. REACTR calculates the dynamic simulation of a chemical reaction in an industrial chemical reactor.

Chemical reaction dynamic simulations have been reported in the literature and have been implemented in commercial computer programs.²⁻⁴ These contributions typically originate in the chemical engineering community, and they have tended to reflect the emphasis of that discipline. The intent of REACTR is to provide the organic chemist with a quantitative estimate of the reaction composition and reaction temperature as a function of time given an initial set of reaction variables.

A primary use for REACTR is to identify unsafe operating conditions where a run-away reaction might be expected to occur. As the scale of a chemical reaction is increased, the reaction volume increases much more rapidly than does the reaction vessel heat-transfer surface area. REACTR provides a means for determining when there is insufficient heat-transfer area to remove heat and maintain the desired reaction temperature. Similarly, REACTR provides the capability to study other ways to control an exothermic reaction. For example, the effects of lowering the temperature of the heat-transfer fluid and increasing its flow rate at the onset of an exotherm may be evaluated.

In addition to providing data for use in process safety determinations, REACTR may be used to explore the effect of process variables on the course of the reaction. REACTR simulation results also may be useful for determining the direction of future process development work.

REACTR is structured so that process scale-up issues of varying difficulty may be evaluated. Listed below are some examples of the types of problems that REACTR can solve. Clearly, these are problems that are not normally addressed by the typical organic chemist:

- calculate heating or cooling curves for materials in a batch reactor
- evaluate the course of a chemical reaction conducted under adiabatic conditions
- estimate the effect of reagent addition rate on the temperature of a reaction
- determine the concentration and the temperature profiles of a reaction in a continuous reactor system during the startup phase of operation
- identify continuous reactor operating conditions that lead to oscillating temperature and concentration profiles

Results and Discussion

Description of REACTR Simulation Models. The REACTR model is of a cylindrical reaction vessel with an agitator and a jacket to provide heating or cooling. The user specifies a reactor diameter and the program automatically adjusts the reactor height to accommodate the volume of materials to be contained in the vessel in the simulation.

The model reaction vessel is equipped with a reflux condenser to condense refluxing solvent. The condenser is of unlimited capacity, and it returns condensate to the reaction vessel at a temperature specified by the user.

Chemical reagents or products **A**, **B**, **C**, and **D** may be present initially in the model reaction vessel or they may be fed into the reaction vessel from a feed tank associated with the reaction vessel. Both reaction vessel and feed tank may contain any amount of the four chemical species as specified by the user. The user also specifies the initial temperatures of the contents of the reaction vessel and the feed tank and the rate at which the feed tank contents are fed into the reaction vessel.

REACTR simulates three reaction operation modes, semi-batch, batch, and continuous. In the semi-batch mode the reagent solution is added to the reaction vessel over time followed by a hold time for completion of the chemical reaction. A batch reaction is a semi-batch reaction for which all reagents have been added to the reaction vessel. The batch and semi-batch reaction operation modes are most commonly used in the fine chemical and pharmaceutical industries.

In the continuous reaction operation mode the reagent solution is added to the reaction vessel at the same rate that a portion of the reaction solution is removed from the vessel. This is also called a continuously stirred tank reactor (CSTR). The CSTR is most commonly used for the production of commodity scale chemicals.

The batch reaction is the easiest model to simulate. In a batch reaction the reactor volume is constant. This means

(1) (a) Kladko, M. The Case of a Real Engineering Design Problem Solved by the Application of Chemical Kinetics. *Chem. Technol.* **1971** (March), 141–147. (b) Etchells, J. C. Why Reactions Run Away. *Org. Process Res. Dev.* **1997**, *1*(6), 435–437.

(2) *BatchCAD*; GSE SYSTEMS INC.: Columbia, MD.

(3) *Aspen Plus*; Aspen Technology, Inc.: Cambridge, MA.

(4) *HYSIM*; Hyprotech: Calgary, Alberta, Canada.

that the concentration of chemical species changes only as a result of chemical reaction. Also, the heat-transfer area of the reaction vessel is constant for a batch reaction.

A CSTR reaction operates with a constant volume and, therefore, with a constant heat-transfer area. The concentration of chemical species changes due to chemical reaction and dilution from the feed solution. Simulation of a CSTR is of intermediate difficulty.

A semi-batch reaction represents a variable reaction volume problem. The concentration of chemical species changes as a result of chemical reaction and as a result of dilution by the feed solution being added to the reaction vessel. Furthermore, the heat-transfer area of the reaction vessel changes as the feed solution is added to the vessel. The semi-batch reaction mode is the most challenging mode to simulate.

REACTR can simulate reactions under isothermal or adiabatic conditions. These are the limiting extremes that are the subject of study in most physical chemistry and chemical engineering textbooks.

Simulation of an isothermal reaction requires the assumptions that no heat is generated due to chemical reaction, no heat transfer occurs through the reactor wall, and no heat transfer occurs due to changes in reaction mass. These simplifying assumptions are not realistic, but they do allow for easier manipulation of the equations that characterize the chemical reaction kinetics.

An adiabatic reaction simulation assumes that heat is generated from the chemical reaction, heat transfer occurs due to changes in reaction mass, but no heat transfer occurs through the reactor wall. Again this simplifying assumption is not realistic, but it does simplify the understanding of the system under question.

REACTR also allows the simulation of the more realistic nonisothermal case where heat is generated from the chemical reaction, heat transfer occurs due to changes in reaction mass, and heat transfer occurs through the reactor wall.

REACTR provides four chemical reaction kinetics models. The No-Kinetics Model allows one to simulate simple dilutions or cooling curves without a chemical reaction occurring. The remaining kinetics models are based on the Arrhenius model for chemical reaction kinetics. The kinetics models utilize the four chemical species, **A**, **B**, **C**, and **D** as reactants and products.

The First-Order Kinetics Model simulates the chemical reaction in eq 1 using first-order kinetics. First-order kinetics serves as the initial model for the study of most organic chemical reactions. This model can be characterized using simple mathematical equations, and the facile solution of these equations ensures its wide use.



The Consecutive First-Order Kinetics Model simulates the consecutive chemical reactions shown in eq 2 with each reaction governed by first-order kinetics. This model is useful for describing the formation of an impurity from an initial reaction product or the formation of a product from an intermediate. It is mathematically complex, and consequently

it enjoys limited use in the practice of chemical process development.



The Second-Order Kinetics Model simulates the second-order chemical reaction given in eq 3 using second-order kinetics. This model is commonly used, but it is mathematically more complex than the first-order model.



Any of the four kinetics models can be used in batch, semi-batch, or continuous reaction modes and under isothermal, adiabatic, or nonisothermal conditions. A total of 36 distinct reaction models are embodied in REACTR as a result of the various possible operating combinations.

REACTR Model Assumptions. The simulation of a chemical reaction in an industrial reactor is a marvelously complex computation, and a number of simplifying assumptions are necessary to make the calculations tractable:

- the vessel itself does not absorb or release heat
- energy input from the agitator is negligible
- the overall heat-transfer coefficient is temperature-independent
- the reaction solution is perfectly mixed and homogeneous
- the heat capacity of the solvent represents a weighted average for all contained components and is temperature-independent
- the density of the solvent represents a weighted average for all contained components and is temperature-independent
- the chemical reactions represented by the kinetics models are irreversible
- the heats of reaction are temperature-independent

Input and Output. REACTR simulations require the user to input a data set consisting of a minimum of 25 individual pieces of data describing the chemical reaction and the reactor. The data input is achieved by entering the appropriate data into a data input form. The REACTR Data Input Form is shown in Exhibit 1.

The units of the input variables and spaces for the data entry are provided on the REACTR Data Input Form. The input variables are grouped in a meaningful way. In addition, the data entered for a given problem can be saved for later use.

Six data entry groups are presented on the REACTR Data Input Form. Data for the reaction mode, kinetics model, number of iterations, and kinetics and enthalpy parameters are entered in the Kinetics group.

The user inputs "S" to specify the semi-batch or batch reaction mode or "C" to select the continuous reaction mode. The kinetics model is chosen by inputting "N" for the No-Kinetics Model, "F" for the First-Order Kinetics Model, "S" for the Second-Order Kinetics Model, and "C" for the Consecutive First-Order Kinetics Model.

The number of iterations for the simulation is entered, and it may be any value from the acceptable range of 1–150 000. A minimum of 10 iterations per second of simulated time is used. Proportionately more iterations per second are used for reactions that have large rate constants.

Exhibit 1. REACTR Data Input Form

Kinetics				Reaction #1	Reaction #2
Reaction Mode (S, C)	_____	Heat of Rxn.	Kcal/mole	_____	_____
Kinetic Model (N,F,S,C)	_____	Energy of Act.	Kcal/mole	_____	_____
Number of Iterations	_____	Pre-exp. Factor	1/sec or L/mole*sec	Exp _____	Exp _____

The diagram shows a central reaction vessel with a stirrer and a diameter input field. To its left is a 'Feed and Hold' tank with 'Feed Rate L/sec' and 'Hold Time sec' inputs. To its right is a 'Condenser' with 'Temp. Returning Distill. °C' input. Below the vessel is a 'Solvent' box with 'Density Kg/L', 'Heat Cap. Kcal/Kg*°C', 'Heat of Vap Kcal/Kg', and 'Boiling Pt. °C' inputs. To the right of the vessel is a 'Coolant' box with 'Temp. °C', 'Flow Rate L/sec', 'Density Kg/L', 'Heat Cap. Kcal/Kg*°C', and 'Overall Heat Transfer Coefficient' (with an 'Exp' input) inputs. To the left of the vessel is a 'Solutions' table with columns for 'Feed' and 'Vessel' and rows for 'Volume L', 'Temperature °C', and concentrations of sol'n A, B, C, and D in mole/L.

Solutions		Feed	Vessel
Volume	L	_____	_____
Temperature	°C	_____	_____
Conc. sol'n A	mole/L	_____	_____
Conc. sol'n B	mole/L	_____	_____
Conc. sol'n C	mole/L	_____	_____
Conc. sol'n D	mole/L	_____	_____

The heat of reaction is entered as a positive value if the reaction is exothermic and as a negative value if the reaction is endothermic. The Arrhenius energy of activation and pre-exponential factor are input with the latter entered as an exponential number. For the Consecutive First-Order Kinetics model, two activation energies, two pre-exponential factors, and two heats of reaction must be entered.

The Feed and Hold group accepts data for the reagent feed-rate and the hold time after the completion of the reagent feed. The feed-rate field must contain a nonzero value even when a batch reaction is being simulated. The user enters the duration of a batch reaction into the Hold Time field.

The volumes, temperatures, and reagent concentrations for both the feed vessel and reaction vessel contents are entered into the Solutions group. The feed solution and the reaction vessel solution may be different temperatures and may contain different concentrations of any of the four chemical species A–D.

Physical properties for the reaction vessel heat-transfer fluid are entered into the Coolant group. The coolant temperature, flow rate, density, and heat capacity are specified. The Coolant group also accepts data for the overall heat-transfer coefficient⁵ for the reaction vessel. The heat-transfer fluid may be used either to cool or to heat the reaction vessel contents in a simulation.

Physical properties for the solvent are entered into the Solvent group. The solvent density, heat capacity, heat of vaporization, and boiling point are entered into the fields in this group.

The temperature of the returning distillate is the single entry in the Condenser group, and the reaction vessel diameter entry is contained within the graphical representation of that vessel.

After the input data are entered, REACTR calculates the simulation model and tabulates the final values of temperature and concentration. In addition, REACTR organizes the simulation data into a report format that, at the user's option, can be displayed on the screen or saved to a file. The report file, in turn, can be viewed on the screen or printed. The data in the report file can be transferred easily to Microsoft Excel for plotting, and this is the method used to prepare the plots presented in this paper.

The REACTR report includes a summary of the input variables upon which the simulation is based, a summary of the simulation results in terms of the final temperature and chemical concentrations, and the individual iteration data, which show the time dependence of the temperature and chemical concentrations. The first two pages of a REACTR report are shown in Exhibit 2.

REACTR Implementation and Structure. REACTR was originally implemented on a Hewlett-Packard HP-41C programmable calculator by one of the authors (T.R.K.). Subsequently, the authors upgraded the program and translated it to DEC VAX Basic. The program is of a modular construction, and it resides on a DEC VAX computer. Most REACTR simulations complete in less than one minute depending upon competing demand for the computational resource.

The program breaks the time period of the simulation into differential time elements or iterations and then sequentially calculates the various integrated equations that govern the

(5) Shilling, R. L.; Bell, K. J.; Bernhagen, P. M.; Flynn, T. M.; Goldschmidt, V. M.; Hrnjak, P. S.; Standiford, F. C.; Timmerhaus, K. D. Heat-Transfer Equipment. In *Perry's Chemical Engineers' Handbook*, 7th ed.; Perry, R. H., Green, D. W. Eds.; McGraw-Hill: New York, 1997; p 11:27.

Report for Reactr Program
Date: 6-Dec-2000

Page: 1
Time: 08:01 AM

Reaction Parameters

Reaction mode: CSTR
Kinetic model: Second Order
Number of iterations: 120000
Heat transfer coeff.: 0.950 E-5 Kcal/cm²*C*sec
Main reactor diameter: 10.0 cm
Distillate return temp.: 56.0 C
Feed rate: 0.001525 L/sec
Hold time: 0.00 sec
Heat of reaction: 22.4 Kcal/mole
Energy of activation: 12.1 Kcal/mole
Pre-exponential factor: 3.37 E5 1/sec or L/mole*sec

Solvent

Density: 0.812 Kg/L
Heat capacity: 0.583 Kcal/Kg*C
Heat of vaporization: 124.4 Kcal/Kg
Boiling point: 56.0 C

Coolant

Density: 1.000 Kg/L
Heat capacity: 0.887 Kcal/Kg*C
Temperature: -3.15 C
Flow rate: 0.00333 L/sec

Solutions

		Feed	Vessel	
Volume:		18.300	1.000	L
Temperature:		10.85	10.85	C
Concentration	Sol. A:	4.2100	0.0000	mole/L
	Sol. B:	5.0600	0.0000	mole/L
	Sol. C:	0.0000	0.0000	mole/L
	Sol. D:	0.0000	0.0000	mole/L

Results

Solution:	A	B	C	D	
Concentration:	2.40	3.25	1.81	0.00	mole/L
Temperature:	19.12 C				

energy and mass balances during the period of the iteration. As the size of the differential time element approaches zero, the results of the simulation approach the results that would derive from the solution of the system of simultaneous nonlinear differential equations that govern the energy and mass balances of the system. This conclusion derives from the fundamental concept of integral calculus expressed in eq 4.

$$\int f(x)dx = \lim_{\Delta x_i \rightarrow 0} \sum_i f(x_i)\Delta x_i \quad (4)$$

The integrated equations used in REACTR were taken from various undergraduate level physical chemistry and chemical engineering textbooks cited in this paper. The equations were adapted to calculate temperature and concentration changes from one iteration to the next. This paper brings these equations together in one place to facilitate the

Report for Reactr Program
Date: 6-Dec-2000

Page: 2
Time: 08:01 AM

Individual Iteration Data

No	Time (sec)	Temp (C)	conc A (mole/L)	conc B (mole/L)	conc C (mole/L)	conc D (mole/L)
1000	100.00	6.18	0.5936782	0.7138947	0.0017468	0.0000000
2000	200.00	3.89	1.0965287	1.3199593	0.0101098	0.0000000
3000	300.00	3.00	1.5189369	1.8309840	0.0266134	0.0000000
4000	400.00	2.94	1.8706077	2.2587380	0.0517788	0.0000000
5000	500.00	3.39	2.1599314	2.6133845	0.0859948	0.0000000
6000	600.00	4.19	2.3941066	2.9036438	0.1296007	0.0000000
7000	700.00	5.23	2.5792952	3.1369844	0.1829064	0.0000000
8000	800.00	6.48	2.7207311	3.3197622	0.2462343	0.0000000
9000	900.00	7.90	2.8227877	3.4573136	0.3199815	0.0000000
10000	1000.00	9.51	2.8890096	3.5540102	0.4046992	0.0000000
11000	1100.00	11.29	2.9221086	3.6132739	0.5011923	0.0000000
12000	1200.00	13.30	2.9239114	3.6375409	0.6106532	0.0000000
13000	1300.00	15.55	2.8952359	3.6281524	0.7348563	0.0000000
14000	1400.00	18.14	2.8356510	3.5851268	0.8764582	0.0000000
15000	1500.00	21.15	2.7430420	3.5067350	1.0394845	0.0000000
16000	1600.00	24.75	2.6128484	3.3887479	1.2301361	0.0000000
17000	1700.00	29.20	2.4368281	3.2232077	1.4580639	0.0000000
18000	1800.00	34.89	2.2016664	2.9970439	1.7377916	0.0000000
19000	1900.00	42.18	1.8916078	2.6947107	2.0861132	0.0000000
20000	2000.00	50.23	1.5179577	2.3276933	2.4926148	0.0000000
21000	2100.00	54.17	1.2022301	2.0176603	2.8365477	0.0000000
22000	2200.00	49.48	1.1056446	1.9259640	2.9573494	0.0000000
23000	2300.00	40.01	1.2052761	2.0297933	2.8785091	0.0000000
24000	2400.00	30.66	1.4022637	2.2303850	2.6993721	0.0000000
25000	2500.00	23.34	1.6306451	2.4618607	2.4863168	0.0000000
26000	2600.00	18.23	1.8562842	2.6901565	2.2738362	0.0000000
27000	2700.00	14.97	2.0628237	2.8989769	2.0785942	0.0000000
28000	2800.00	13.09	2.2429923	3.0811039	1.9081253	0.0000000
29000	2900.00	12.21	2.3940520	3.2338450	1.7653934	0.0000000
30000	3000.00	12.05	2.5154996	3.3567362	1.6510958	0.0000000
31000	3100.00	12.42	2.6078906	3.4503666	1.5648435	0.0000000
32000	3200.00	13.20	2.6722111	3.5157512	1.5057936	0.0000000
33000	3300.00	14.32	2.7095174	3.5539712	1.4730124	0.0000000
34000	3400.00	15.73	2.7207106	3.5659487	1.4657044	0.0000000
35000	3500.00	17.43	2.7063783	3.5522900	1.4833723	0.0000000
36000	3600.00	19.41	2.6666759	3.5131657	1.5259386	0.0000000
37000	3700.00	21.70	2.6012460	3.4482323	1.5938274	0.0000000
38000	3800.00	24.33	2.5092336	3.3566461	1.6879508	0.0000000
39000	3900.00	27.33	2.3895770	3.2373555	1.8094199	0.0000000
40000	4000.00	30.70	2.2420673	3.0901599	1.9584859	0.0000000

understanding of how they contribute in concert to the dynamic simulation of a chemical reaction in an industrial chemical reactor. A Glossary of REACTR terminology is provided at the conclusion of this paper.

REACTR Equations. Differential Time Element. The differential time element t is calculated as shown in eq 5 as the quotient of the reaction time and the number of iterations N_{iter} . The reaction time is the sum of the hold time H_{time} and

the reagent addition time that, in turn, derives from the volume of the feed V_f and the volumetric feed rate Q_f .

$$t = [(V_f/Q_f) + H_{time}]/N_{iter} \quad (5)$$

Energy Balance. Heat is added to or removed from the reaction vessel contents in a REACTR simulation by five mechanisms:

- heat exchange with heat-transfer fluid
- addition of reagent feed solution
- solvent distillation
- chemical reaction
- removal of reaction solution in the CSTR model

Heat Exchange with Heat-Transfer Fluid. REACTR uses eqs 6–10 to calculate the heat transferred into or out of the reaction vessel due to the heat-transfer fluid flowing through the jacket. These equations were derived from a set of equations for determining heat exchanger capacity.⁶ The log-mean temperature difference between the reaction vessel contents and the heat-transfer fluid is used as the basis for the heat balance across the reactor wall. The reader is referred to the original literature for a detailed summary of the underlying logic of these complex equations.

$$T_{(i+1)} = [T_i[B - Z] + BT_c[C - 1]]/[CB - Z] \quad (6)$$

where

$$A_i = 4000V_i/D \quad (7)$$

$$B = tQ_c\rho_c C_{pc} \quad (8)$$

$$C = \exp[tUA_i[B - Z]/BZ] \quad (9)$$

$$Z = V_i\rho C_p \quad (10)$$

In eq 6 $T_{(i+1)}$ is the calculated temperature in the reaction vessel for the $(i + 1)$ th differential time element and T_i is the temperature from the previous iteration. T_c is the inlet temperature of the heat-transfer fluid.

The heat-transfer area A_i is calculated in eq 7 from the volume of the reaction vessel V_i during the i th iteration and the vessel diameter D . The reader will recognize that eq 7 calculates the vertical wall area of the reaction vessel and neglects any contribution to the heat-transfer area from the bottom horizontal section of the vessel.

The contributions of the volumetric flow rate Q_c , the density ρ_c , and the heat capacity C_{pc} of the heat-transfer fluid are contained in eq 8. The effects of the density ρ and heat capacity C_p of the reaction mixture are determined in eq 10.

Addition of Reagent Feed Solution. The reagent feed solution and the solution in the reaction vessel (if any) may have different temperatures in a REACTR simulation. This temperature difference is accommodated using eqs 11–12. The mass of feed solution M_{fi} added to the reaction vessel during a differential time element is calculated using eq 11. M_{fi} is used with the temperature of the feed solution T_f and the mass M_i and temperature T_i of the reaction vessel contents in eq 12 to calculate $T_{(i+1)}$, the new temperature of those contents as a result of addition of the feed solution.

$$M_{fi} = t\rho Q_f \quad (11)$$

$$T_{(i+1)} = [M_{fi}T_f + M_iT_i]/[M_{fi} + M_i] \quad (12)$$

Solvent Distillation. In a REACTR simulation, appropriately, the temperature of the reaction solution never exceeds the boiling point of the solvent. When the heat input to the system would cause the temperature of the reaction solution to exceed the boiling point, REACTR uses the heat of vaporization H_{vap} of the solvent to calculate the mass of distilled solvent, M_d using eq 13.

$$M_d = M_i C_p [T_i - T_b]/H_{vap} \quad (13)$$

In the simulation the condensed distillate is returned to the reaction vessel at temperature T_d as specified by the user. The effect of the returned distillate on the temperature of the reaction vessel contents is calculated using eq 14 recognizing that M_i is the sum of the mass of the reaction mixture remaining in the reactor after distillation, M_r and the mass of the distilled solvent, M_d (eq 15).

$$T_{(i+1)} = [M_r T_b + M_d T_d]/M_i \quad (14)$$

$$M_i = M_r + M_d \quad (15)$$

Chemical Reaction. The heats q_1 and q_2 generated in each of the two possible chemical reactions in a REACTR simulation are calculated using eqs 16–17. These equations are identical except for the different reaction species concentrations. For the First-Order Kinetics Model, the concentration of reagent **A**, $C_{i(A)}$, is used in eq 16. For the Second-Order Kinetics Model, the concentrations of reagents **A** and **B**, $C_{i(A)}$ and $C_{i(B)}$, respectively, are used in eq 16. The Consecutive First-Order Kinetics Model requires the use of both eqs 16–17.

$$q_1 = tk_1 H_1 V_i C_{i(A,B)} \quad (16)$$

$$q_2 = tk_2 H_2 V_i C_{i(C)} \quad (17)$$

The heat generated from the chemical reaction(s) during a differential time element is used in eq 18 to calculate the temperature change due to chemical reaction during that interval.

$$T_{(i+1)} = T_i + [(q_1 + q_2)/\rho C_p V_i] \quad (18)$$

Removal of Reaction Solution in the CSTR Model. Heat removal from a CSTR reactor is accomplished by the mechanism used to maintain the reaction volume constant. Details of this mechanism are presented in the mass balance section that follows.

Mass Balance. Mass is added to or removed from the reaction vessel in a REACTR simulation by three mechanisms:

- solvent distillation
- addition of reagent feed solution
- removal of reaction solution in the CSTR model

Solvent Distillation. Solvent distillation removes mass from the reaction, but in the REACTR model the condensed distillate is returned back to the reaction vessel. Consequently there is no net change in mass as a result of solvent distillation.

(6) Petrosky, J. T. Direct Calculation of Exchanger Exit Temperatures. In *Calculation and Shortcut Deskbook Published by Chemical Engineering*; McGraw-Hill: New York; p 46.

Addition of Reagent Feed Solution. The mass of the feed solution added during a differential time element, M_{fi} , is given by eq 11. This mass is added to the mass of the reaction solution, M_i , to give the new mass of the reaction solution, $M_{(i+1)}$ as shown in eq 19.

$$M_{(i+1)} = M_i + M_{fi} \quad (19)$$

The total volume of the final reaction solution, V_T shown in eq 20, is the sum of the volume of the feed solution, V_f , and the initial volume of solution in the reaction vessel, V_r . A more important issue for REACTR is the volume change during a differential time element and its effect on the concentration of the various chemical species present.

$$V_T = V_f + V_r \quad (20)$$

The molar concentrations of the chemical species in the reaction solution in the $(i + 1)$ th differential time element is given by eq 21. The number of moles of a chemical species added via the reagent feed solution is divided by the reaction solution volume V_i to give intermediate chemical species concentration I as shown in eq 22. Concentration I for each chemical species is added to the molar concentration of that species in the reaction solution, and the sum is attenuated by the volume adjustment factor V_a defined in eq 23.

$$C_{(i+1)(A,B,C,D)} = V_a [C_{i(A,B,C,D)} + I] \quad (21)$$

where

$$I = tQ_f C_{f(A,B,C,D)} / V_i \quad (22)$$

$$V_a = V_i / [tQ_f + V_i] \quad (23)$$

Removal of Reaction Solution in the CSTR Model. The initial reaction solution volume, V_r is used as the volume throughout a CSTR model simulation. Consequently, the volume adjustment factor, V_a accomplishes, mathematically, the removal of reaction solution equal in volume to the feed solution added during each differential time element. This adjustment addresses both the removal of heat and the removal of mass from the system.

Kinetics. Common Kinetic Expressions. REACTR uses the Arrhenius kinetic model as the basis for its kinetic models. The rate constant for the first reaction k_1 , expressed in eq 24, is defined in terms of the pre-exponential factor A_1 and the exponential containing the energy of activation E_{a1} , the temperature T_i expressed in K, and the universal gas constant R . The rate constant for the second reaction is defined in the same fashion in eq 25. Equations 26–27 define common kinetic expressions that are used to calculate chemical species concentrations for the First-Order Kinetics and Consecutive First-Order Kinetics Models.

$$k_1 = A_1 \exp[-E_{a1}/RT_i] \quad (24)$$

$$k_2 = A_2 \exp[-E_{a2}/RT_i] \quad (25)$$

$$S_1 = \exp[-k_1 t] \quad (26)$$

$$S_2 = \exp[-k_2 t] \quad (27)$$

The equations that calculate the chemical species concentrations for the $(i + 1)$ th differential time element for each of the kinetic models are given below. These equations are based on the reaction rate constants and the chemical species concentrations from the preceding iteration.

First-Order Reaction Kinetics.

$$C_{(i+1)(A)} = C_{i(A)} S_1 \quad (28)$$

$$C_{(i+1)(C)} = C_{i(C)} + C_{i(A)} [1 - S_1] \quad (29)$$

Consecutive First-Order Reaction Kinetics.

$$C_{(i+1)(A)} = C_{i(A)} S_1 \quad (30)$$

$$C_{(i+1)(C)} = C_{i(C)} S_2 + [k_1 C_{i(A)} [S_1 - S_2] / [k_2 - k_1]] \quad (31)$$

$$C_{(i+1)(D)} = C_{i(D)} + C_{i(C)} [1 - S_2] +$$

$$C_{i(A)} [1 - [k_2 S_1 / [k_2 - k_1]] + [k_1 S_2 / [k_2 - k_1]]] \quad (32)$$

Second-Order Reaction Kinetics.

$$C_{(i+1)(A)} = C_{i(A)} [C_{i(B)} - C_{i(A)}] / [C_{i(B)} \exp[\alpha] - C_{i(A)}] \quad (33)$$

where

$$\alpha = k_1 t [C_{i(B)} - C_{i(A)}] \quad (34)$$

$$C_{(i+1)(B)} = C_{i(B)} [C_{i(A)} - C_{i(B)}] / [C_{i(A)} \exp[\beta] - C_{i(B)}] \quad (35)$$

where

$$\beta = k_1 t [C_{i(A)} - C_{i(B)}] \quad (36)$$

$$C_{(i+1)(C)} = C_{i(C)} + C_{i(A)} - C_{(i+1)(A)} \quad (37)$$

Validation. Validation of a computer program is simply a demonstration that the program will output the correct results for a given set of input. While it is impossible to investigate all combinations of input variables (≥ 25) for a program of the magnitude of REACTR, it is certainly desirable to explore representative data sets such that all parts of the program are evaluated to some extent. Achievement of this goal is limited by the examples available in the literature and the extreme complexity of doing these types of calculations manually.

A set of 18 test problems was selected from the literature, and each of the problems was simulated with REACTR. The objective of the validation was to achieve temperatures and concentrations within 5 °C and 0.2 M of the literature or calculated values, respectively. The results of the REACTR validation exercises are summarized in the REACTR Validation Table presented in Table 1.

For each of the test problems, REACTR performed the required simulation remarkably well. Calculated temperatures were within 2 °C, and calculated concentrations were within 0.15 M of the literature values. In fact, most of the results were even much closer to the literature values. The validation

Table 1. REACTR Validation Table

entry	operation	thermal	kinetics	test	REACTR	source	ref
1a	continuous	isothermal	first-order	time to reach 99% of equilibrium concentration	710.00 s	708.47 s	8
1b	continuous	isothermal	first-order	concentration of A at 99% of equilibrium concentration	6.3097 M	6.3081 M	8
2	continuous	isothermal	first-order	concentration of A at 1000 s	6.3635 M	6.3622 M	8
3a	continuous	isothermal	second-order	conversion at equilibrium for 1 M initial concentration	40.38%	40.38%	9
3b	continuous	isothermal	second-order	conversion at equilibrium for 2 M initial concentration	52.11%	52.11%	9
3c	continuous	isothermal	second-order	conversion at equilibrium for 5 M initial concentration	65.92%	65.93%	9
4a	continuous	isothermal	consecutive first-order	concentration of A at equilibrium	2.6307 M	2.6315 M	10
4b	continuous	isothermal	consecutive first-order	concentration of C at equilibrium	0.1534 M	0.1535 M	10
4c	continuous	isothermal	consecutive first-order	concentration of D at equilibrium	0.2133 M	0.2149 M	10
5	continuous	isothermal	no-kinetics	weight of contained A at 3000 s	0.1494 kg	0.1491 kg	11
6a	continuous	adiabatic	first-order	temperature at equilibrium	68.77 °C	67.22 °C	12
6b	continuous	adiabatic	first-order	concentration of C at equilibrium	1.8302 M	1.7959 M	12
7a	continuous	nonisothermal	first-order	temperature at equilibrium	41.61 °C	40.00 °C	13
7b	continuous	nonisothermal	first-order	concentration of C at equilibrium	0.8381 M	0.7817 M	13
8a	continuous	nonisothermal	first-order	temperature at equilibrium for first steady state	20.74 °C	20.55 °C	14
8b	continuous	nonisothermal	first-order	concentration of A at equilibrium for first steady state	4.5185 M	4.6668 M	14
8c	continuous	nonisothermal	first-order	temperature at equilibrium for second steady state	110.50 °C	108.83 °C	14
8d	continuous	nonisothermal	first-order	concentration of A at equilibrium for second steady state	0.1782 M	0.1952 M	14
9	batch	isothermal	first-order	time to 70% conversion	890 s	894 s	15
10	batch	isothermal	first-order	concentration of C at 600 s	0.955 M	0.957 M	16
11	batch	isothermal	second-order	concentration of A and B and 100 s	0.08331 M	0.083325 M	17
12	batch	isothermal	second-order	concentration of C at 99 s	0.0998269 M	0.0998269 M	18
13	semi-batch	isothermal	second-order	concentration of A at 500 s	0.01250 M	0.01256 M	19
14a	batch	isothermal	consecutive first-order	concentration of A at 1000 s	1.1036 M	1.1036 M	20
14b	batch	isothermal	consecutive first-order	concentration of C at 1000 s	0.1226 M	0.1226 M	20
14c	batch	isothermal	consecutive first-order	concentration of D at 1000 s	1.7737 M	1.7737 M	20
15	semi-batch	isothermal	no-kinetics	concentration of A at 3000 s	0.02349 M	0.02348 M	21
16a	batch	adiabatic	first-order	temperature at specified time	22.83 °C (680s)	23.00 °C (684 s)	15
16b	batch	adiabatic	first-order	conversion at specified time	71.16% (680 s)	70.00% (684 s)	15
17a	batch	adiabatic	consecutive first-order	temperature as a function of heat of reaction and reaction rate	49.96 °C	49.89 °C	22
17b	batch	adiabatic	consecutive first-order	temperature as a function of heat of reaction and reaction rate	65.12 °C	64.88 °C	22
18	batch	non-isothermal	no-kinetics	cooling curve	48.95 °C (9300 s)	48.88 °C (9288 s)	23 24

goals were achieved, and on the basis of those results we conclude that REACTR operates according to design.

CSTR problems constitute approximately one-half of the problems that were used to validate REACTR. The CSTR is a natural extension of the REACTR semi-batch model, and the extensive body of CSTR sample problems in the

chemical engineering literature was used to facilitate the validation of the REACTR program.

While the CSTR does not enjoy extensive use in the pharmaceutical or fine chemical industries, a cascade of four CSTR reactors has been reported to be useful for the conduct of a small-scale organic reaction.⁷ The inclusion of the CSTR

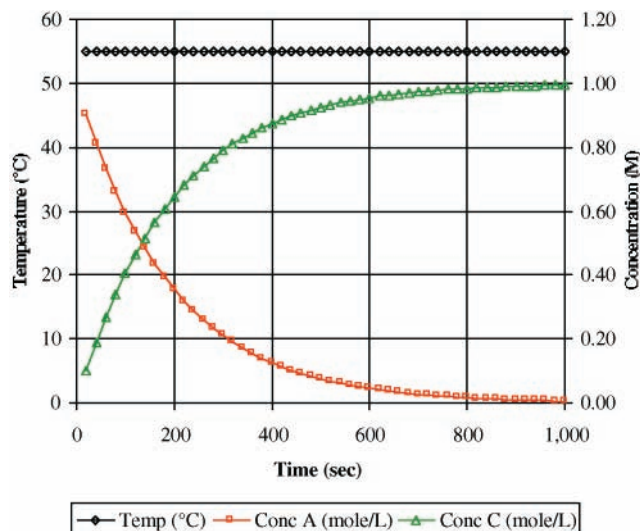


Figure 1. REACTR simulation of a first-order kinetics reaction ($A \rightarrow C$) conducted in a batch reactor under isothermal conditions (entry 10 of Table 1).

model in REACTR also provides an additional tool for organic chemists to consider during the development of new chemical processes.

Selected Problems

In this section the results from several of the REACTR validation problems are presented in greater detail. These examples show how REACTR may be used to provide valuable information for process development and scale-up of chemical reactions.

Figure 1 shows the results from a REACTR simulation of a first-order reaction in a batch reactor operating under isothermal conditions (entry 10 of Table 1). This is an entry-level problem for a chemical kinetics simulation program, and REACTR performs well. It estimates the concentration of C after 600 s to be 0.955 M, which compares favorably to the 0.957 M concentration of C calculated in the original problem.¹⁶

The results from a REACTR simulation of consecutive first-order reactions conducted in a batch reactor operating under isothermal conditions are shown in Figure 2 (entry 14). In this example intermediate C does not accumulate to a substantial extent. However, REACTR correctly calculates

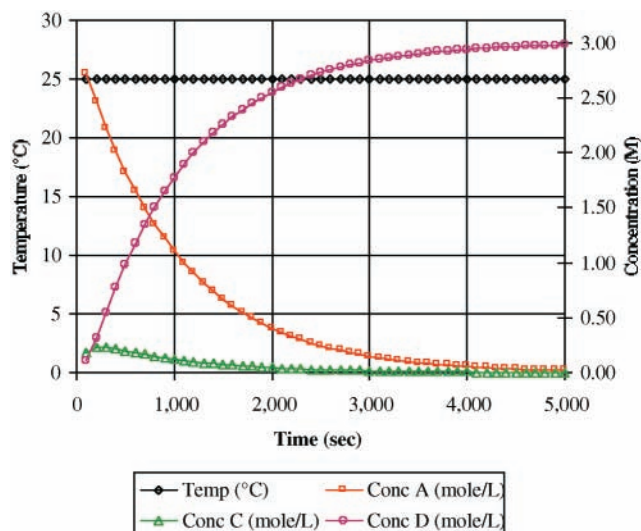


Figure 2. REACTR simulation of consecutive first-order kinetics reactions ($A \rightarrow C \rightarrow D$) conducted in a batch reactor under isothermal conditions (entry 14 of Table 1).

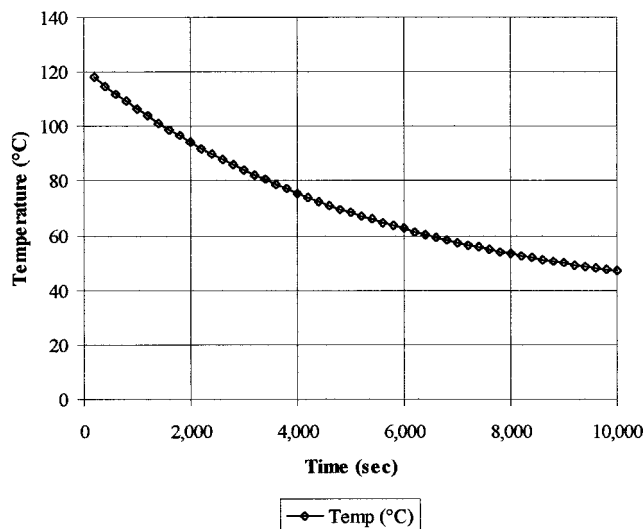


Figure 3. REACTR simulation of cooling the contents of a batch reactor (entry 18 of Table 1).

the same concentrations for species A, C, and D as reported in the original problem.²⁰

The rate of heating or cooling a material in a reactor can be an important consideration in the development of a robust chemical process. The temperature history of a reaction or the cooling curve for a crystallization can significantly impact the quality of a chemical product. The calculation of a heating or cooling curve is not an easy problem, as it requires the solution of eqs 6–10. Figure 3 shows a cooling curve calculated with REACTR (entry 18). The objective of this problem is to determine the time required to cool a reactor contents from 120 to 50 °C. REACTR estimated the reactor contents are cooled to 48.95 °C in 9300

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- (8) Fogler, H. S. *Elements of Chemical Reaction Engineering*; Prentice Hall: Englewood Cliffs, NJ, 1988; pp117–120, 143–144.
- (9) Fogler, H. S. *Elements of Chemical Reaction Engineering*; Prentice Hall: Englewood Cliffs, NJ, 1988; p116.
- (10) Froment, G. F.; Bischoff, K. B. *Chemical Reactor Analysis and Design*; John Wiley & Sons: New York, 1979; p 432 and calculation.
- (11) Himmelblau, D. A. *Basic Principles and Calculations in Chemical Engineering*; Prentice Hall: New York, 1979; pp 449–451.
- (12) Fogler, H. S. *Elements of Chemical Reaction Engineering*; Prentice Hall: Englewood Cliffs, NJ, 1988; pp 366–371.
- (13) Fogler, H. S. *Elements of Chemical Reaction Engineering*; Prentice Hall: Englewood Cliffs, NJ, 1988; pp 371–372.
- (14) Han, C. D. Determination of Start-Up Conditions for Chemical Reactor Stability. *Ind. Eng. Chem. Fundam.* **1970**, *9*(4), 634–640.
- (15) Bisio, A.; Kabel, R. L. *Scaleup of Chemical Processes*; John Wiley & Sons: New York, 1985; pp 136–138.
- (16) Fogler, H. S. *Elements of Chemical Reaction Engineering*; Prentice Hall: Englewood Cliffs, NJ, 1988; pp 109–112.

- (17) Clausen, C. A.; Mattson, G. *Principles of Industrial Chemistry*; John Wiley & Sons: New York, 1978; p 175.
- (18) Moore, W. J. *Physical Chemistry*; Prentice Hall: Englewood Cliffs, NJ, 1962; p 262.
- (19) Fogler, H. S. *Elements of Chemical Reaction Engineering*; Prentice Hall: Englewood Cliffs, NJ, 1988; pp 144–151.
- (20) Froment, G. F.; Bischoff, K. B. *Chemical Reactor Analysis and Design*; John Wiley & Sons: New York, 1979; p 18 and calculation.

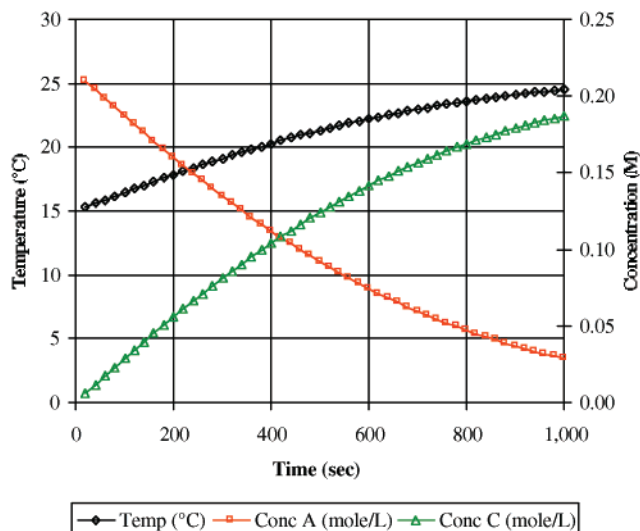


Figure 4. REACTR simulation of a first-order kinetics reaction conducted in a batch reactor ($A \rightarrow C$) under adiabatic conditions (entry 16 of Table 1).

s. These results compare very well to the temperature of 48.88 °C and time of 9288 s calculated in the original papers.^{23,24}

The conduct of a chemical reaction under adiabatic conditions is not normally practiced. However, it may be useful to predict the adiabatic temperature rise for a reaction in order to understand its safe operating range. The results from a REACTR simulation of a first-order reaction run in a batch reactor under adiabatic conditions are presented in Figure 4 (entry 16). The temperature increase was modest in this example, and the original problem reported a temperature rise to 23 °C in 684 s. REACTR predicted a temperature rise to 22.83 °C in 680 s.¹⁵

The semi-batch operation mode is the most commonly practiced for chemical reactions conducted in the pharmaceutical and fine chemical industries. However, the effect of reagent addition time on the outcome of the reaction is rarely quantified and modeled. The results from a REACTR simulation of a second-order reaction conducted in a semi-batch reactor under isothermal conditions are presented in Figure 5 (entry 13). In this example, reagent **A** is added to a solution of reagent **B** in the reactor. This problem is sufficiently complex that the problem source describes a computer program for its solution.¹⁹ REACTR predicted a concentration of 0.01250 M for reagent **A** at 500 s, while the source reported a concentration of 0.01256 M for **A** at the same time point.

CSTR reaction systems present some very interesting opportunities for testing a simulation program such as REACTR. CSTR systems initially are unstable, and the temperature and chemical concentrations are changing. Eventually a steady state is achieved, and the reaction

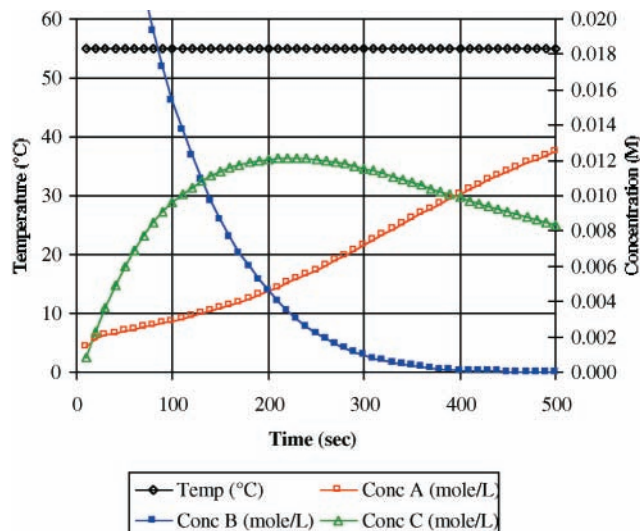


Figure 5. REACTR simulation of a second-order kinetics reaction ($A + B \rightarrow C$) conducted in a semi-batch reactor under isothermal conditions (entry 13 of Table 1).

concentrations and temperature are maintained at constant values.

CSTR systems also are capable of achieving multiple steady states. Steady states are realized when the rates of heat generation and heat removal are equal for the system. Three steady states are possible for a single chemical reaction conducted in a CSTR. One of these steady states is not stable. Consequently, the CSTR system may equilibrate at either of two stable steady states.

The evaluation of CSTR examples with REACTR provides a unique opportunity to test the viability of the program. The REACTR code does not contain any of the equations that are used to characterize the behavior of CSTR systems. Therefore, CSTR characteristics exhibited by REACTR simulations would be emergent properties of the program and would show that it is capable of producing results that extend beyond its underlying equations. The demonstration of steady states and, especially, the demonstration of multiple steady states in a CSTR simulation would verify that REACTR is a robust simulation tool for the organic chemist.

The results from a REACTR simulation of a first-order reaction conducted in a CSTR under adiabatic operating conditions are presented in Figure 6 (entry 6). The reaction under study is the hydrolysis of propylene oxide **A** in methanol solution to produce propylene glycol **C**. The concentration of **A** in the reactor increases early in the reaction and then decreases to a low steady-state level as the CSTR system reaches equilibrium. The temperature and the concentration of **C** steadily increase to their equilibrium values of 68.77 °C and 1.8302 M, respectively. The REACTR estimates of the steady-state temperature and concentrations were consistent with those of the source problem.¹² Prediction of the pre-equilibrium concentration and temperature profiles can provide very useful information for the scale-up of a CSTR system.

The propylene oxide hydrolysis reaction also was simulated by REACTR using nonisothermal operating conditions, and the results are presented in Figure 7 (entry 7). The

(21) Himmelblau, D. A. *Basic Principles and Calculations in Chemical Engineering*; Prentice Hall: New York, 1979; pp 449–451 and calculation.
 (22) Calculation.
 (23) Guy, John L. Modeling Heat-Transfer Systems. *Chem. Eng. (N.Y.)* **1982**, 89(9), 93–98.
 (24) Guy, J. L. Dynamic Modeling of Tank-type Reactor Systems. *Chem. Eng. (N.Y.)* **1982**, 89(13), 97–100.

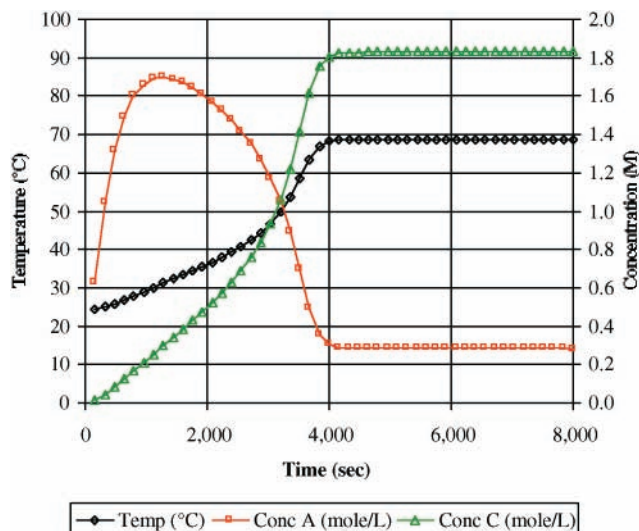


Figure 6. REACTR simulation of a first-order kinetics reaction ($A \rightarrow C$) conducted in a CSTR under adiabatic conditions (entry 6 of Table 1).

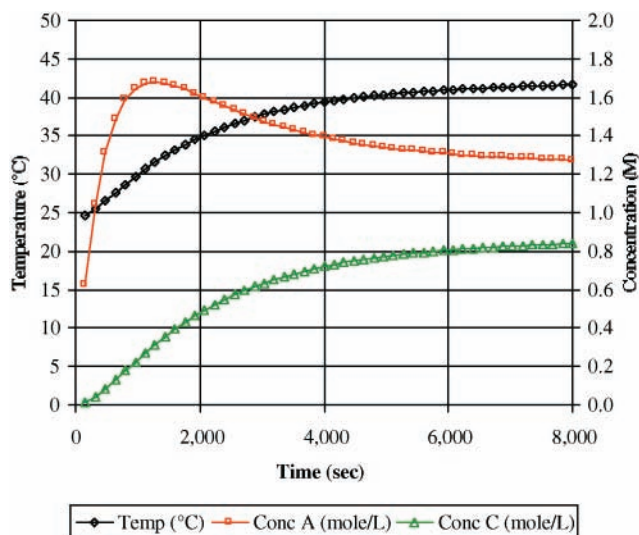


Figure 7. REACTR simulation of a first-order kinetics reaction ($A \rightarrow C$) conducted in a CSTR under nonisothermal conditions (entry 7 of Table 1).

reaction profile in this simulation is qualitatively similar to that of the previous example. However, the equilibrium temperature, 41.61 °C, and the equilibrium concentration of C, 0.8381 M, are substantially different. Again the REACTR steady-state conditions reflected the steady-state conditions reported in the original problem.¹³

The two different sets of equilibrium temperature and concentration values in these examples reflect two different steady states that are achieved under the two different thermal operating modes. In the adiabatic reaction, the heat generated by the chemical reaction is balanced by the heat used for heating the feed solution and the heat removed in the reaction solution that flows from the reactor.

For the nonisothermal case, the heat generated by the chemical reaction is balanced by the heat removed by heat transfer to the reactor coolant as well as the heat removed by the same mechanisms in the adiabatic case. The more efficient heat removal for the nonisothermal reaction posi-

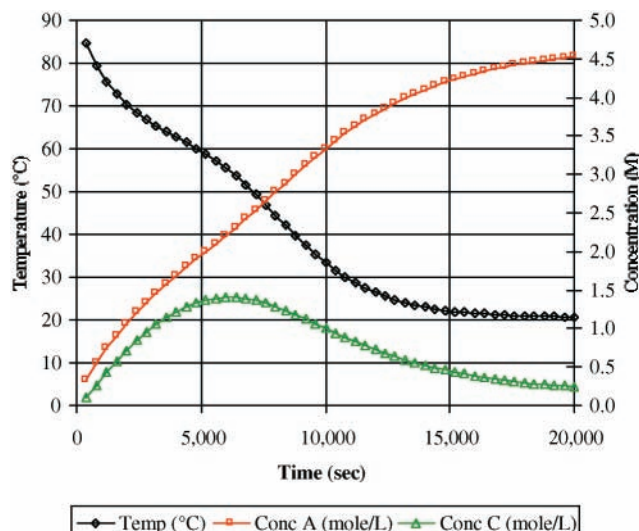


Figure 8. REACTR simulation of a first-order kinetics reaction ($A \rightarrow C$) conducted in a CSTR under nonisothermal conditions (entries 8a–b of Table 1).

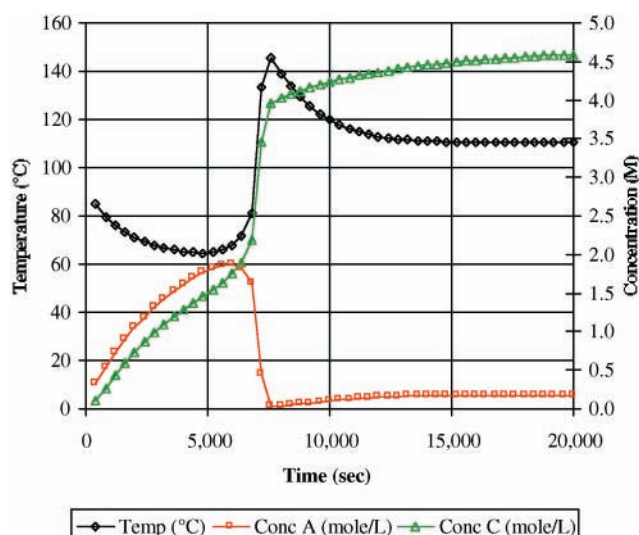


Figure 9. REACTR simulation of a first-order kinetics reaction ($A \rightarrow C$) conducted in a CSTR under nonisothermal conditions (entries 8c–d of Table 1).

tions the system in the steady state with a lower operating temperature and a lower conversion of A to C.

The steady state achieved by a CSTR system may be determined by subtle factors. Figures 8 and 9 show the results of REACTR simulations of another first-order reaction in a CSTR operating under nonisothermal conditions. The temperature of the solvent in the reactor at the start of the reaction is different in these two cases.

The Figure 8 simulation (entries 8a–b) represents the case in which the initial temperature of the solvent is 95.00 °C. The reaction temperature decreases steadily until the equilibrium temperature of 20.73 °C is reached. The reference paper reported a steady-state temperature of 20.55 °C, and the corresponding steady-state chemical concentrations also were in close agreement.¹⁴

For the case presented in the Figure 9 simulation (entries 8c–d), the initial solvent temperature is 95.25 °C. This small change in the temperature of the solvent in the reactor results

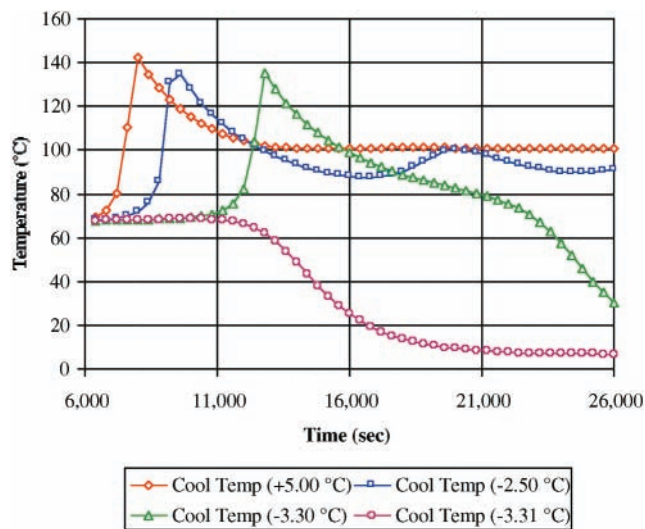


Figure 10. REACTR simulation demonstrating the effect of different reactor coolant temperatures applied at the start (6000 sec) of the exotherm of the reaction shown in Figure 9.

in a completely different reaction profile. The reaction temperature initially decreases and appears to have reached a steady state. Then the temperature increases dramatically from about 70 to nearly 150 °C in only 1200 s. The steady-state temperature of 110.50 °C calculated by REACTR was in close agreement with the temperature of 108.83 °C reported in the original paper. The simulation steady-state chemical concentrations also were congruent with the reference paper.¹⁴

The sudden exotherm suggested by this simulation would likely build up pressure in a real reactor. Such a pressure increase could result in dangerous consequences. REACTR was used to evaluate the effect of responding to the exotherm by changing the temperature of the heat-transfer fluid in the reactor jacket. The original coolant temperature of 17.2 °C was changed to 5.00, -2.50, -3.30, and -3.31 °C at the 6000 s time point in subsequent simulations of this exothermic reaction to determine if the exotherm could be prevented. Figure 10 summarizes the results of these REACTR simulations, which begin at the 6000 s time point of the simulation presented in Figure 9.

The results in Figure 10 show that lowering the coolant temperature from 17.2 to 5.00, -2.5, or -3.30 °C delays the onset of the exotherm. Also, the magnitude of the exotherm is attenuated slightly. However, only the coolest heat-transfer fluid at -3.31 °C was calculated to inhibit the exotherm and force the system into its new lower-temperature steady state. It is remarkable that such a small temperature difference in coolant temperature is sufficient to preclude the exotherm in this CSTR system. These simulations provide insight into the ways in which subtle changes in experimental conditions can make duplication of experiments difficult.

The important conclusion from these sets of examples is that they demonstrate that CSTR steady-state characteristics are emergent properties of REACTR simulations. However, there are even more complex properties exhibited by CSTR systems. A chemical reaction in a CSTR, under appropriate conditions, can generate periodic or oscillating output from

an input stream of constant reagent concentration and constant temperature. Indeed, one can discern incipient temperature oscillation in the -2.50 °C curve of Figure 10.

Douglas et al. studied the reaction of acetyl chloride and water in a CSTR.²⁵ The hydrolysis of acetyl chloride is exothermic, and it is governed by second-order kinetics. In this study acetyl chloride (A, 4.21 M) and an acetone solution of water (B, 5.06 M) are added to the CSTR as two separate streams. A circulating heat-transfer fluid cools the reactor. The resulting system exhibits a decaying oscillation of temperature and reagent and product concentrations. The cycle time of the oscillation is 2220 s, and the temperature in the reactor ranges from 18 to 27 °C in a semi-stable region of the experiment. Ultimately, the oscillation decays to a stable system that operates with a constant reagent concentration (A, 2.185 M) and a constant temperature (22 °C).

The Douglas experiment presents experimental data from an extremely complex system against which to test REACTR. REACTR was never envisioned for the simulation of a system with the complexity of an oscillating CSTR. However, the ability of REACTR to model such a system would further validate its value as a simulation tool for process development.

The Douglas experiment was simulated using REACTR. Indeed, REACTR produced a simulation that exhibits oscillatory behavior. The oscillation cycle time was 1860 s, and the temperature in the reactor ranged from 14 to 56 °C in a semi-stable region of the simulation. The results of the simulation were encouraging, but the variance of the cycle time and temperature range from the experimental values was disconcerting.

The Douglas paper reports data for the determination of the energy of activation for acetyl chloride hydrolysis. These data show considerable variability. Therefore, the REACTR simulation was repeated using an activation energy of 12.1 kcal/mol in lieu of the 12.0 kcal/mol value used in the initial simulation. Exhibit 2, presented earlier in this paper, shows the first two pages of the REACTR report for this simulation.

The second simulation predicted an oscillating system with an oscillation cycle time of 2235 s and a temperature in the reactor that ranged from 18 to 29 °C in a semi-stable region of the simulation. The simulation also predicted decay of the oscillation to a stable system that operates with a constant reagent concentration (A, 2.292 M) and a constant temperature (23 °C). The results of the second REACTR simulation of the Douglas experiments are presented in Figure 11.

The results from the second REACTR simulation of the Douglas experiment are remarkable. Clearly the cycle times and the temperature ranges for the real and simulated experiments differ only slightly. Further, the simulated steady-state concentration and temperature are comparable to those reported by Douglas. However, even in the absence of such accurate results, the knowledge of possible oscillatory behavior of the CSTR system would be of significant value to a chemical professional about to scale up a new reaction.

(25) Baccaro, G. P.; Gaitonde, N. Y.; Douglas, J. M. An Experimental Study of Oscillating Reactors. *AIChE J* **1970**, *16*(2), 249–254.

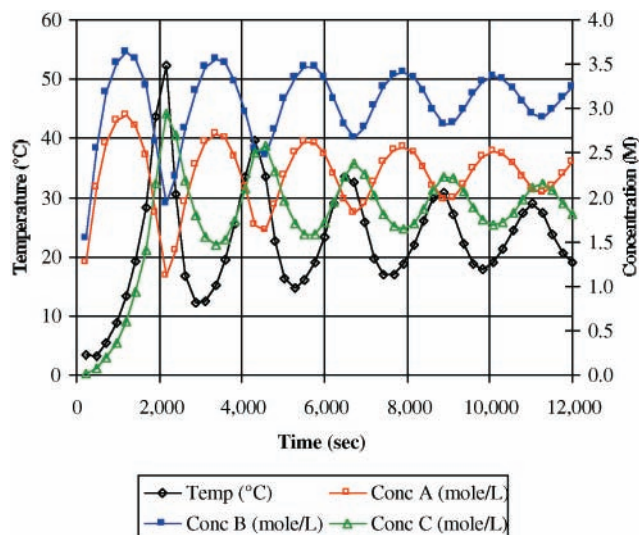


Figure 11. REACTR simulation of a second-order kinetics reaction ($A + B \rightarrow C$) conducted in a CSTR under nonisothermal conditions (Douglas experiment).

Conclusions

REACTR is a computer program designed to simulate the conduct of a chemical reaction in an industrial chemical reactor. REACTR calculates the temperature and chemical concentration profile of the reaction as a function of time. REACTR provides the means to evaluate safe operating conditions for a chemical reaction prior to scale-up. It also may be used to estimate the effect of some process variables on the outcome of the reaction.

REACTR can simulate reactions governed by first-order, second-order, and consecutive first-order kinetics. It can simulate batch, semi-batch, and continuous reactor operation modes. Further, it can simulate any combination of kinetics model and operation mode under isothermal, adiabatic, or nonisothermal operating conditions.

The REACTR logic and underlying equations upon which it is based demonstrate how the program is constructed and how it functions. These equations are familiar to chemists and chemical engineers. The role of REACTR is to facilitate the simultaneous use of these equations to produce accurate simulations of chemical processes.

REACTR was evaluated with an extensive validation program, and it provided exceptionally accurate results for all of the validation test problems. A detailed examination of several of the validation problems shows how REACTR may be used to guide the development of safe and effective chemical processes.

The identification of multiple steady states and oscillation in CSTR systems by REACTR simulations shows that the program is capable of producing results that extend beyond its design. These emergent properties are produced in REACTR simulations without the use of the equations that characterize CSTR systems. These results provide additional assurance that REACTR produces simulations that can add value to chemical process development.

The successful REACTR simulation of the acetyl chloride hydrolysis experimental data firmly connects the program to the laboratory. REACTR simulations should be used to

design laboratory experiments that predict the outcome of a chemical process scale-up. The actual scale-up should be based on the results of those laboratory experiments and not on the results of REACTR simulations.

REACTR provides an interesting environment in which students of the chemical sciences may study and explore the operation of chemical processes on an industrial scale. In particular, chemists may find REACTR to be an especially useful tool for learning some important principles of chemical engineering.

Glossary of REACTR Terminology

A	Chemical species A
A_1	Pre-exponential factor for first reaction (1 s^{-1} or $\text{L mol}^{-1} \text{ s}^{-1}$)
A_2	Pre-exponential factor for second reaction (1 s^{-1})
A_i	Area available for heat-transfer through reactor jacket (cm^2)
B	Intermediate term in heat-transfer fluid calculation ($\text{kcal } ^\circ\text{C}^{-1}$)
B	Chemical species B
C	Intermediate term in heat-transfer fluid calculation (dimensionless)
C	Chemical species C
$C_{f(A,B,C,D)}$	Concentration of components A, B, C, D in the feed solution (mol L^{-1})
C_p	Heat capacity of the solvent ($\text{kcal kg}^{-1} \text{ } ^\circ\text{C}^{-1}$)
C_{pc}	Heat capacity of the coolant ($\text{kcal kg}^{-1} \text{ } ^\circ\text{C}^{-1}$)
$C_{i(A,B,C,D)}$	Concentration of components A, B, C, D in the reactor solution during i th iteration (mol L^{-1})
$C_{(i+1)(A,B,C,D)}$	Concentration of components A, B, C, D in the reactor solution during $(i + 1)$ th iteration (mol L^{-1})
D	Diameter of the reactor (cm)
D	Chemical species D
E_{a1}	Energy of activation for first reaction (kcal mol^{-1})
E_{a2}	Energy of activation for second reaction (kcal mol^{-1})
H_1	Heat of reaction for first reaction (kcal mol^{-1})
H_2	Heat of reaction for second reaction (kcal mol^{-1})
H_{time}	Hold time after completion of addition of the feed solution (s)
H_{vap}	Heat of vaporization of solvent (kcal kg^{-1})
I	Incremental concentration change due to addition of reagent feed solution (mol L^{-1})
k_1	Rate constant for first reaction (1 s^{-1} or $\text{L mol}^{-1} \text{ s}^{-1}$)
k_2	Rate constant for second reaction (1 s^{-1})
M_d	Mass of refluxed solvent per differential time element (kg)
M_{fi}	Mass of feed solution per differential time element (kg)
M_i	Mass of reactor solution during i th iteration (kg)
$M_{(i+1)}$	Mass of reactor solution during $(i + 1)$ th iteration (kg)
M_r	Mass of reaction mixture remaining in the reactor after reflux of solvent (kg)
N_{iter}	Number of iterations specified (dimensionless)

q_1	Heat generated by the first reaction within differential time element (kcal)	V_a	Volume adjustment factor (dimensionless)
q_2	Heat generated by the second reaction within differential time element (kcal)	V_f	Initial volume of the feed solution (L)
Q_c	Rate of flow of the coolant (L s ⁻¹)	V_i	Volume of the reactor solution during the <i>i</i> th iteration (L)
Q_f	Rate of addition of the reagent feed solution (L s ⁻¹)	V_r	Initial volume of solution in the reactor (L)
R	Universal gas constant (kcal mol ⁻¹ K ⁻¹)	V_T	Total reaction volume (L)
ρ	Density of the reactor and feed solutions (kg L ⁻¹)	Z	Intermediate term in heat-transfer calculation (kcal °C ⁻¹)
ρ_c	Density of the coolant (kg L ⁻¹)		
S_1	Common Kinetic Expression One (dimensionless)		
S_2	Common Kinetic Expression Two (dimensionless)		
t	Differential time element (s)		
T_b	Boiling point of the solvent (°C)		
T_c	Temperature of coolant (°C)		
T_d	Temperature of returning distillate (°C)		
T_f	Temperature of the feed solution (°C)		
T_i	Temperature of the reactor solution during <i>i</i> th iteration (°C and K)		
$T_{(i+1)}$	Temperature of the reactor solution during (<i>i</i> + 1)th iteration (°C)		
U	Overall heat transfer coefficient (kcal (cm ²) ⁻¹ °C ⁻¹ s ⁻¹)		

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Note Added after ASAP: An incorrect version of Exhibit 2 was posted ASAP May 26, 2001; the correct version was posted June 8, 2001.

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