THE DYNAMIC RESPONSE OF A MULTIPLE FEED RECYCLE REACTOR

by

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ABSTRACT

In this study theoretical and experimental transient response data for a multible feed recycle reactor are presented. The reaction used is the irreversible second order homogeneous liquid phase saponifacation of methyl acetate with sodium hydroxide.

A theoretical model solving the partial differential equations using finite difference technique is used. The predicted dynamic response data by the theoretical model for simultaneous upsets are in good agreement with the experimental data.

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INTRODUCTION

Although highly theoretical work has been done on the design and operation of chemical reactors, little experimentally verified research has been done on the dynamics of chemical reactors. The CFSTR (continuous flow stirred tank reactor) is the most completely studied chemical reactor, but very little work has been done with the tubular reactor.

The purpose of this research was to conduct transient response studies on a multiple feed recycle reactor and to develop a theoretical model to predict the response. The experimental system was a multiple feed tubular reactor with recycle, and it was operated in the laminar region under isothermal conditions. The reaction used was the homogeneous liquid phase saponification of methyl acetate with sodium hydroxide. This reaction was used because it is an irreversible second order reaction with a high reaction rate constant at the temperature of study.

The system can be represented by a set of non-linear differential equations. Since these equations were unsolvable by analytical techniques, a lumped parameter model, that can be used in a digital computer, was developed to describe the dynamic response of the system.

This thesis covers a literature survey on related studies, a description of the experimental work, a derivation of the theoretical model, the interpretation of results, and the conclusions.

LITERATURE SURVEY

The experimental verification of the theory for tubular reactors with recycle has been lacking in literature because of the comlexity of mathematics involved. Recent work on tubular reactors was done by Ramaswamy (1), McKinstry (2), and Dunn (3). Ramaswamy (1) and McKinstry (2) experimentally confirmed the analytical methods and solutions for the dynamic nature of the tubular reactor and the tubular reactor with recycle. Dunn (3), in his work, verified the use of finite difference techniques in solving the dynamic equations for a packed bed reactor with recycle.

Koppel (4,5,6), in his various publications, discusses several linearization techniques employed in analytical solution to the dynamics of an isothermal, homogeneous plug-flow tubular reactor with non-linear kinetics.

Denbigh (7) and Levenspiel (8) discuss many aspects of tubular reactor in their books. According to Denbigh (7), the construction of the tubular reactor in the form of a spiral, instead of a straight, tube gives closer performance to plug flow. Levenspiel (8) correlates the longitudinal dispersion coefficients of a non-plug flow regime to a finite number of ideal stirred tank reactors placed in series.

McGovin and Perlmutter (9) investigated the individual effects of radial gradients and axial mixing on the steady state and stability characteristics of the tubular reactor-recycle system.

Bischoff and Levenspiel (10), in their article, discuss the method, for packed and unpacked tubes, to find dispersion coefficients experimentally and to correlate Reynold's number to the dispersion coefficient.

Ramaswamy, Stermole, and McKinstry (11) presented a method for relating the tubular reactor equations to batch reactor equations and solving the dynamic response of a tubular reactor to flow upsets.

Deans and Lapidus (12), in their article, discuss the method to solve dynamic equations by using finite difference techniques.

EXPERIMENTAL STUDY

In this section the reaction kinetics, description of the equipment, the operation of the equipment, and an outline of the experimental data is presented.

Kinetics

In this study the reaction used was the saponification of methyl acetate with sodium hydroxide and it is given by

$$CH_3COOCH_3 + NaOH \rightarrow CH_3OH + CH_3COONa$$

The liquid-phase reaction had an irreversible second-order kinetics with a high rate constant at the temperature of study. In the concentration range studied there was no appreciable heat of mixing.

The rate constant data was obtained from previous studies and a value of 24.0 liter/mole-min was used.

Apparatus

Equipment

The experimental system is shown schematically in Figure 1. The main reactor was 15 ft (457.2 cm) long $\frac{1}{4}$-in.-diameter copper tube in the form of spiral. The recycle line was 22 in. (55.88 cm) long $\frac{1}{4}$-in.-diameter copper tube and reaction was assumed in the reycyle line. All the flow lines to the reactor system were Imperial-Eastman ¼-in. polyflow tubing. The sodium hydroxide reactants were stored in tanks 18 and 19, and the methyl acetate reactants were stored in tanks 20 and 21, as shown in Figure 1. They were pumped to the reactor by air. The air pressure was controlled by regulators 22 and 23 and measured by manometers 24 and 25, and were operated at about 12 inches of mercury.

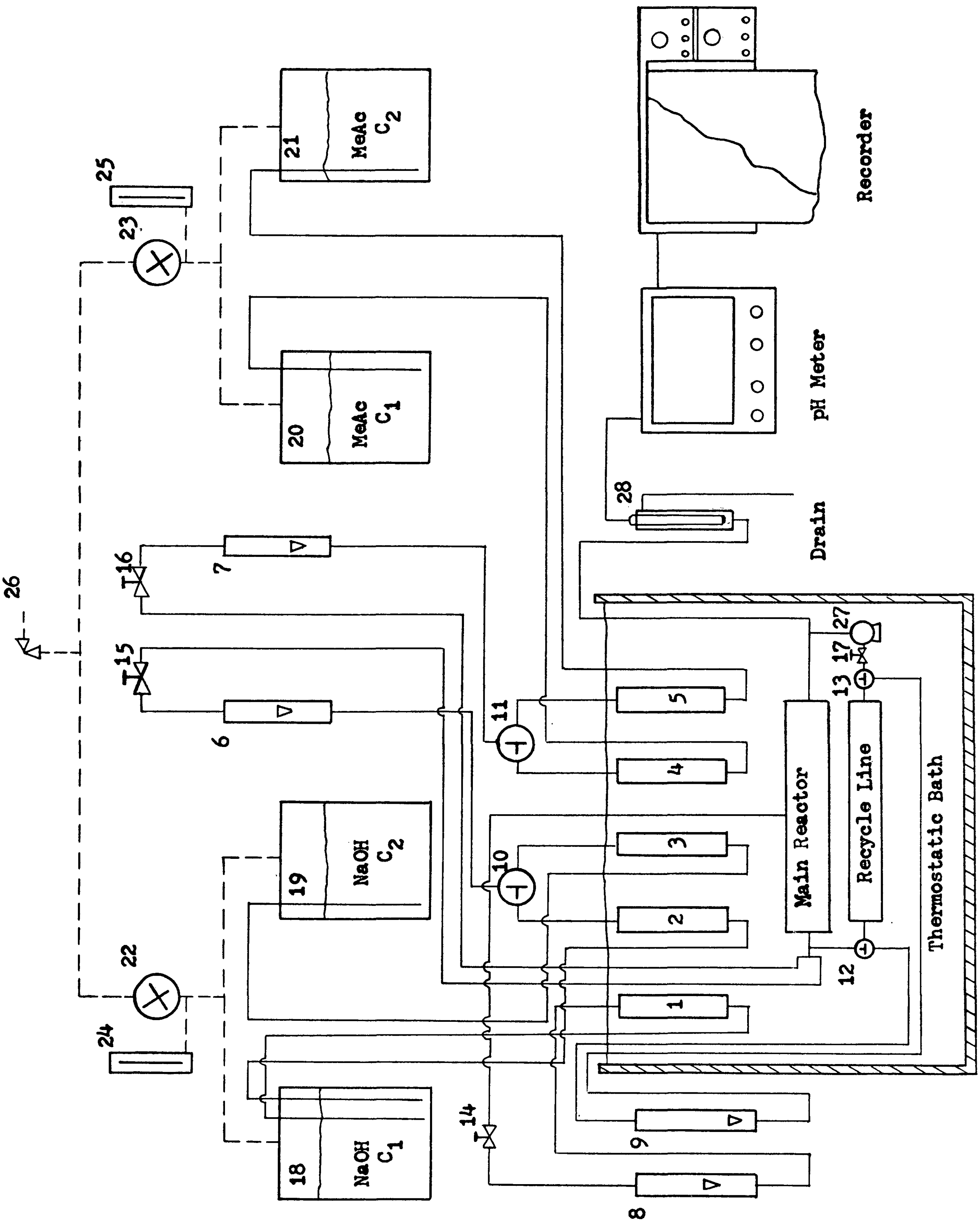
The reactants were pumped through preheaters 1,2,3,4, and 5 of 10-ft coils of 0.482-cm-diameter copper tube immersed in a thermostatic bath which was maintained at 40° C. The preheated reactants were selected by the three-way Teflon valves 10 and 11, and their flow was metered with rotameters 6 and 7. The flow was controlled with ¼-in. needle valves 15 and 16. The flow rate of the side feed reactant was controlled with needle valve 14 and metered with rotameter 8.

The metered streams of reactants then entered the reactor, which was kept at the same temperature as the preheaters by immersing in the same thermostatic bath maintained at 40° C; therefore an essentially isothermal operation was provided. The outlet concentration of the reactor was fed back to the inlet of the main reactor through the recycle line by means of a small centrifugal pump 27 and the recycle flow was controlled by a 1/8-in. vernier needle valve 17. A bypass line, with a rotameter 9, was used to monitor the recycle flow rate.

The effluent from the reactor passed through a flow cell, where the concentration was monitored with a Sargent/Jena combination electrode (range 0 to 14 pH) coupled with a Leeds and Northrup Model 7401 pH meter. The pH was recorded on a Mosely strip-chart recorder.

Figure 1. Flow diagram of the experimental apparatus.

1,2,3,4,5	Preheaters
6,7,8,9	Flow rotameters
10,11,12,13	Three-way valves
14,15,16	Flow needle valves
17	Vernier needle valve
18,19,20,21	Feed tanks
22,23	Pressure regulators
24,25	Manometers
26	Safety relief valve
27	Recycle pump
28	Flow cell with electrode


MeAc C2
MeAc C1
NaOH C2
NaOH C1
Recorder
pH Meter
Drain
Main Reactor
Recycle Line
Thermostatic Bath

Operation of the Equipment

The reactants were prepared with reagent grade sodium hydroxide pellets (97.0 percent) and reagent grade methyl acetate (99.9 percent, anhyd. max. 0.1 percent alc.). The concentrations of approximately 0.25 N and 0.125 N were prepared by using standard titration techniques.

The system was pressurized with all valves closed. The desired concentrations of reactants were chosen by the three-way valves 10 and 11, and the needle valves 14,15, and 16 were opened to establish the operating flow rates. Then the recycle pump was operated and the desired flow rate established with the needle valve 17 and metered by the rotameter 9.

When the concentration reached steady state, several samples were collected at the reactor outlet by quenching with excess hydrochloric acid in order to stop the saponification reaction and the concentration of the reactant effluent was obtained by back titration. Then the upsets were made by the manipulation of the respective valves. After the new steady state was reached, the sodium hydroxide content was determined as mentioned before.

Experimental Data

The data were obtained from a 15-ft reactor with an inside diameter of 0.482 cm. Three types of upsets were made. The types of upsets were:

(1) Methyl acetate concentration and side feed sodium hydroxide flow

(2) Methyl acetate flow and side feed sodium hydroxide flow

(3) Sodium hydroxide concentration and side feed sodium hydroxide flow

The reactor and the recycle line were operated in the laminar region.

The data consisted of pH readings versus time which were converted to sodium hydroxide concentration. The output results are tabulated in the Appendix.

The system had an inherent response time lag which was determined to be 2.4 seconds. This time lag was used in the mathematical model by incorporating into the response of the outlet concentration.

MATHEMATICAL MODEL

This section discusses the methods used to determine the steady state of the multiple feed recycle reactor and numerical solutions to the finite difference approximation of the distributed parameter system used in the prediction of dynamic response. The mixing of fresh feeds are assumed to be instantaneous and perfect.

Analysis of the Steady State

The plug-flow reactor at maximum conversion could be considered as an infinite number of stirred tanks. However, at minimum conversion, only one CFSTR could be considered. The tubular reactor usually lies in between these two extremes and it can be represented by a finite number of CFSTR. In this case, the flow regime in the reactor was considered to be in the laminar range where $Re < 2100$. Since there is a concentration gradient in the reactor, dispersion occurs. The dispersion causes the reactor to deviate from ideal plug-flow and the conversion is less than the predicted from plug-flow reactor equations. In the case for the flow in circular tubes, Levenspiel (13) has correlated the Reynold's number and the effective dispersion coefficient with the Schmidt number as a parameter. The following equation can be used to predict the number of stirred tank reactors that will experimentally give the correct outlet concentration for an effective dispersion coefficient:

$$\frac{1}{j} = \frac{2\ D_{eff}}{v\ l} \tag{1}$$

The number of stirred tanks for the tubular reactor in the flow range studied was 40 for the main reactor, and 3 for the recycle line.

By using the steady state stirred tank equations (2) and (3), and solving these equations N successive times, the steady state outlet concentration of the tubular reactor could be determined. The following are based on material balances over a CFSTR at steady state:

$$C_{A0}\ v - C_A\ v - kVC_AC_B = 0 \tag{2}$$

$$C_{B0}\ v - C_B\ v - kVC_AC_B = 0 \tag{3}$$

Relating equations (2) and (3) by stoichiometry, the following equations can be written:

$$C_{B0} - C_{A0} = M_0 = C_B - C_A \tag{4}$$

or

$$C_B = M_0 + C_A \tag{5}$$

Substitution of equation (5) into equation (2) and by subscripting, the following quadratic polynomial in C_A results, and C_A could be solved directly by the quadratic formula:

$$C_A(I) = -\tfrac{1}{2}(M_0 + \frac{v}{V\ k}) + \tfrac{1}{2}((M_0 + \frac{v}{V\ k})^2 + \frac{4vC_A(I-1)}{V\ k}\ )^{\frac{1}{2}} \tag{6}$$

Subscription of the equation (5) gives:

$$C_B(I) = M_0 + C_A(I) \tag{7}$$

Equation (6) and (7) were used for the main reactor before the side feed. The outlet $C_A(N1)$ and $C_B(N1)$ were used with side feed C_{AS1} and C_{BS1} to calculate the new entrance concentrations to the main reactor after the side feed from:

$$C_{AS}(1) = \frac{C_A(N1)\ Q}{Q_S} + \frac{C_{AS1}\ F_{AS1}}{Q_S} \tag{8}$$

$$C_{BS}(1) = \frac{C_B(N1)\ Q}{Q_S} + \frac{C_{BS1}\ F_{BS1}}{Q_S} \tag{9}$$

Then equation (7) becomes:

$$M_0 = C_{BS}(1) - C_{AS}(1) \tag{10}$$

Equation (6) was also used for the main reactor after the side feed by using v_S, V_S, M_{0S}, and $C_{AS}(I)$ instead of v, V, M_0, $C_A(I)$. The material balance for the recycle was of the same form as the main reactor except v', V', $M_{0S'}$ and $C_{AR}(I)$ were used in equation (6) instead of v, V, M_0, and $C_A(I)$. The outlet $C_{AR}(M)$ and $C_{BR}(M)$ were used to recalculate the new entrance concentrations from:

$$C_A(1) = \frac{C_{A0}\ F_{A0}}{Q} + \frac{C_{AR}(M)\ Q_R}{Q} \tag{11}$$

$$C_B(1) = \frac{C_{B0}\ F_{B0}}{Q} + \frac{C_{BR}(M)\ Q_R}{Q} \tag{12}$$

Equation (6) indicates the necessity of an iterative technique to obtain the steady state profile. The iteration was done by first assuming zero for

$C_{AR}(M)$ and $C_{BR}(M)$, and calculating the concentration profile down the reactor and the recycle line. Then the recalculated $C_A(1)$ and $C_B(1)$ were compared with their initial values. If they were not very near, the new values of $C_A(1)$ and $C_B(1)$ were used to calculate the new profile. The iteration was repeated until the new calculated values became very near the previous values of $C_A(1)$ and $C_B(1)$.

Analysis of the Dynamic Response

The mass balance equations for a second order isothermal plug-flow system could be written over a differential element of the reactor resulting in the basic equations describing the concentration history in the reactor:

$$\frac{\partial C_A}{\partial t} + v\frac{\partial C_A}{\partial x} = -kC_AC_B \qquad (13)$$

$$\frac{\partial C_B}{\partial t} + v\frac{\partial C_B}{\partial x} = -kC_AC_B \qquad (14)$$

By lumping equations (13) and (14) in the space coordinate and approximating the time by finite difference, the following equations could be obtained:

$$\frac{C_A'(I) - C_A(I)}{\Delta t} = \frac{vC_A(I-1)}{\Delta x} - \frac{vC_A(I)}{\Delta x} - kC_A(I)C_B(I) \qquad (15)$$

$$\frac{C_B'(I) - C_B(I)}{\Delta t} = \frac{vC_B(I-1)}{\Delta x} - \frac{vC_B(I)}{\Delta x} - kC_A(I)C_B(I) \qquad (16)$$

After rearranging equations (15) and (16), the outlet concentration from each Δx segment could be calculated by the following:

$$C_A'(I) = C_A(I)(1.0 - \frac{v\Delta t}{\Delta x} - k\Delta t C_B(I)) + \frac{v\Delta t C_A(I-1)}{\Delta x} \quad (17)$$

$$C_B'(I) = C_B(I)(1.0 - \frac{v\Delta t}{\Delta x} - k\Delta t C_A(I)) + \frac{v\Delta t C_B(I-1)}{\Delta x} \quad (18)$$

Equations (17) and (18) were used for the main reactor before the side feed, and the initial and boundary conditions for this part of the reactor are:

$$C_A(0,t) = \lambda C_A(1',t) + (1-\lambda)C_{A0} \quad (19)$$

$$C_A(x,0) = C_A(x) \quad (20)$$

$$C_B(0,t) = \lambda C_B(1',t) + (1-\lambda)C_{B0} \quad (21)$$

$$C_B(x,0) = C_B(x) \quad (22)$$

The equations used for the main reactor after the side feed were obtained by substituting v_S and Δx_S for v and Δx in equations (17) and (18). The initial and boundary conditions for the main reactor after the side feed are:

$$C_{AS}(0,t) = \tau C_{AS1} + (1-\tau)C_A(1,t) \quad (23)$$

$$C_{AS}(x_S,0) = C_{AS}(x_S) \quad (24)$$

$$C_{BS}(0,t) = \tau C_{BS1} + (1-\tau)C_B(1,t) \quad (25)$$

$$C_{BS}(x_S,0) = C_{BS}(x_S) \quad (26)$$

The equations used for the recycle line were obtained by substituting v' and $\Delta x'$ for v and Δx in equations (17) and (18). The initial and boundary conditions for the recycle line are:

$$C_{AR}(0,t) = C_{AS}(1_S) \quad (27)$$

$$C_{AR}(x',0) = C_{AR}(x') \quad (28)$$

$$C_{BR}(0,t) = C_{BS}(1_S) \quad (29)$$

$$C_{BR}(x',0) = C_{BR}(x') \quad (30)$$

As seen in equations (17) and (18), the terms

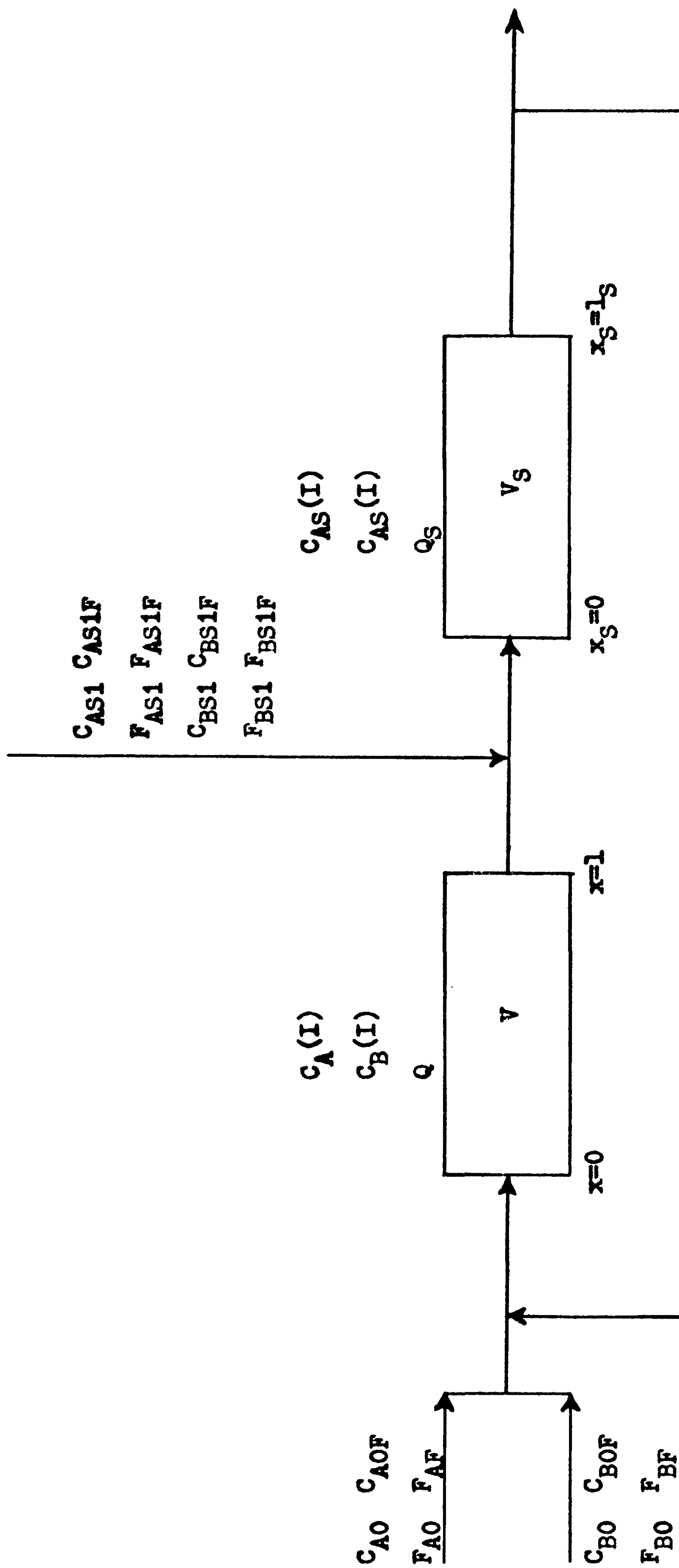
$$(1.0 - \frac{v\Delta t}{\Delta x} - k\Delta tC_B(I)) \qquad (31)$$

$$(1.0 - \frac{v\Delta t}{\Delta x} - k\Delta tC_A(I)) \qquad (32)$$

must not change sign in order to have a stable solution. This stability criteria was checked by calculating Δt values for the first and last cell of the main reactor, the first and last cell of the recycle line, and the cells before and after the side feed at the initial and final steady states for components A and B.

This was done by PDP-10 digital computer. The computer program which is presented in the Appendix was designed to calculate the transient response for any type of upset, concentration, flow, or both.

Figure 2. Multiple feed recycle reactor with nomenclature.
(See page 93 for notation.)


C_{AO} C_{AOF}
F_{AO} F_{AF}
C_{BO} C_{BOF}
F_{BO} F_{BF}
$C_A(I)$
$C_B(I)$
Q
V
$x=0$
$x=1$
C_{AS1} C_{AS1F}
F_{AS1} F_{AS1F}
C_{BS1} C_{BS1F}
F_{BS1} F_{BS1F}
$C_{AS}(I)$
$C_{AS}(I)$
Q_S
V_S
$x_S=0$
$x_S=l_S$
$C_{AR}(I)$
$C_{BR}(I)$
Q_R
V'
$x'=0$
$x'=l'$

INTERPRETATION OF RESULTS

In Tables 1 and 2, experimental conditions are listed. Table 1 gives the initial inlet fresh feed concentrations and flow rates. Table 2 gives the final fresh feed concentrations and flow rates.

Simultaneous upsets in methyl acetate concentration and side feed sodium hydroxide flow are shown in Figures 3,4,7,8,17,18,21, and 22. In runs 1,5,15, and 19, the methyl acetate concentration was increased and the side feed sodium hydroxide flow was decreased. The outlet sodium hydroxide concentration started to decrease immediately after the upset. The decrease in the side feed flow rate increased the residence time and produced an increase in reaction time causing the sodium hydroxide concentration to decrease. This change in concentration caused a noticeable decrease in the outlet sodium hydroxide concentration after the first residence time of the second part of the reactor. Then the decrease in concentration slowed down to its initial rate. After the second residence time, for the second part of the reactor, the outlet sodium hydroxide concentration started dropping to its final value. Since the reactor effluents were fed back through the recycle line to be mixed with the fresh feed, another concentration upset was produced at the inlet of the reactor. These were repeated after each residence time of the reactor as step changes and their magnitude decreased with each residence time due to mixing of fresh feed and recycle line effluent. At higher flow rates the effect of decrease in side feed flow rate was not observed clearly as shown in Figure 21. These effects were more significant when the fresh feed flow rates were low, Runs 1 and 15. The changes were not sharp due to dispersion caused by laminar flow regime.

In Runs 2,6,16, and 20, the methyl acetate concentration was decreased and side feed sodium hydroxide flow was increased. As a result, residence time, for the second part of the reactor, decreased and also reaction time decreased, causing less sodium hydroxide to react. This was observed as a slow increase of outlet sodium hydroxide concentration on the response curve. After the first residence time, of the second half of the reactor, the new concentration profile reached the exit and the outlet sodium hydroxide concentration increased. The increase in sodium hydroxide concentration slowed down to a rate lower than its initial value for the second residence time. These slow changes were more significant for the first residence time because, after the upset, the fluid elements near the exit of the reactor were less affected than the fluid elements at the entrance of the reactor. Then the outlet sodium hydroxide concentration increased noticeably due to decrease in fresh feed methyl acetate concentration. The final concentration was reached by non-linear curves produced by the effect of mixing the fresh feed with the changing concentrations of the recycle line. Since the change in side feed flow rate was small and the side feed sodium hydroxide concentration was low, when compared with the fresh feed concentrations, the effect of increase in side feed flow was not significant as in Run 20, Figure 22.

Simultaneous upsets in sodium hydroxide concentration and side feed sodium hydroxide flow were made and the results are shown in Figures 5,6,9,10,15,16,19, and 20. The results were similar to the ones obtained by simultaneous upsets in methyl acetate concentration and side feed sodium hydroxide flow. The effect of side feed flow for Runs 3,7,13, and 17 was observed as a slow decrease in outlet sodium hydroxide concentration due to the increased residence time. Then a small sudden decrease was caused by the decrease in sodium hydroxide concentration due to reduced side feed flow rate. After the second residence time, of the second part of the reactor, the exit concentration of sodium hydroxide decreased suddenly because of the decrease in fresh feed sodium hydroxide concentration. The final steady state concentration was reached by smoother curves created by the effect of mixing of recycle line effluent and the fresh feeds.

In Runs 4,8,14, and 18, the sodium hydroxide concentration and side feed sodium hydroxide flow were increased. The results are shown in Figures 6,10,16, and 20, and they were close to mirror image of Figures 5,9,15, and 19. Again the effect of change in side feed flow was not significant in Figures 19 and 20 because of the high fresh feed flow rates and concentration.

In Figures 11,12,13,14,23,24,25, and 26, the results are shown for simultaneous upsets in methyl acetate flow and side feed sodium hydroxide flow. Interesting response curves with maximum and minimum points were observed.

In Figures 11,13,24, and 26, the decrease in methyl acetate flow was higher in magnitude than the increase in side feed sodium hydroxide flow and as a result the residence time increased. This new residence time increased the reaction time and caused the outlet sodium hydroxide concentration to decrease during the first residence time of the second part of reactor. The effect of increase in side feed flow increased the exit concentration suddenly. The fresh feed concentrations used in Run 11 were lower than in Run 9, and this caused the effect of side feed to be greater in magnitude, as shown in Figures 11 and 13. During the second residence time, the concentration decreased because the fluid elements in the reactor were not affected by the decrease in methyl acetate flow. Then the outlet sodium hydroxide concentration increased and reached its steady state value after several residence times of the main reactor. When the reactor was operated at high fresh feed concentrations, the decrease in sodium hydroxide in the reactor effluent was not observed during the second residence time for the second half of the reactor.

In Figures 12,14,23, and 25, the results are shown for methyl acetate flow (increase) and side feed sodium hydroxide flow (decrease). The change in methyl acetate flow was more dominant than the side feed flow. This resulted in decreased residence time causing the outlet sodium hydroxide concentration to increase during the first residence time of the second part of the reactor. When the new concentration profile, produced by the decrease in side feed flow, reached the probe, the exit concentration dropped suddenly. The outlet sodium hydroxide concentration increased during the second residence time for the second half of reactor in Runs 10 and 21, but decreased in Runs 12 and 23. Since the fresh feed concentrations were higher in Runs 10 and 21 than in Runs 12 and 23 the reaction rates were also high. The increase in methyl acetate flow actually gave simultaneous upsets in inlet concentration and residence time. The effect of change in residence time was observed immediately after the upset but the upset in concentration become effective after the first residence time as a decrease in the outlet sodium hydroxide concentration.

Many factors influenced the multiple feed recycle reactor outlet concentration response. The important factors that determined the shape of the response curves were the initial inlet conditions, the change in residence time, and the changes in concentration of the fresh feed reactants at the inlet of the reactor at the time of upset.

Table 1

Experimental Inlet Multiple Feed Recycle Reactor Initial Operating Conditions Before the Upset

(See Table 2 for Final Operating Conditions)

Run	C_{AO}	C_{BO}	C_{AS1}	C_{BS1}	F_{AO}	F_{BO}	F_{AS1}	F_{BS1}	Q_R	Fig.
1	.1973	.1066	.0944	.0	.019	.048	.022	.0	.021	3
2	.1973	.1885	.0944	.0	.019	.048	.010	.0	.021	4
3	.1973	.1066	.0944	.0	.019	.048	.022	.0	.021	5
4	.0944	.1066	.0944	.0	.019	.048	.010	.0	.021	6
5	.1973	.1066	.0944	.0	.050	.074	.040	.0	.021	7
6	.1973	.1885	.0944	.0	.050	.074	.022	.0	.021	8
7	.1973	.1066	.0944	.0	.050	.074	.040	.0	.021	9
8	.0944	.1066	.0944	.0	.050	.074	.022	.0	.021	10
9	.1973	.1885	.0944	.0	.044	.074	.010	.0	.021	11
10	.1973	.1885	.0944	.0	.044	.048	.022	.0	.021	12
11	.0944	.1066	.0944	.0	.044	.074	.010	.0	.021	13
12	.0944	.1066	.0944	.0	.044	.048	.022	.0	.021	14
13	.2239	.1186	.1121	.0	.032	.048	.022	.0	.036	15
14	.1121	.1186	.1121	.0	.032	.048	.010	.0	.036	16
15	.2239	.1186	.1121	.0	.032	.048	.022	.0	.036	17
16	.2239	.2090	.1121	.0	.032	.048	.010	.0	.036	18
17	.2239	.1186	.1121	.0	.050	.074	.040	.0	.036	19
18	.1121	.1186	.1121	.0	.050	.074	.022	.0	.036	20
19	.2239	.1186	.1121	.0	.050	.074	.040	.0	.036	21
20	.2239	.2090	.1121	.0	.050	.074	.022	.0	.036	22
21	.2239	.2090	.1121	.0	.044	.048	.022	.0	.036	23
22	.2239	.2090	.1121	.0	.044	.074	.010	.0	.036	24
23	.1121	.1186	.1121	.0	.044	.048	.022	.0	.036	25
24	.1121	.1186	.1121	.0	.044	.074	.010	.0	.036	26

Table 2

Experimental Inlet Multiple Feed Recycle Reactor Final Operating Conditions After the Upset

(See Table 1 for Initial Operating Conditions)

Run	C_{AOF}	C_{BOF}	C_{AS1F}	C_{BS1F}	F_{AF}	F_{BF}	F_{AS1F}	F_{BS1F}	Q_{RF}	Fig.
1	.1973	.1885	.0944	.0	.019	.048	.010	.0	.021	3
2	.1973	.1066	.0944	.0	.019	.048	.022	.0	.021	4
3	.0944	.1066	.0944	.0	.019	.048	.010	.0	.021	5
4	.1973	.1066	.0944	.0	.019	.048	.022	.0	.021	6
5	.1973	.1885	.0944	.0	.050	.074	.022	.0	.021	7
6	.1973	.1066	.0944	.0	.050	.074	.040	.0	.021	8
7	.0944	.1066	.0944	.0	.050	.074	.022	.0	.021	9
8	.1973	.1066	.0944	.0	.050	.074	.040	.0	.021	10
9	.1973	.1885	.0944	.0	.044	.048	.022	.0	.021	11
10	.1973	.1885	.0944	.0	.044	.074	.010	.0	.021	12
11	.0944	.1066	.0944	.0	.044	.048	.022	.0	.021	13
12	.0944	.1066	.0944	.0	.044	.074	.010	.0	.021	14
13	.1121	.1186	.1121	.0	.032	.048	.010	.0	.036	15
14	.2239	.1186	.1121	.0	.032	.048	.022	.0	.036	16
15	.2239	.2090	.1121	.0	.032	.048	.010	.0	.036	17
16	.2239	.1186	.1121	.0	.032	.048	.022	.0	.036	18
17	.1121	.1186	.1121	.0	.050	.074	.022	.0	.036	19
18	.2239	.1186	.1121	.0	.050	.074	.040	.0	.036	20
19	.2239	.2090	.1121	.0	.050	.074	.022	.0	.036	21
20	.2239	.1186	.1121	.0	.050	.074	.040	.0	.036	22
21	.2239	.2090	.1121	.0	.044	.074	.010	.0	.036	23
22	.2239	.2090	.1121	.0	.044	.048	.022	.0	.036	24
23	.1121	.1186	.1121	.0	.044	.074	.010	.0	.036	25
24	.1121	.1186	.1121	.0	.044	.048	.022	.0	.036	26

Figure 3. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in methyl acetate concentration (increase) and side feed sodium hydroxide flow (decrease) for multiple feed recycle reactor (Run 1).

○ Experimental data

——— Numerical model

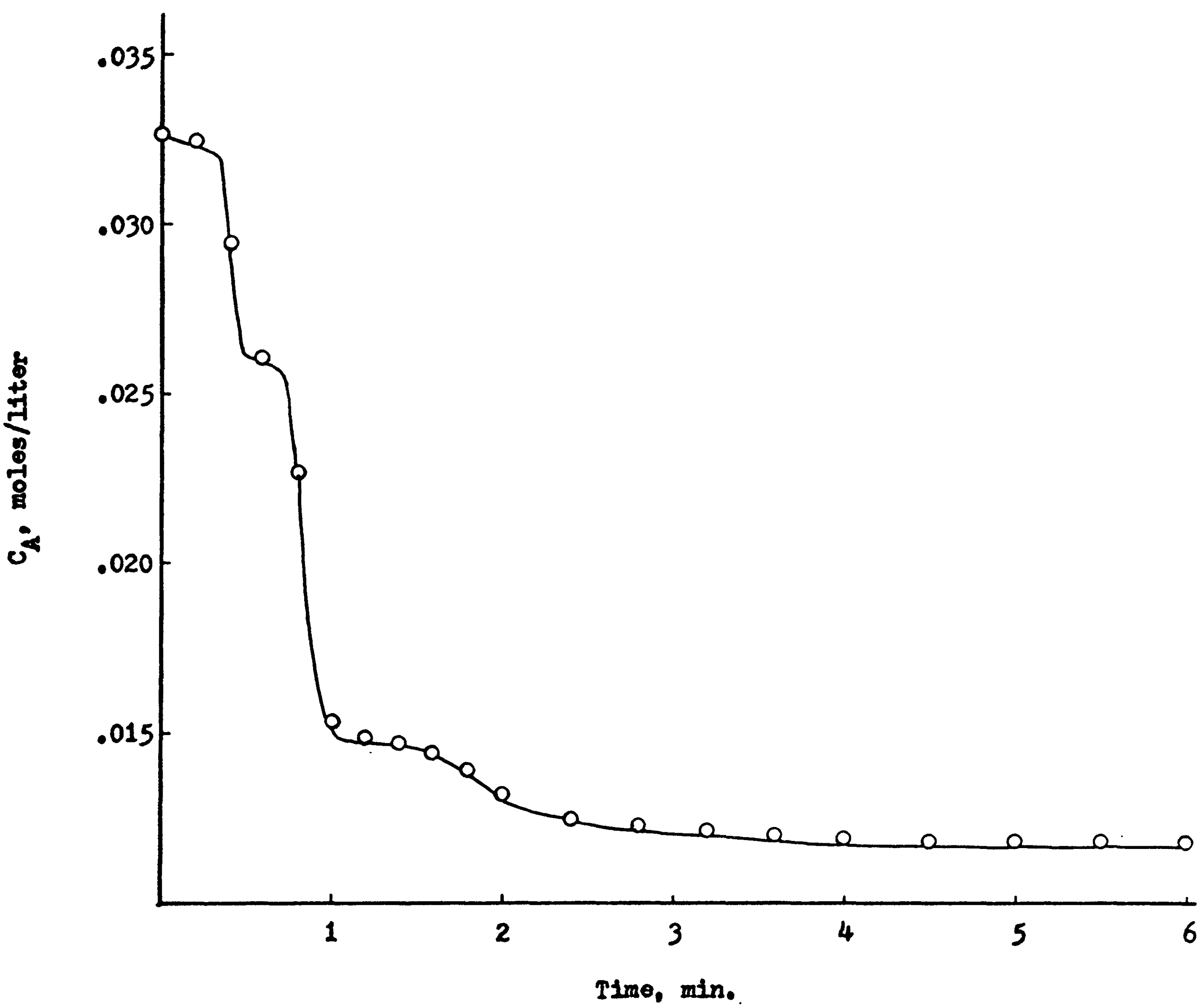

.035
.030
.025
.020
.015
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 4. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in methyl acetate concentration (decrease) and side feed sodium hydroxide flow (increase) for multiple feed recycle reactor (Run 2).

O Experimental data

——— Numerical model

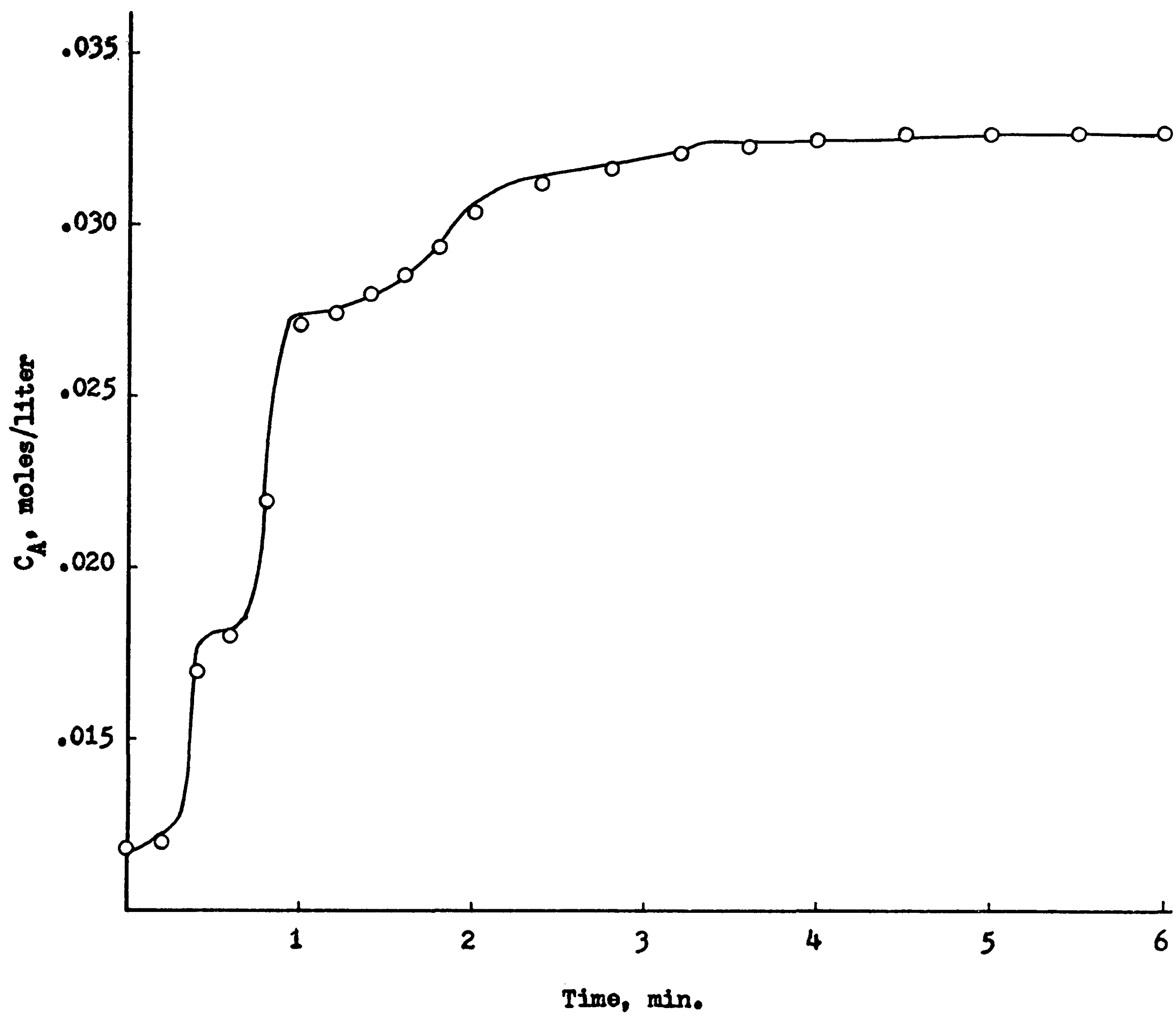

.035
.030
.025
.020
.015
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 5. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in sodium hydroxide concentration (decrease) and side feed sodium hydroxide flow (decrease) for multiple feed recycle reactor (Run 3).

○ Experimental data

——— Numerical model

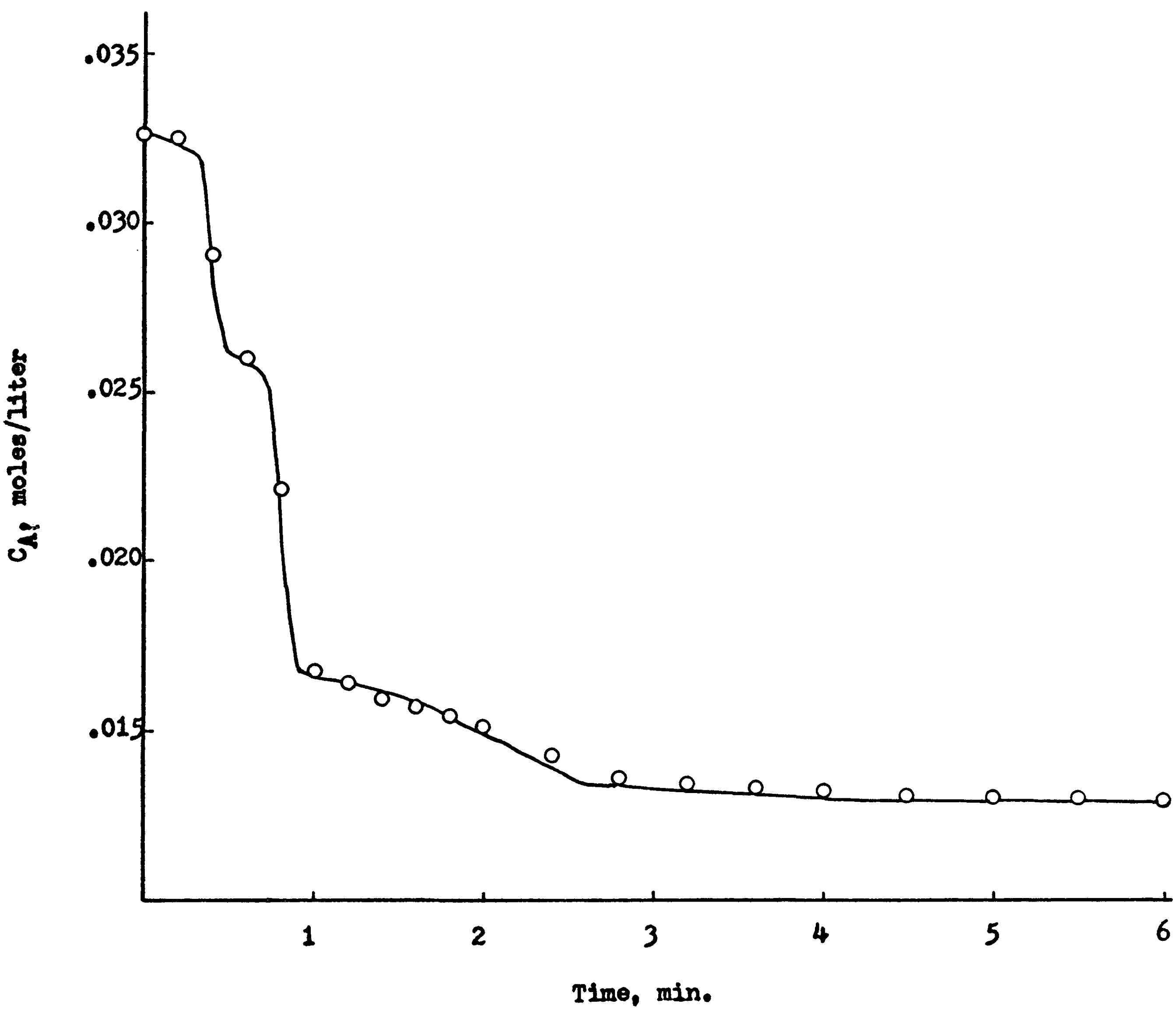

.035
.030
.025
.020
.015
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 6. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in sodium hydroxide concentration (increase) and side feed sodium hydroxide flow (increase) for multiple feed recycle reactor (Run 4).

○ Experimental data

——— Numerical model

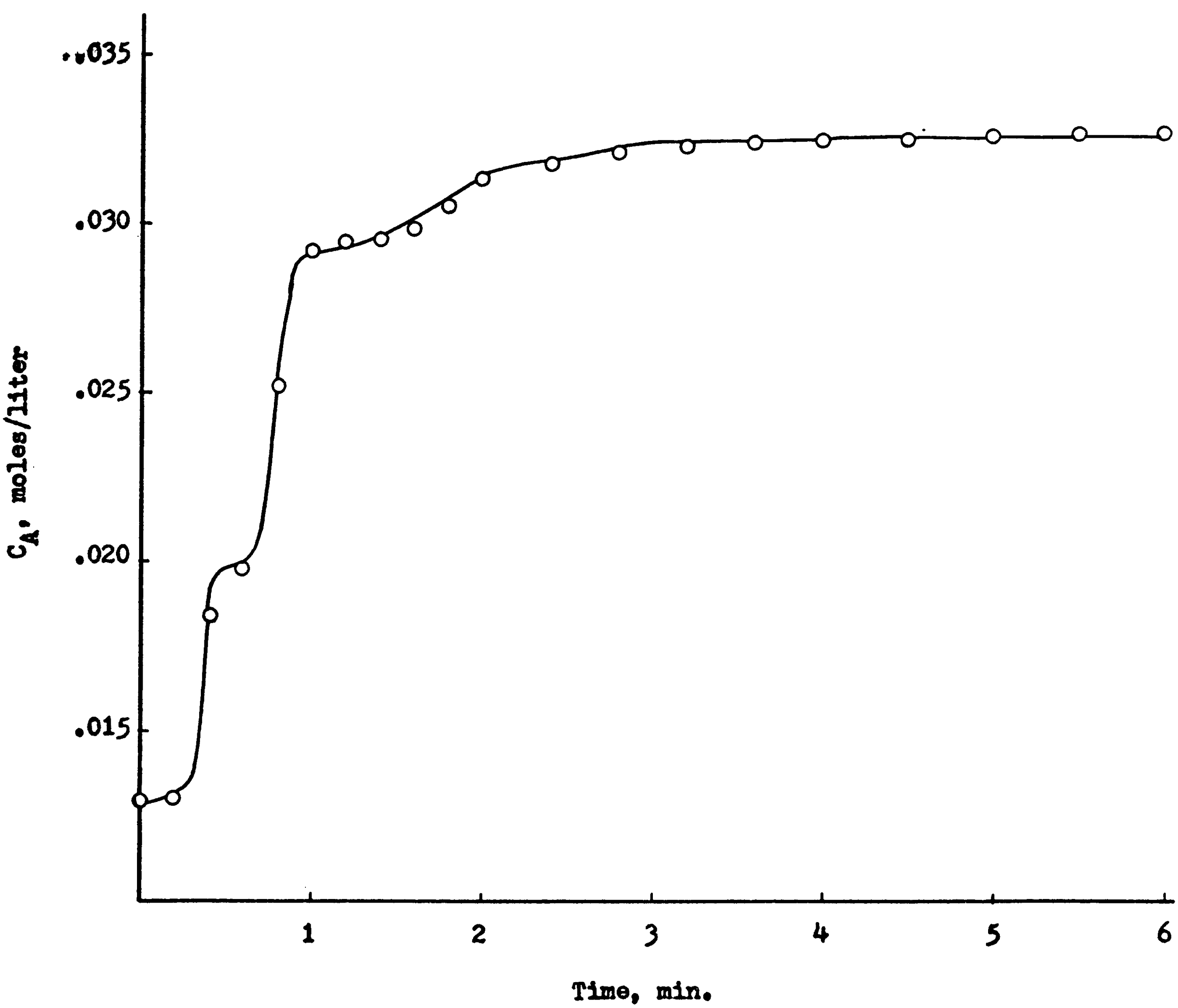

.035
.030
.025
.020
.015
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 7. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in methyl acetate concentration (increase) and side feed sodium hydroxide flow (decrease) for multiple feed recycle reactor (Run 5).

○ Experimental data

——— Numerical model

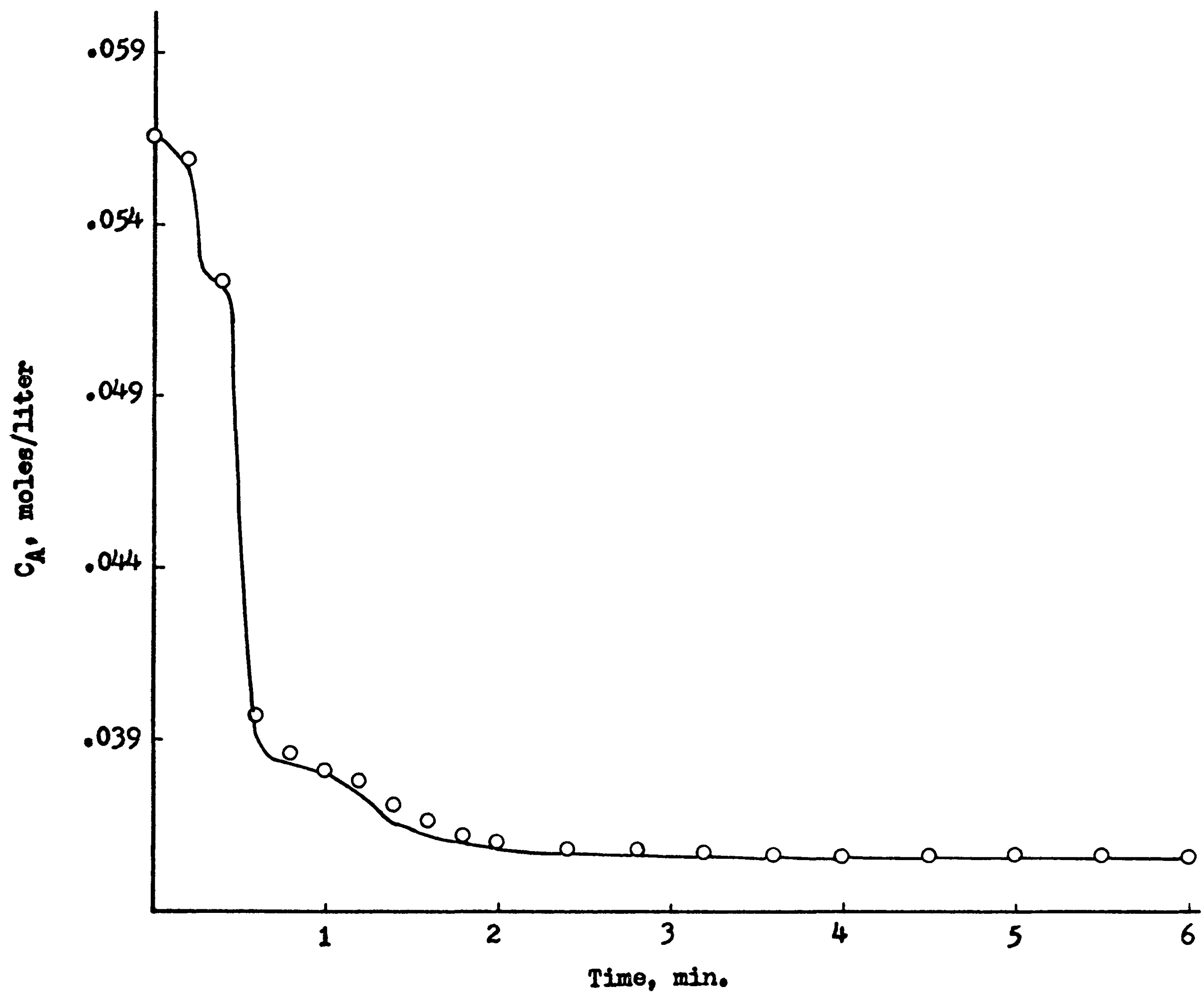

.059
.054
.049
.044
.039
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 8. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in methyl acetate concentration (decrease) and side feed sodium hydroxide flow (increase) for multiple feed recycle reactor (Run 6).

O Experimental data

—— Numerical model

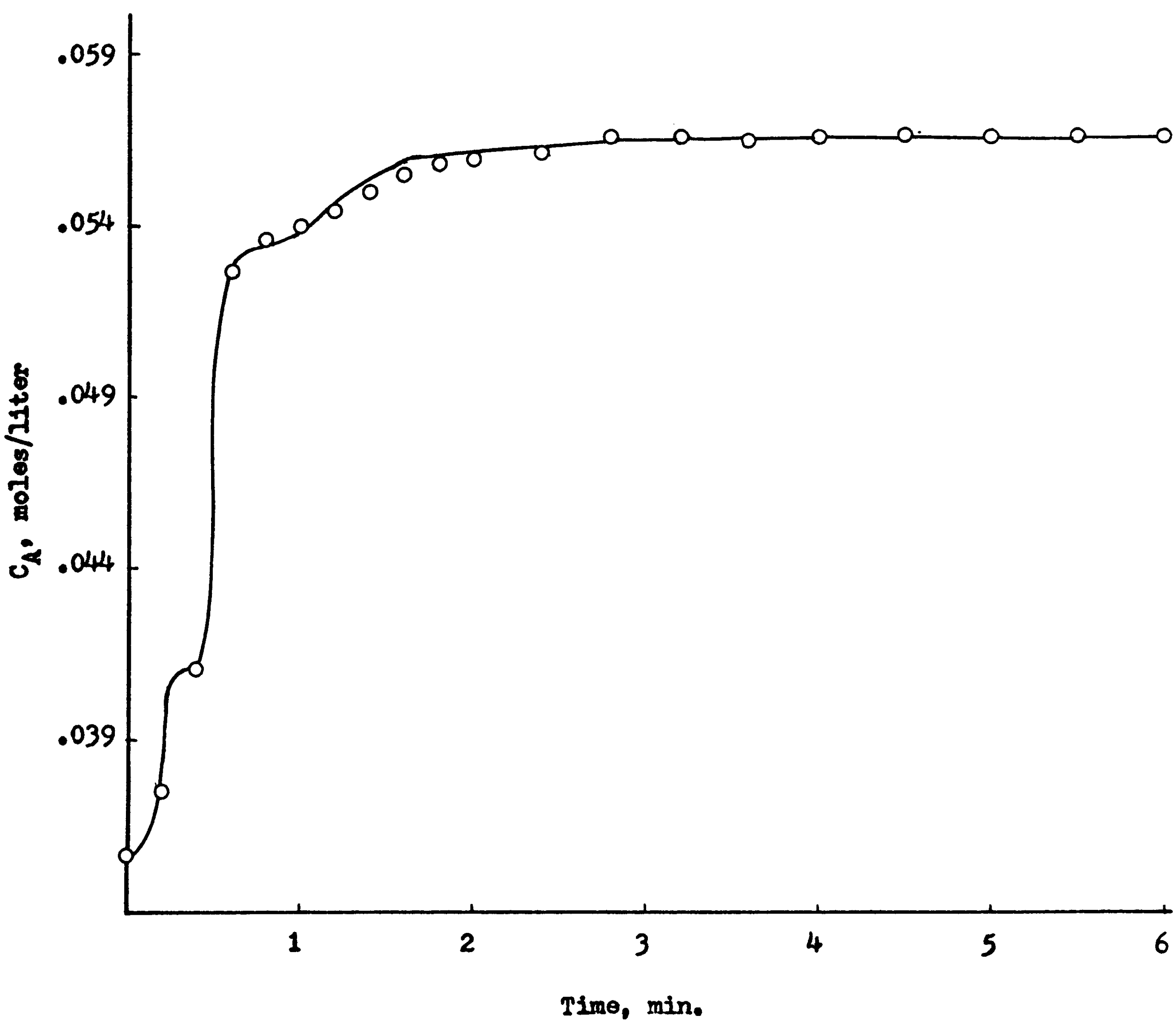

.059
.054
.049
.044
.039
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 9. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in sodium hydroxide concentration (decrease) and side feed sodium hydroxide flow (decrease) for multiple feed recycle reactor (Run 7).

O Experimental data

——— Numerical model

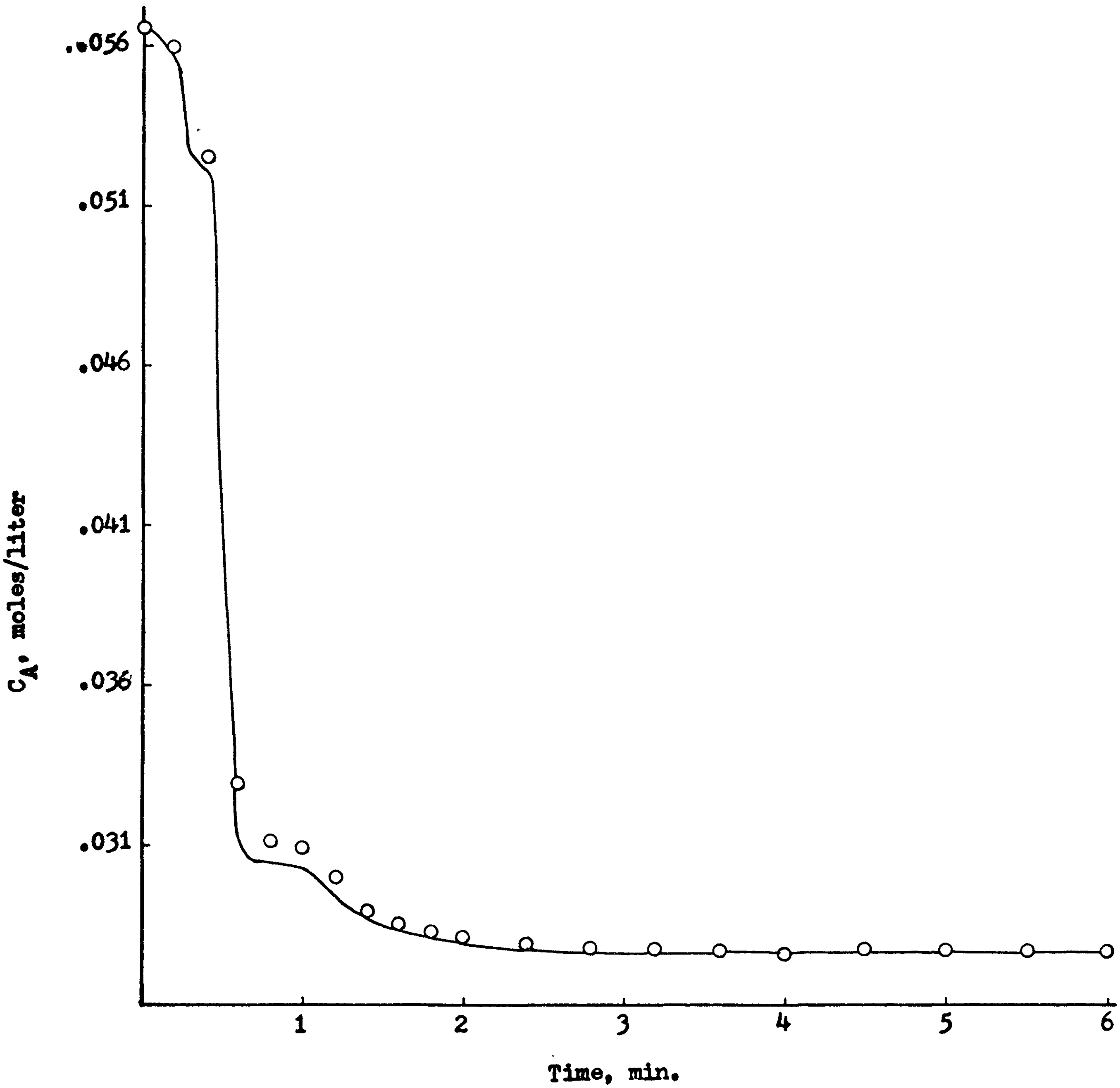

.056
.051
.046
.041
.036
.031
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 10. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in sodium hydroxide concentration (increase) and side feed sodium hydroxide flow (increase) for multiple feed recycle reactor (Run 8).

O Experimental data

—— Numerical model

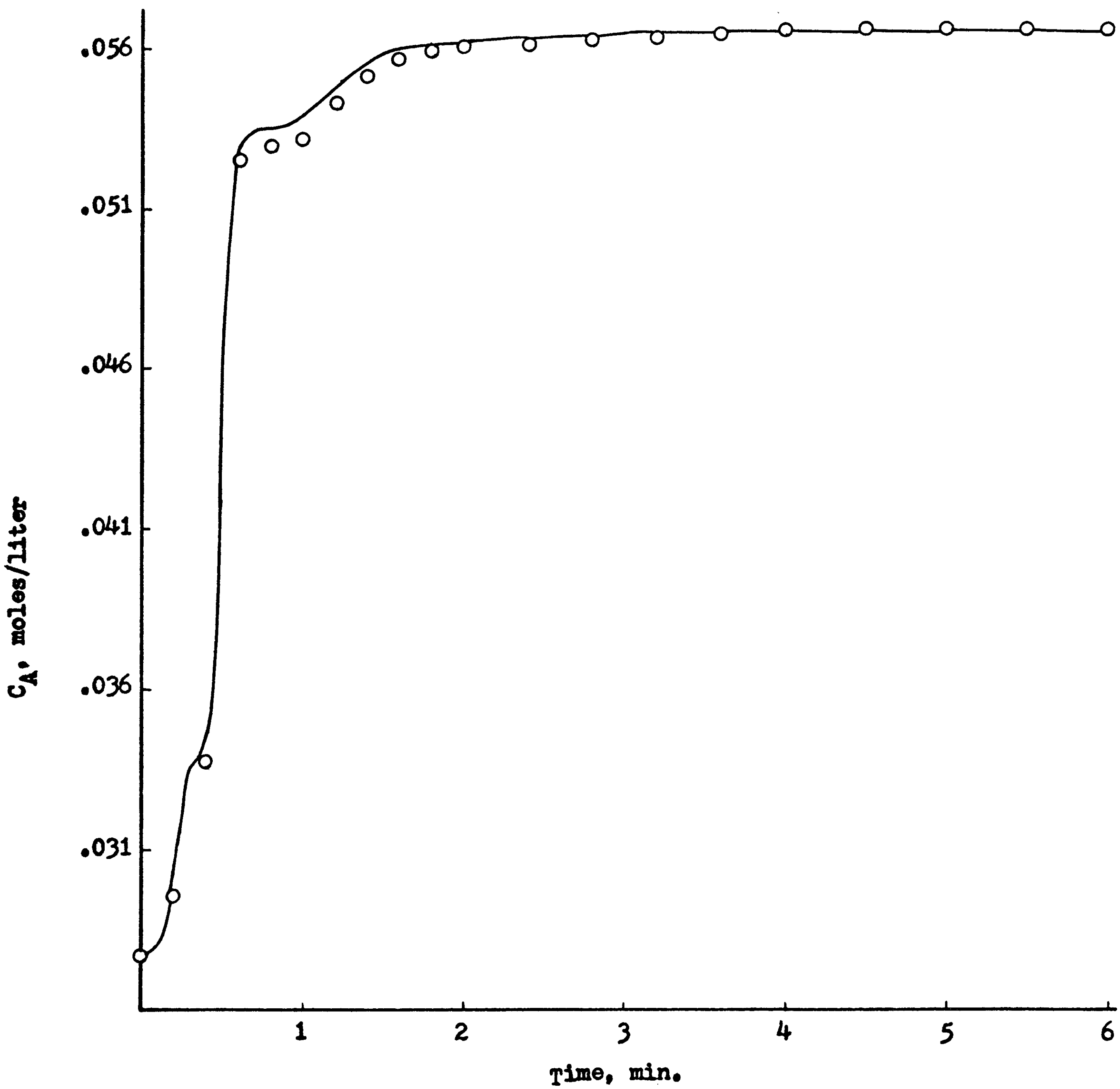
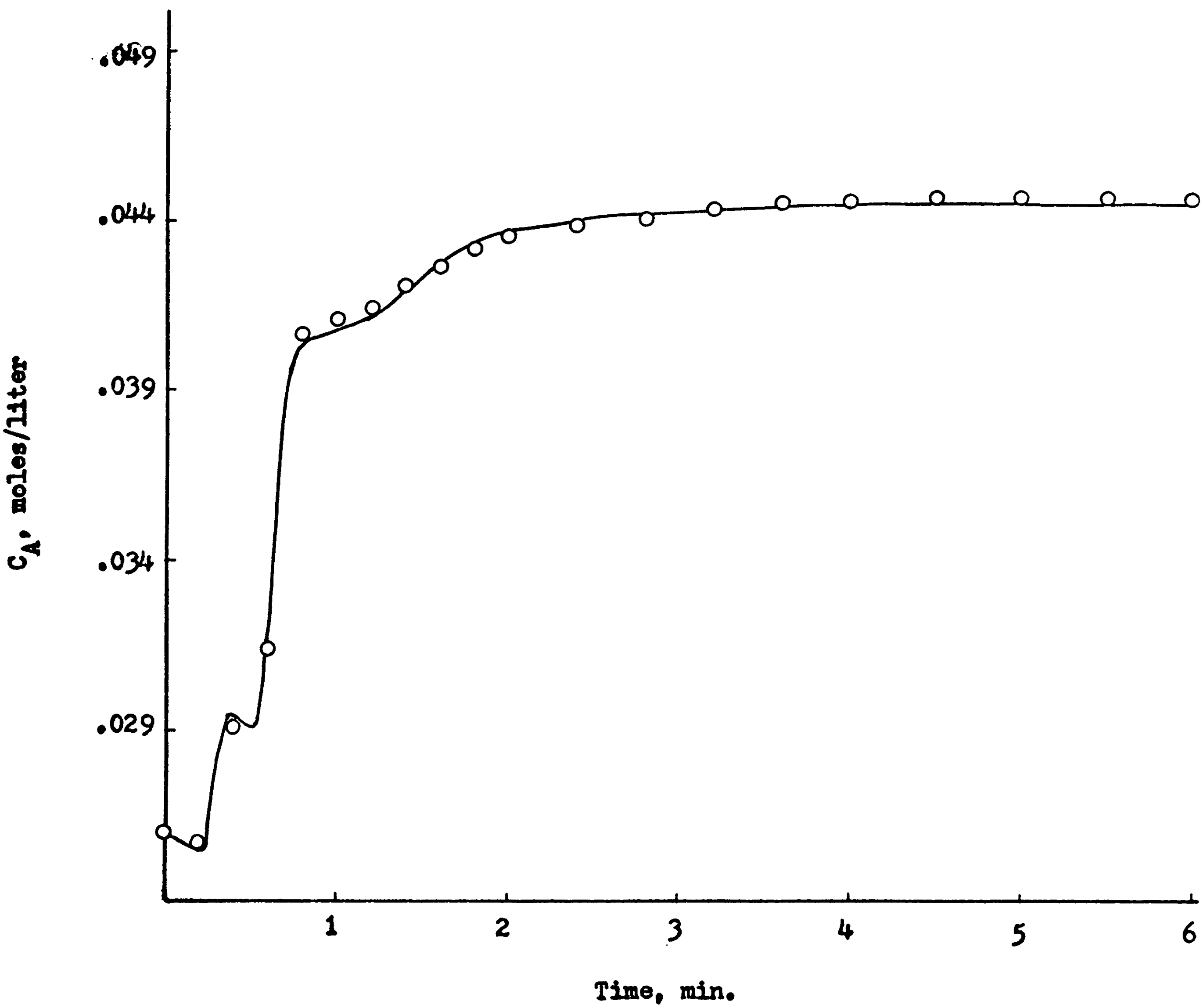

.056
.051
.046
.041
.036
.031
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 11. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in methyl acetate flow (decrease) and side feed sodium hydroxide flow (increase) for multiple feed recycle reactor (Run 9).

O Experimental data

——— Numerical model



.049
.044
.039
.034
.029
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 12. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in methyl acetate flow (increase) and side feed sodium hydroxide flow (decrease) for multiple feed recycle reactor (Run 10).

○ Experimental data

——— Numerical model

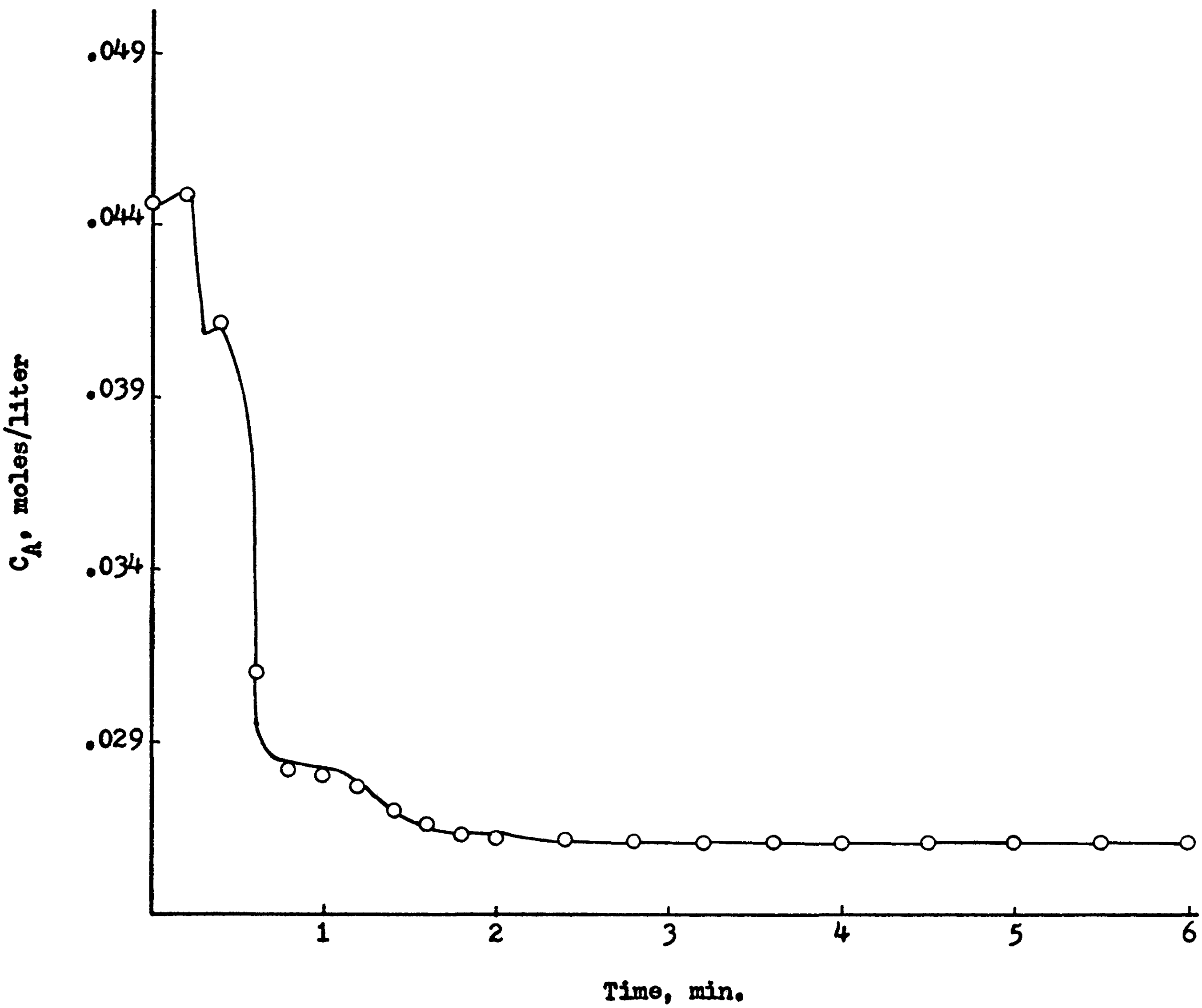

.049
.044
.039
.034
.029
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 13. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in methyl acetate flow (decrease) and side feed sodium hydroxide flow (increase) for multiple feed recycle reactor (Run 11).

○ Experimental data

——— Numerical model

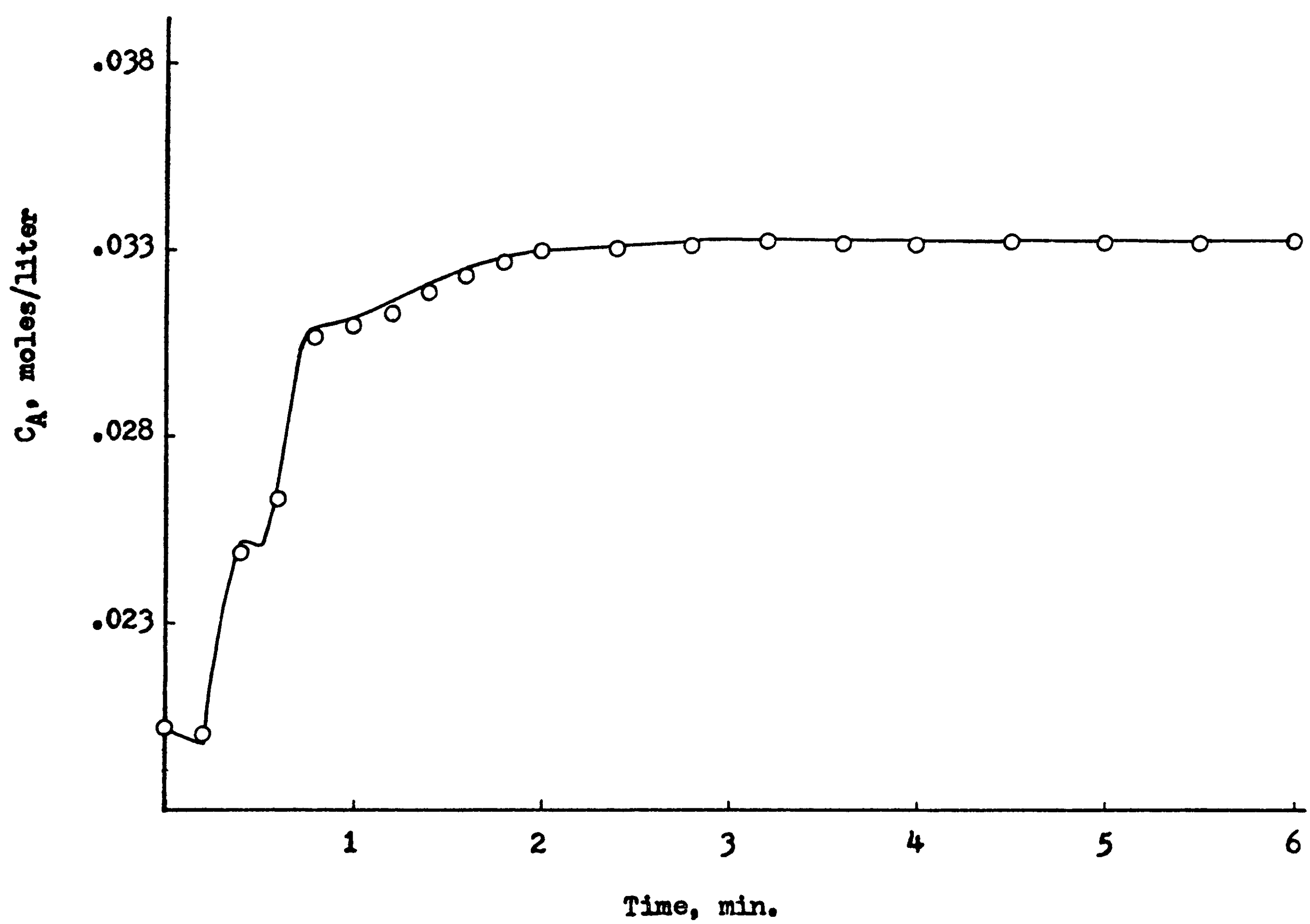

.038
.033
.028
.023
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 14. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in methyl acetate flow (increase) and side feed sodium hydroxide flow (decrease) for multiple feed recycle reactor (Run 12).

o Experimental data

——— Numerical model

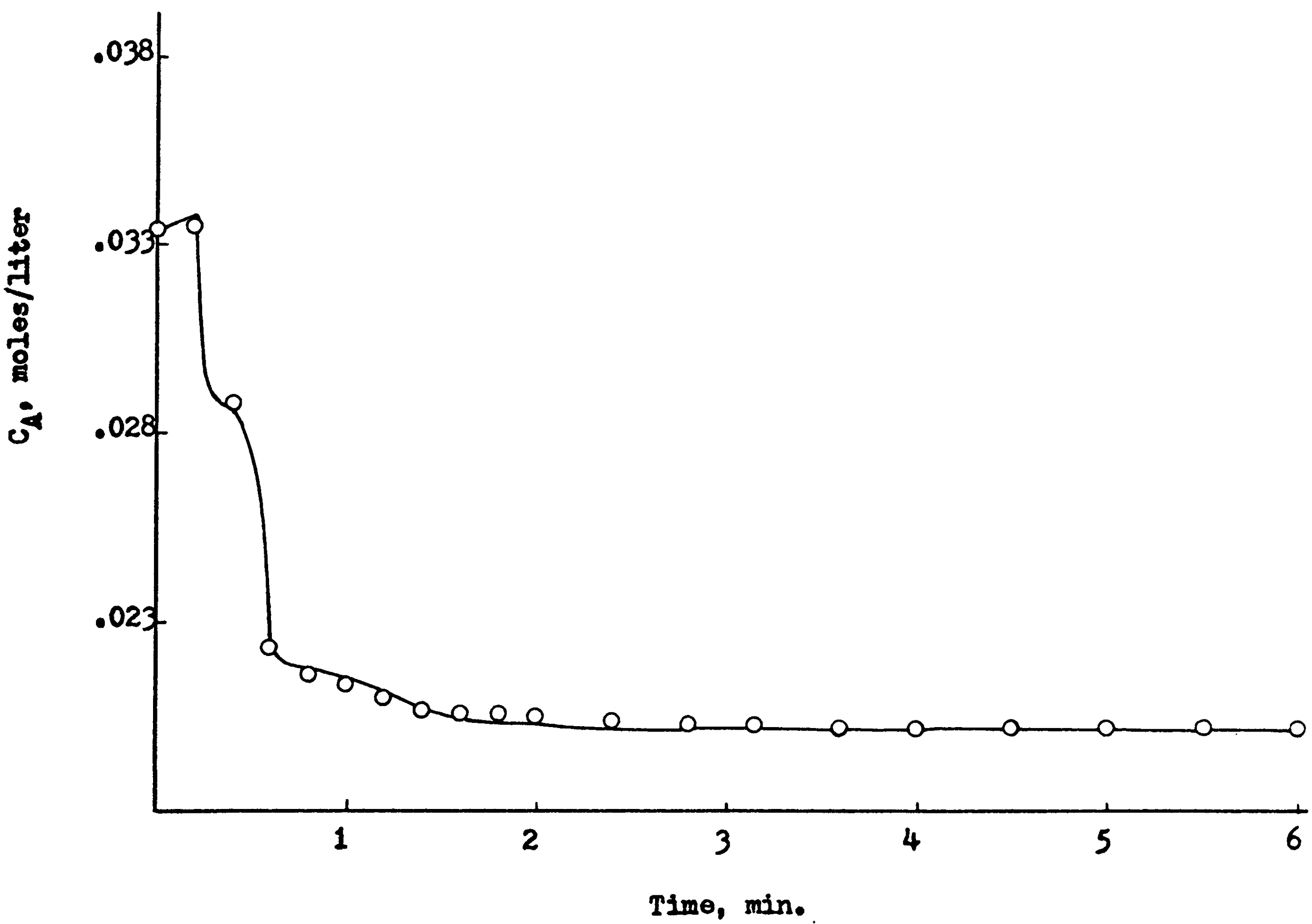

.038
.033
.028
.023
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 15. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in sodium hydroxide concentration (decrease) and side feed sodium hydroxide flow (decrease) for multiple feed recycle reactor (Run 13).

o Experimental data

—— Numerical model

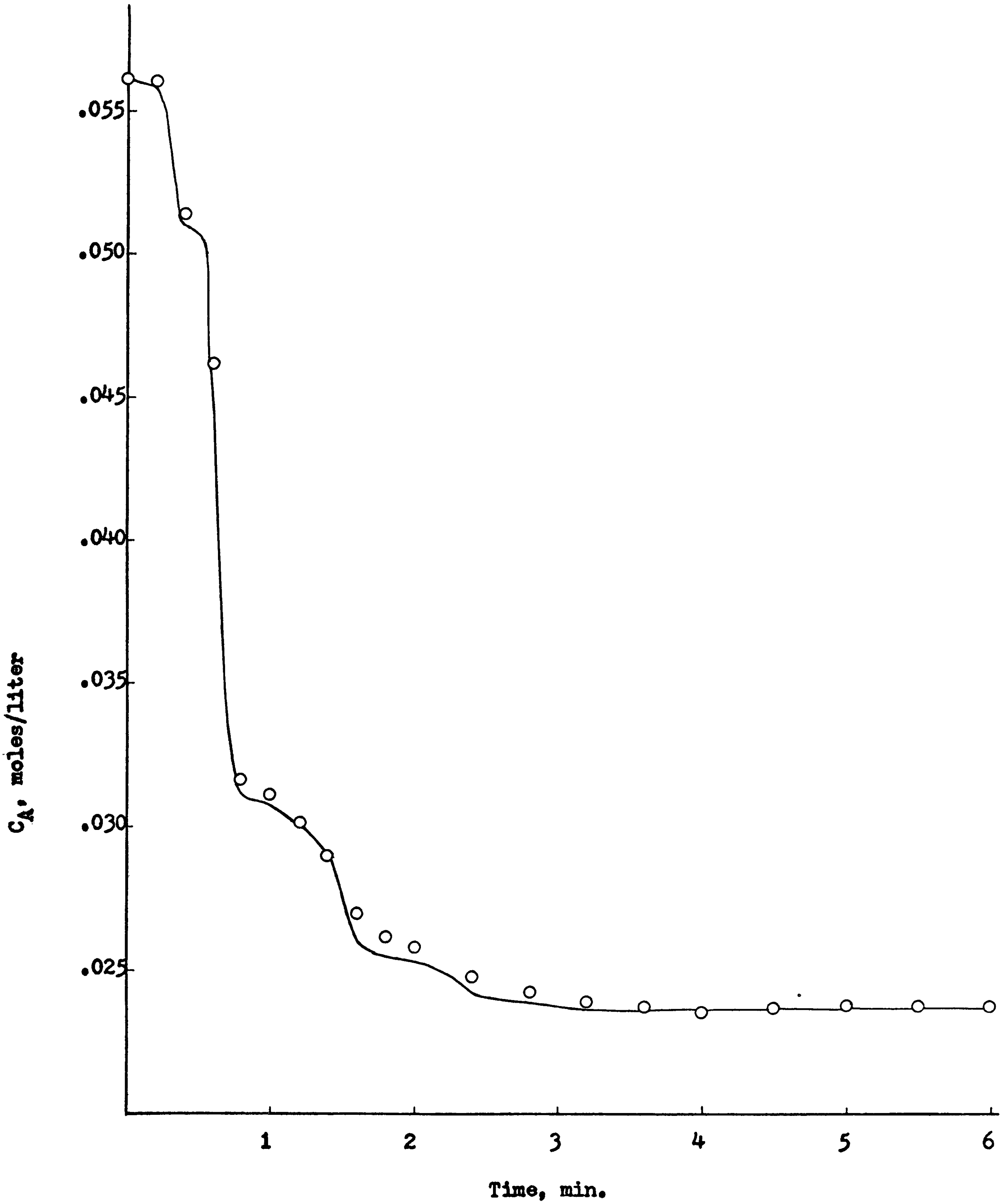

.055
.050
.045
.040
.035
.030
.025
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 16. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in sodium hydroxide concentration (increase) and side feed sodium hydroxide flow (increase) for multiple feed recycle reactor (Run 14).

o Experimental data

——— Numerical model

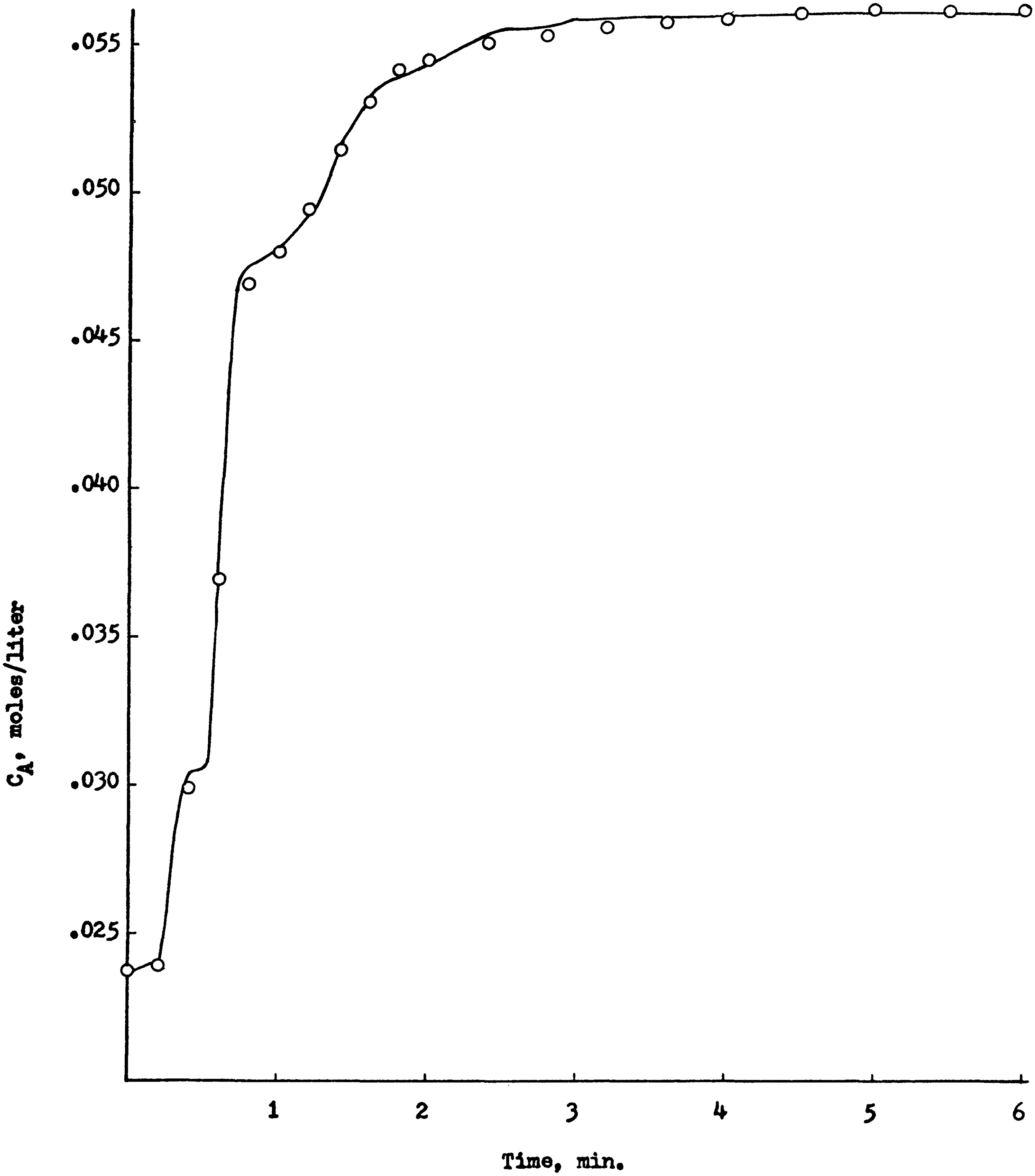

.055
.050
.045
.040
.035
.030
.025
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 17. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in methyl acetate concentration (increase) and side feed sodium hydroxide flow (decrease) for multiple feed recycle reactor (Run 15).

o Experimental data

——— Numerical model

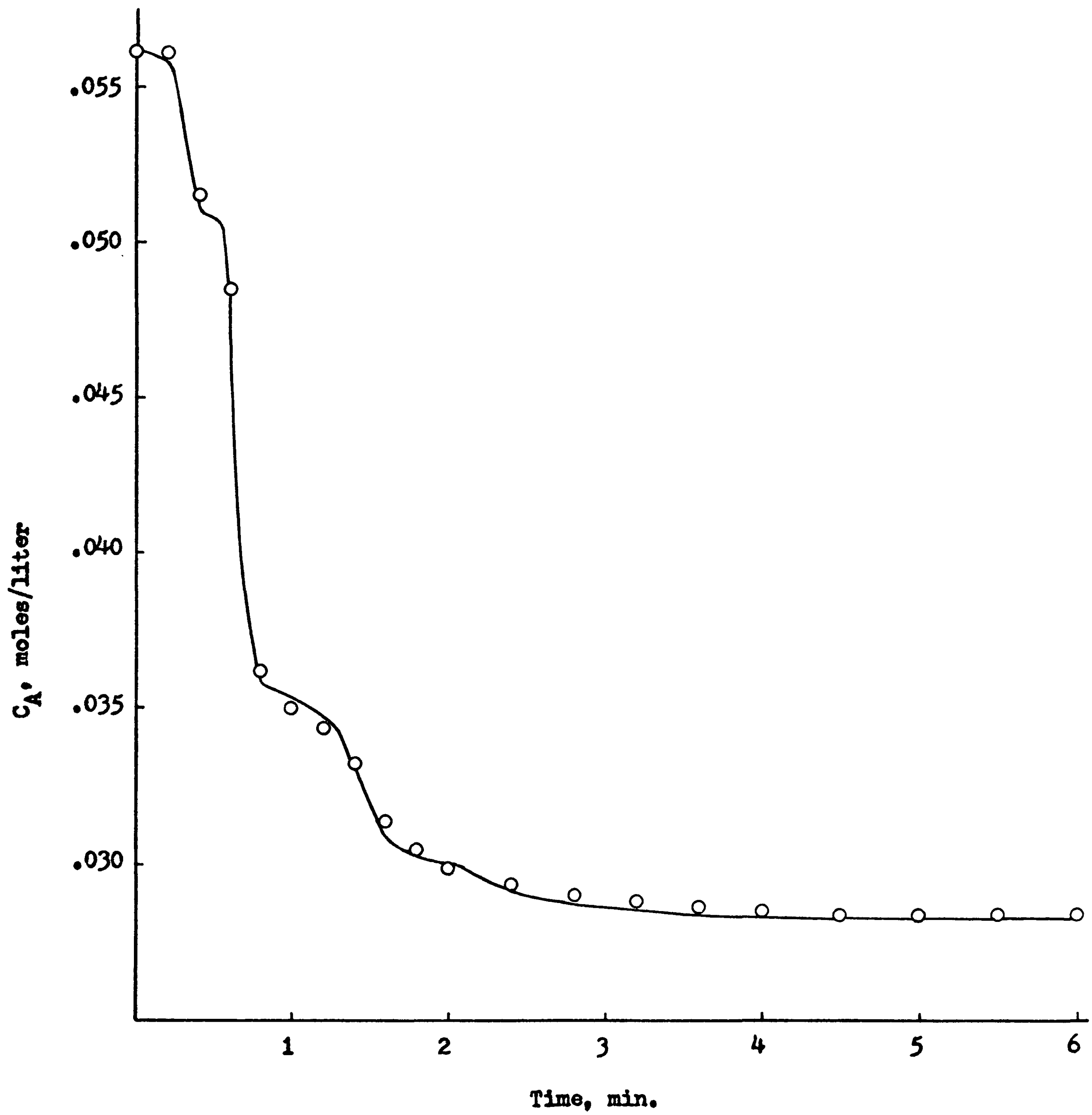
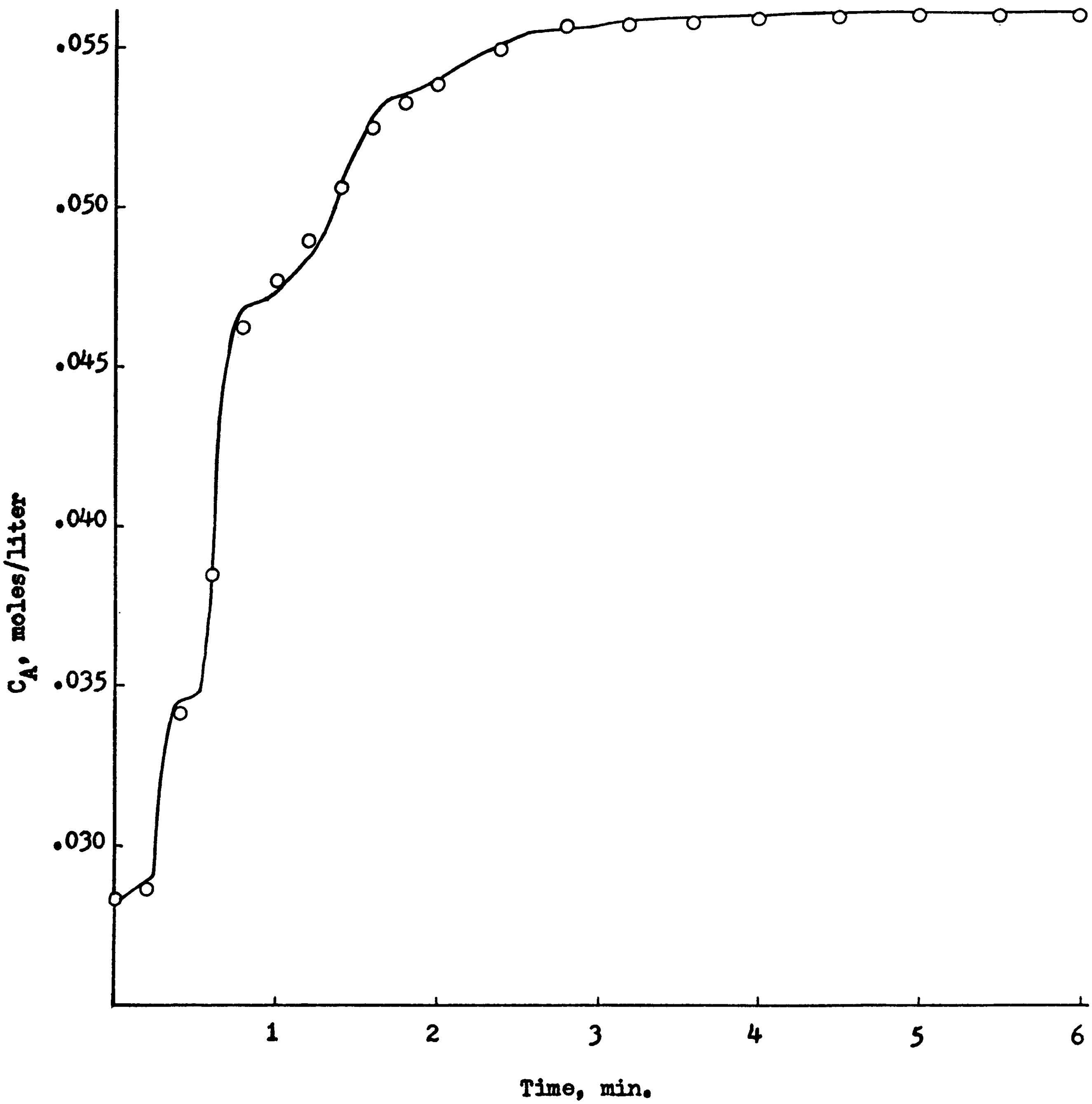

.055
.050
.045
.040
.035
.030
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 18. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in methyl acetate concentration (decrease) and side feed sodium hydroxide flow (increase) for multiple feed recycle reactor (Run 16).

o Experimental data

—— Numerical model



.055
.050
.045
.040
.035
.030
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 19. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in sodium hydroxide concentration (decrease) and side feed sodium hydroxide flow (decrease) for multiple feed recycle reactor (Run 17).

o Experimental data

——— Numerical model

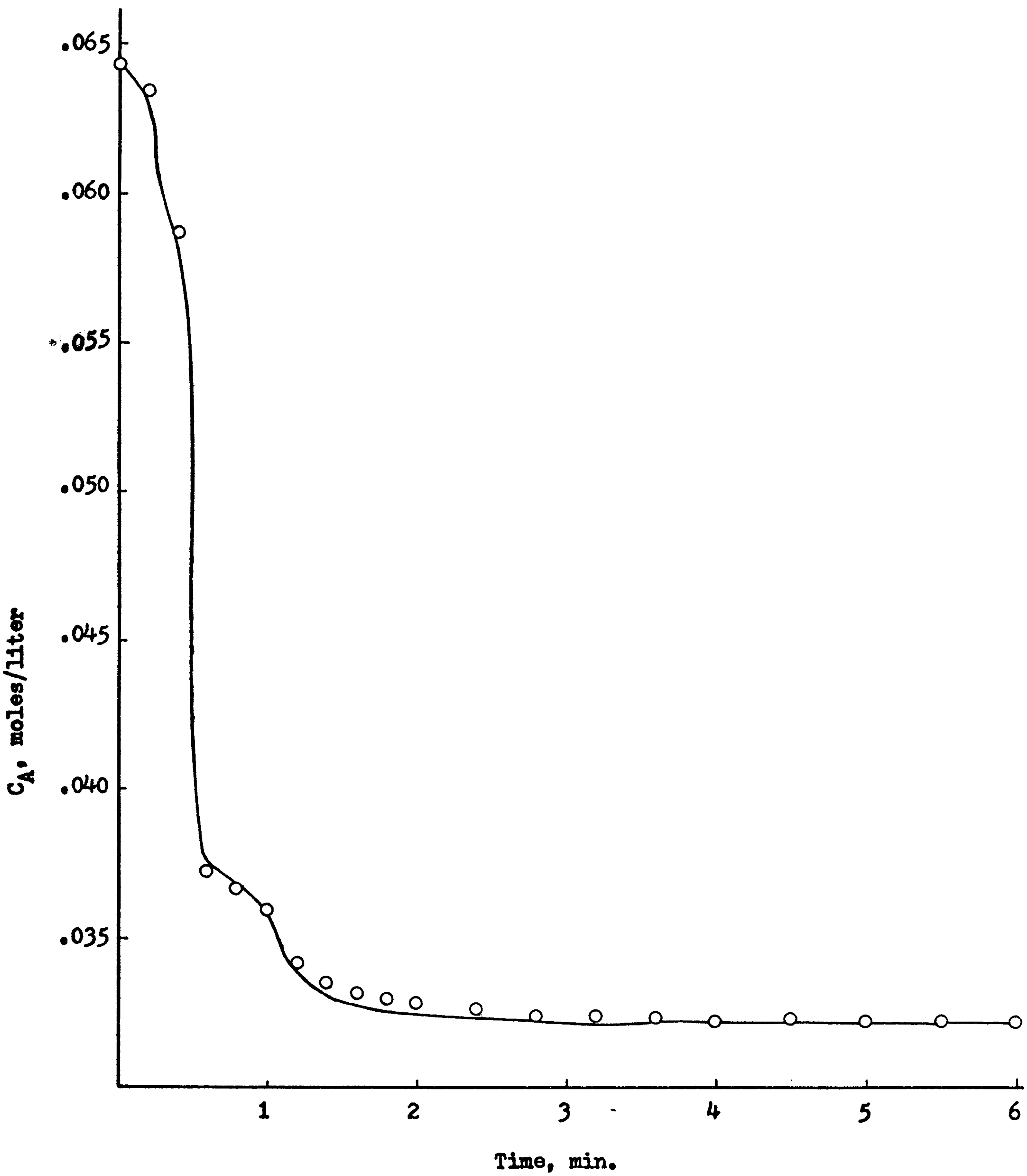

.065
.060
.055
.050
.045
.040
.035
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 20. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in sodium hydroxide concentration (increase) and side feed sodium hydroxide flow (increase) for multiple feed recycle reactor (Run 18).

O Experimental data

——— Numerical model

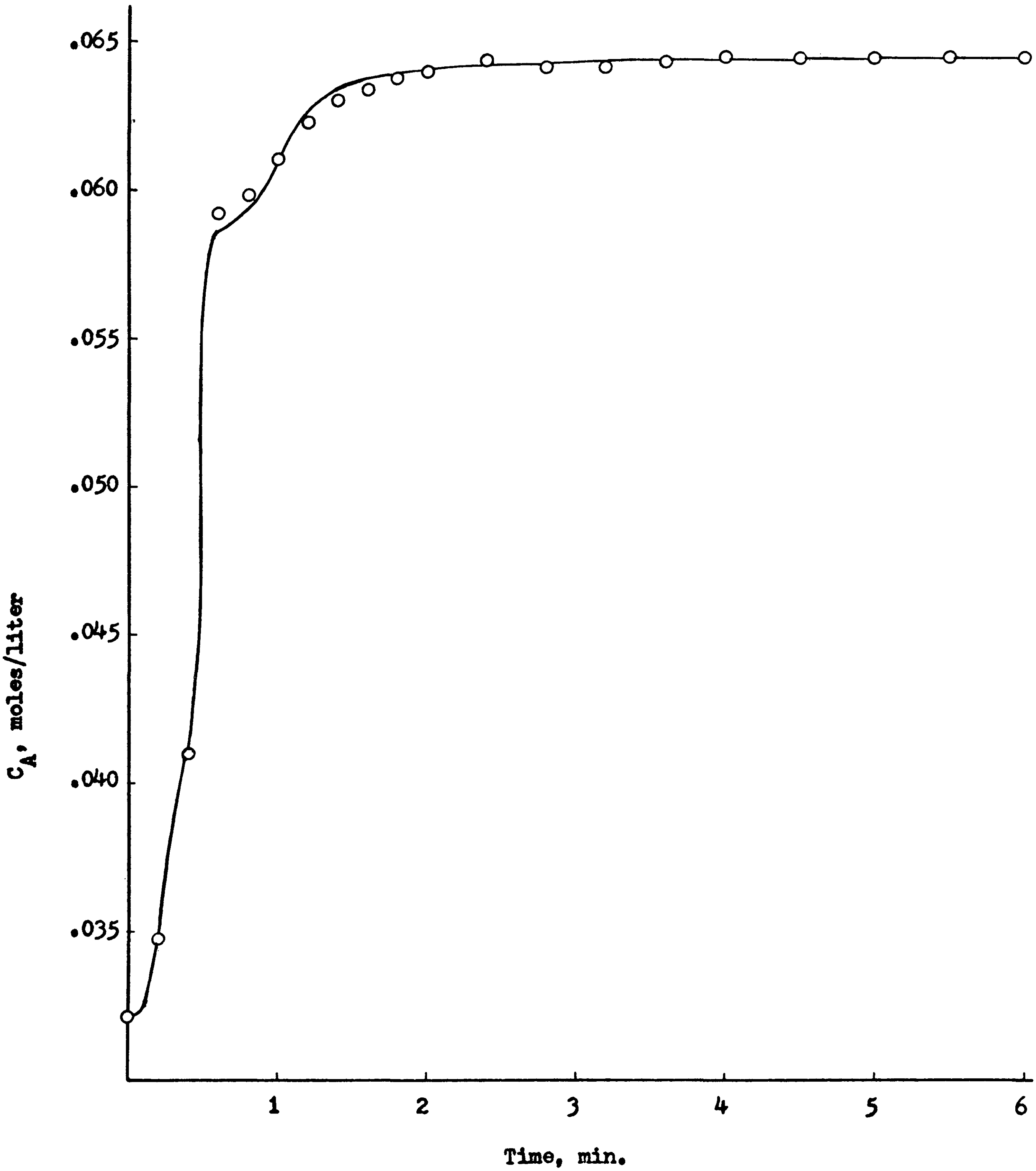

.065
.060
.055
.050
.045
.040
.035
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 21. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in methyl acetate concentration (increase) and side feed sodium hydroxide flow (decrease) for multiple feed recycle reactor (Run 19).

O Experimental data

——— Numerical model

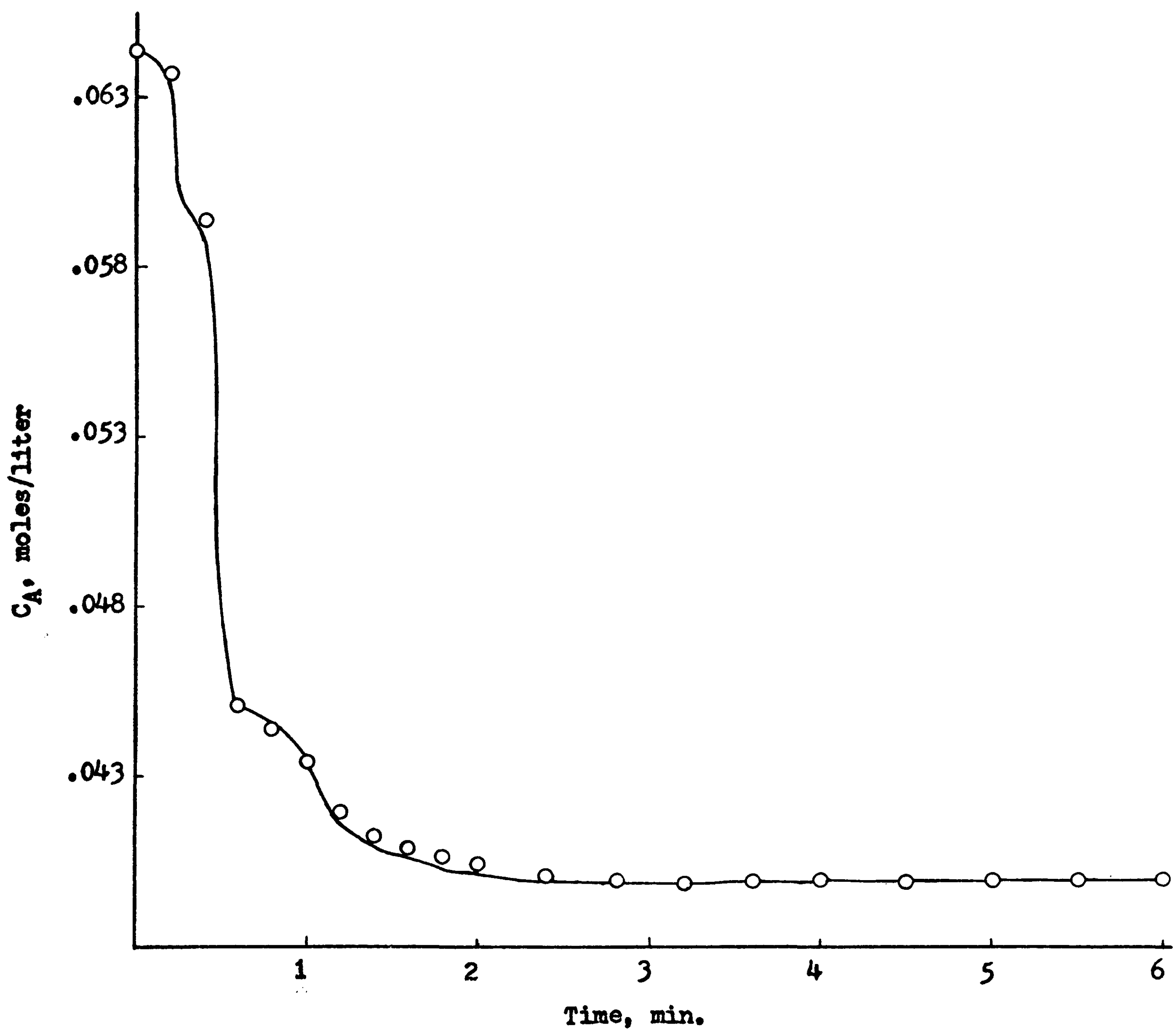

.063
.058
.053
.048
.043
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 22. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in methyl acetate concentration (decrease) and side feed sodium hydroxide flow (increase) for multiple feed recycle reactor (Run 20).

○ Experimental data

——— Numerical model

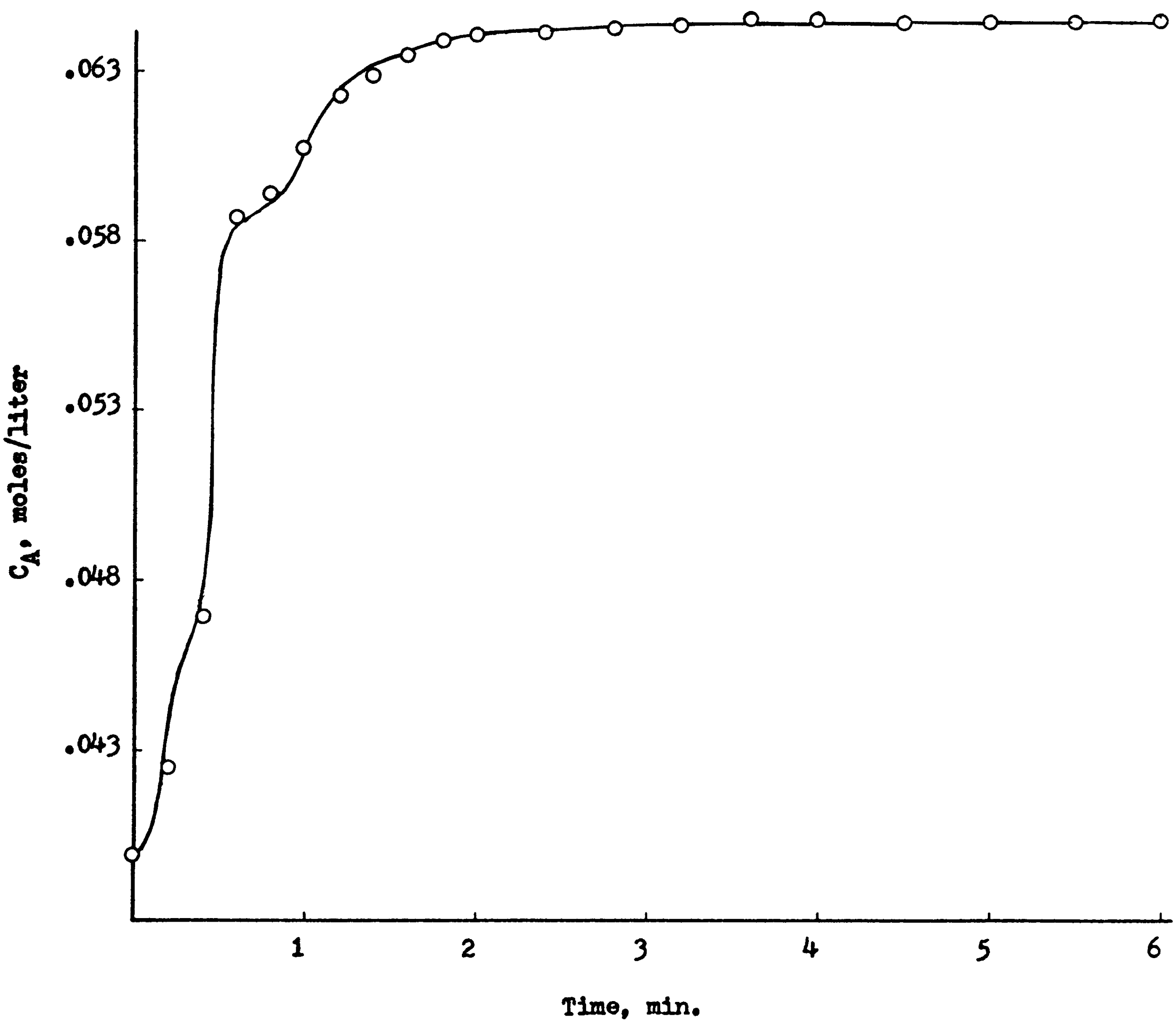

.063
.058
.053
.048
.043
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 23. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in methyl acetate flow (increase) and side feed sodium hydroxide flow (decrease) for multiple feed recycle reactor (Run 21).

o Experimental data

——— Numerical model

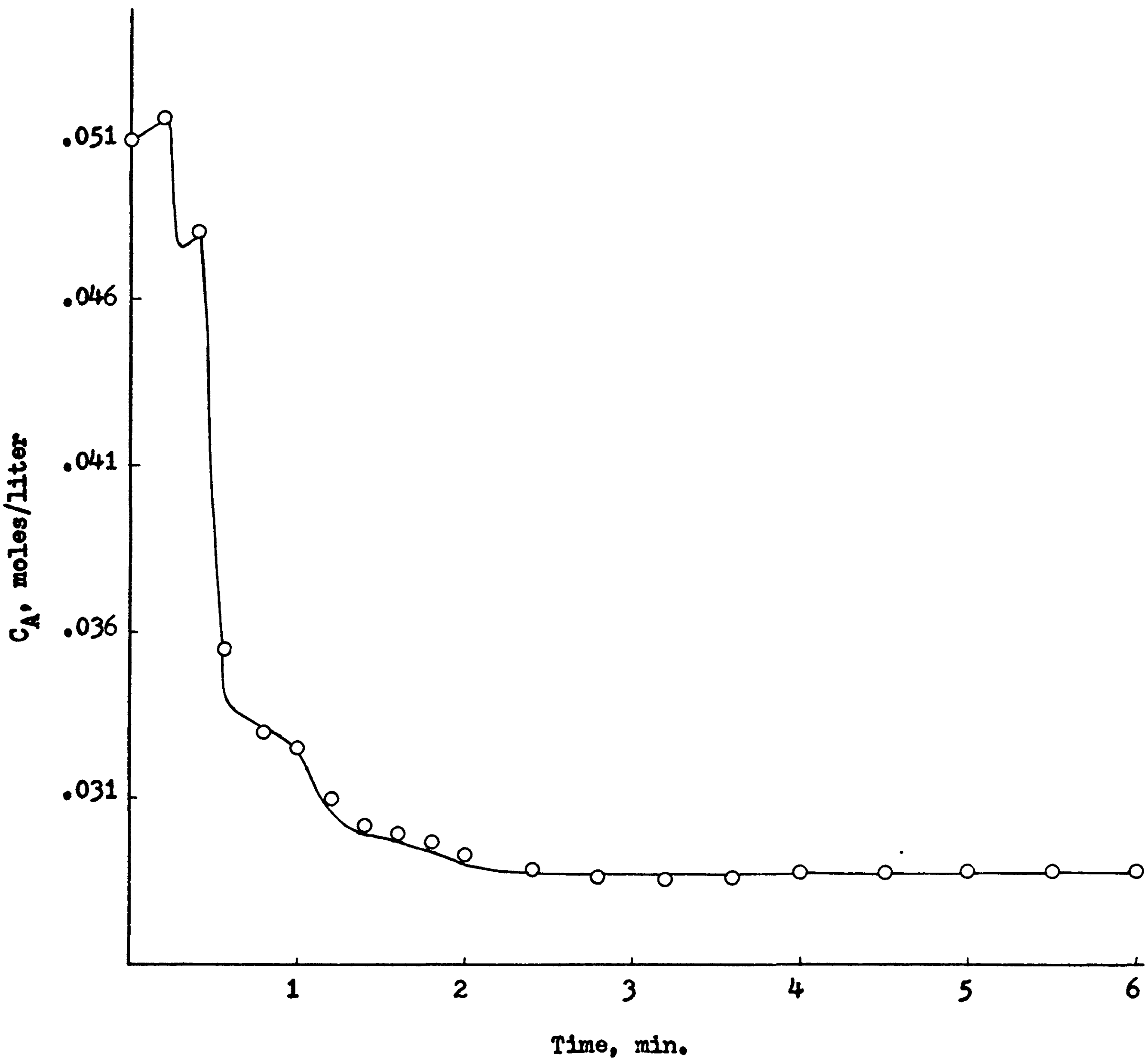

.051
.046
.041
.036
.031
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 24. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in methyl acetate flow (decrease) and side feed sodium hydroxide flow (increase) for multiple feed recycle reactor (Run 22).

o Experimental data

——— Numerical model

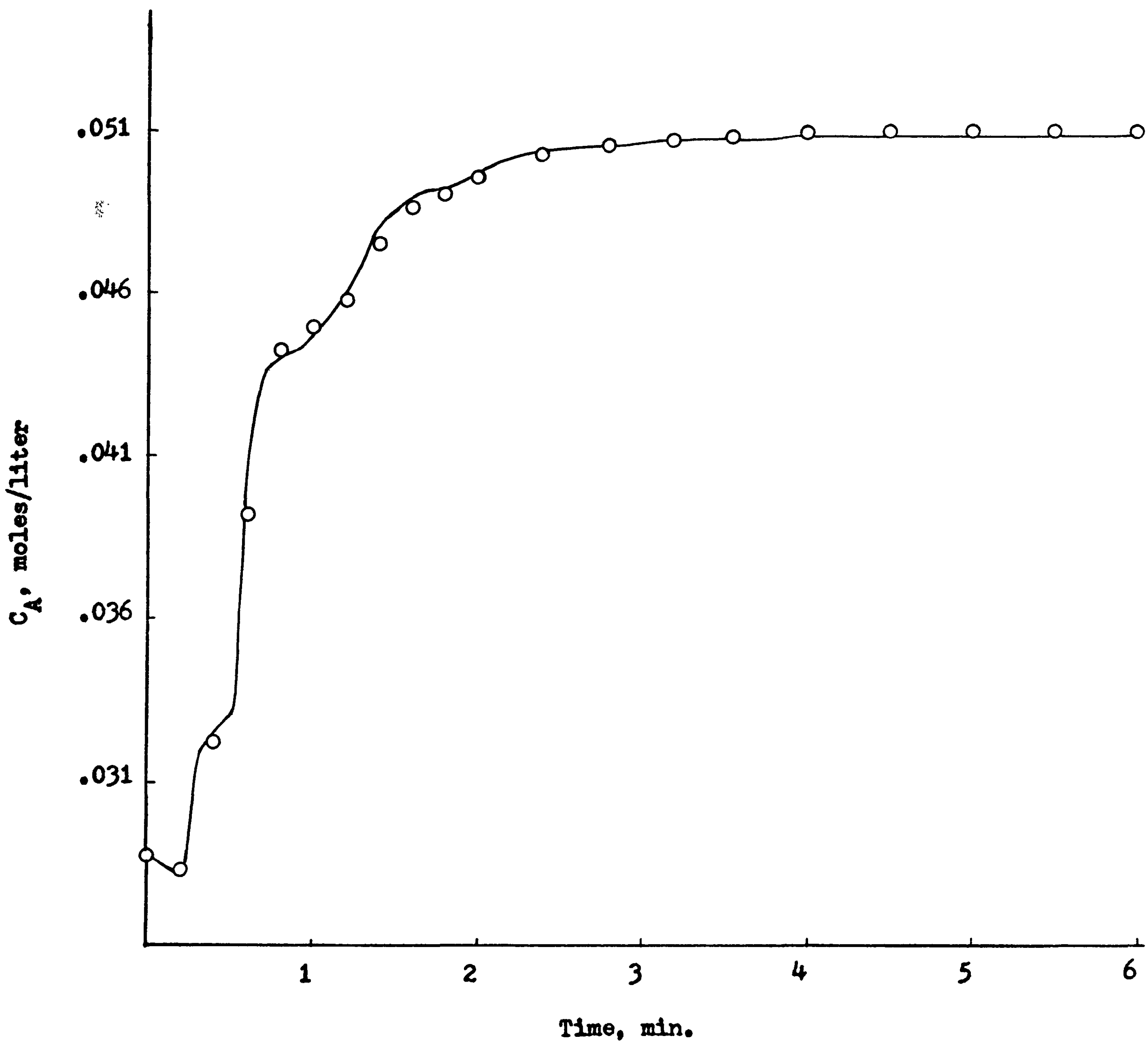

.051
.046
.041
.036
.031
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 25. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in methyl acetate flow (increase) and side feed sodium hydroxide flow (decrease) for multiple feed recycle reactor (Run 23).

O Experimental data

——— Numerical model

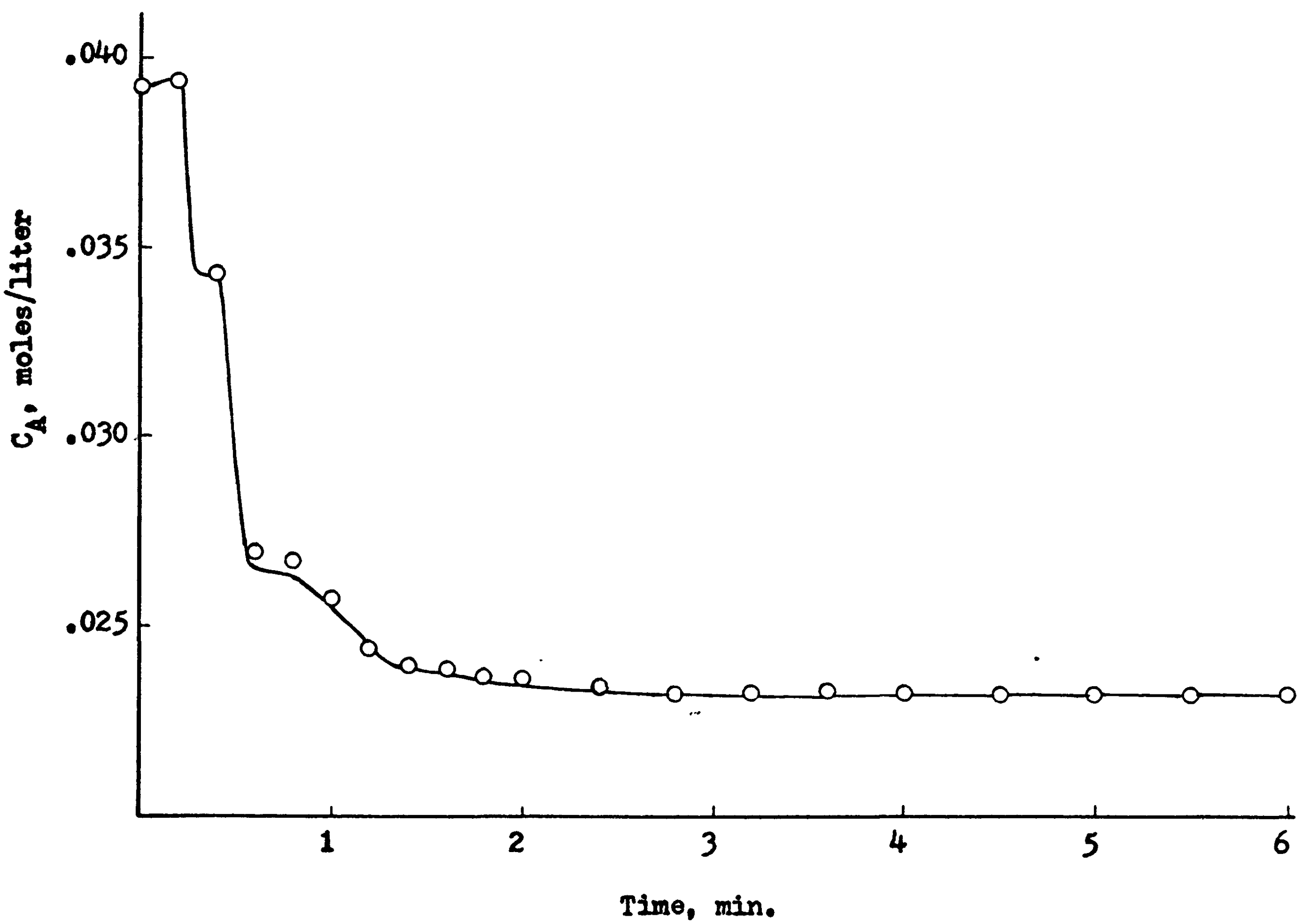
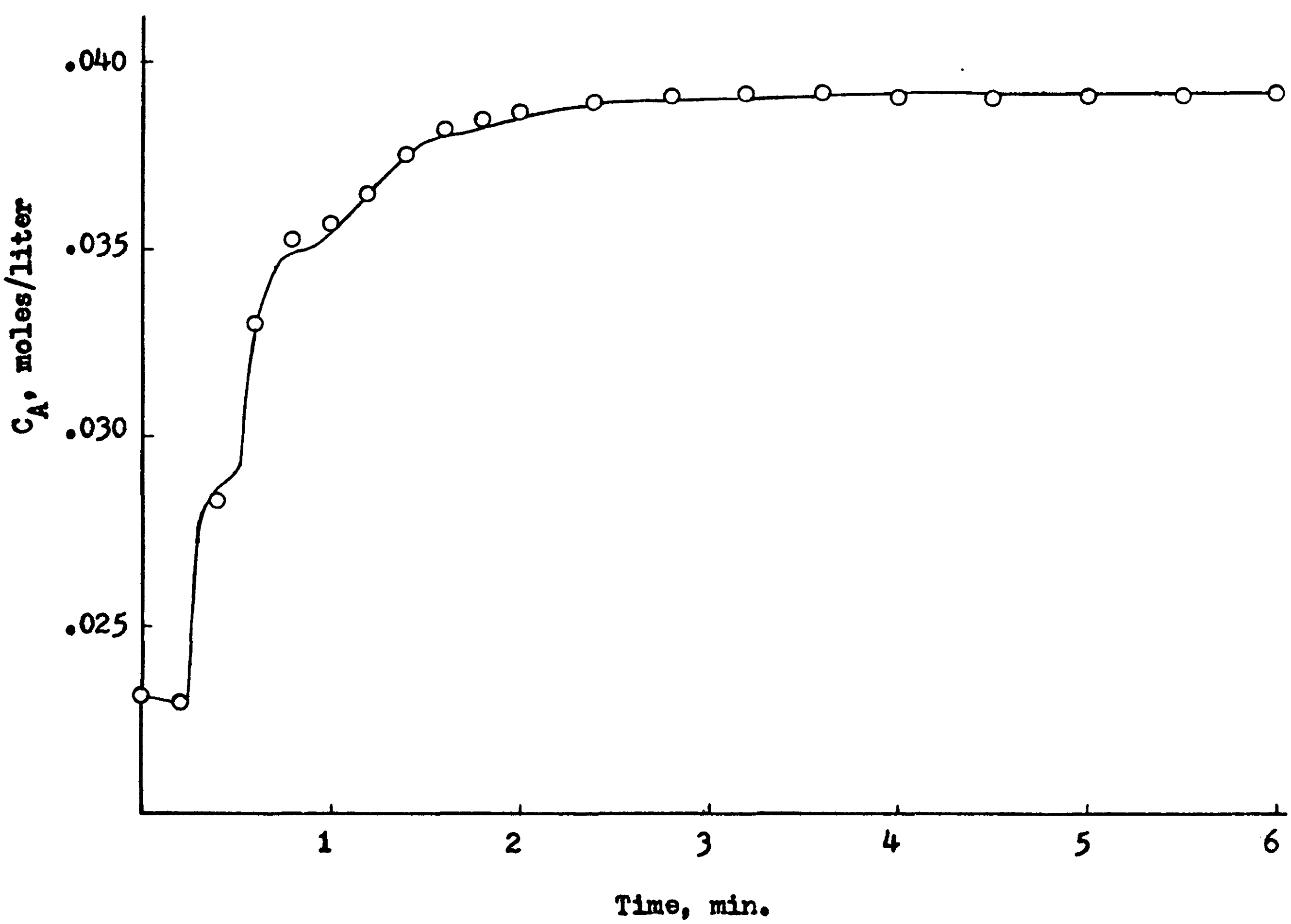

.040
.035
.030
.025
C_A, moles/liter
1
2
3
4
5
6
Time, min.

Figure 26. Transient response of outlet sodium hydroxide concentration to simultaneous upsets in methyl acetate flow (decrease) and side feed sodium hydroxide flow (increase) for multiple feed recycle reactor (Run 24).

O Experimental data

——— Numerical model


.040
.035
.030
.025
C_A, moles/liter
1
2
3
4
5
6
Time, min.

CONCLUSIONS

The experimental and theoretical results led to the following conclusions:

1. The numerical model was effective in predicting the dynamic response of the multiple feed recycle reactor.

2. The dynamic response curves were magnified by thr upsets in side feed.

3. Since the side feed was operated at low flow rates and concentrations, its effect was not significant when the high fresh feed flow rates and concentrations were used for the multiple feed recycle reactor.

4. A faster control of product concentration was achieved by the side feed upsets.

5. The agreement between the experimental data and the dynamic response predicted by the mathematical model was good within 5%.

6. The deviations which occur between the numerical model and the experimental data were probably caused by radial dispersion.

APPENDIX I

Experimental Data

Table 3

Run 1		Run 2	
C_{A0} =.1973	C_{A0F} =.1973	C_{A0} =.1973	C_{A0F} =.1973
C_{B0} =.1066	C_{B0F} =.1885	C_{B0} =.1885	C_{B0F} =.1066
C_{AS1} =.0944	C_{AS1F} =.0944	C_{AS1} =.0944	C_{AS1F} =.0944
C_{BS1} =.0	C_{BS1F} =.0	C_{BS1} =.0	C_{BS1F} =.0
F_{A0} =.019	F_{AF} =.019	F_{A0} =.019	F_{AF} =.019
F_{B0} =.048	F_{BF} =.048	F_{B0} =.048	F_{BF} =.048
F_{AS1} =.022	F_{AS1F} =.010	F_{AS1} =.010	F_{AS1F} =.022
F_{BS1} =.0	F_{BS1F} =.0	F_{BS1} =.0	F_{BS1F} =.0
Q_R =.021	Q_{RF} =.021	Q_R =.021	Q_{RF} =.021

Time (min)	C_A (moles/liter)	Time (min)	C_A (moles/liter)
0.0	0.0327	0.0	0.0118
0.2	0.0324	0.2	0.0121
0.4	0.0295	0.4	0.0170
0.6	0.0261	0.6	0.0181
0.8	0.0227	0.8	0.0220
1.0	0.0154	1.0	0.0272
1.2	0.0149	1.2	0.0275
1.4	0.0147	1.4	0.0281
1.6	0.0144	1.6	0.0286
1.8	0.0139	1.8	0.0293
2.0	0.0133	2.0	0.0304
2.4	0.0125	2.4	0.0313
2.8	0.0123	2.8	0.0317
3.2	0.0122	3.2	0.0321
3.6	0.0121	3.6	0.0323
4.0	0.0119	4.0	0.0325
4.5	0.0118	4.5	0.0326
5.0	0.0118	5.0	0.0327
5.5	0.0118	5.5	0.0327

Table 4

Run 3		Run 4	
C_{AO} =.1973	C_{AOF} =.0944	C_{AO} =.0944	C_{AOF} =.1973
C_{BO} =.1066	C_{BOF} =.1066	C_{BO} =.1066	C_{BOF} =.1066
C_{AS1} =.0944	C_{AS1F} =.0944	C_{AS1} =.0944	C_{AS1F} =.0944
C_{BS1} =.0	C_{BS1F} =.0	C_{BS1} =.0	C_{BS1F} =.0
F_{AO} =.019	F_{AF} =.019	F_{AO} =.019	F_{AF} =.019
F_{BO} =.048	F_{BF} =.048	F_{BO} =.048	F_{BF} =.048
F_{AS1} =.022	F_{AS1F} =.010	F_{AS1} =.010	F_{AS1F} =.022
Q_R =.021	Q_{RF} =.021	Q_R =.021	Q_{RF} =.021

Time (min)	C_A (moles/liter)	Time (min)	C_A (moles/liter)
0.0	0.0327	0.0	0.0130
0.2	0.0325	0.2	0.0131
0.4	0.0291	0.4	0.0185
0.6	0.0260	0.6	0.0198
0.8	0.0222	0.8	0.0252
1.0	0.0168	1.0	0.0292
1.2	0.0164	1.2	0.0294
1.4	0.0160	1.4	0.0296
1.6	0.0157	1.6	0.0299
1.8	0.0155	1.8	0.0306
2.0	0.0152	2.0	0.0314
2.4	0.0143	2.4	0.0321
2.8	0.0136	2.8	0.0322
3.2	0.0134	3.2	0.0323
3.6	0.0133	3.6	0.0324
4.0	0.0132	4.0	0.0325
4.5	0.0131	4.5	0.0326
5.0	0.0130	5.0	0.0327
5.5	0.0130	5.5	0.0327

Table 5

Run 5

C_{A0}	=.1973	C_{A0F}	=.1973
C_{B0}	=.1066	C_{B0F}	=.1885
C_{AS1}	=.0944	C_{AS1F}	=.0944
C_{BS1}	=.0	C_{BS1F}	=.0
F_{A0}	=.050	F_{AF}	=.050
F_{AF}	=.074	F_{BF}	=.074
F_{AS1}	=.040	F_{AS1F}	=.022
F_{BS1}	=.0	F_{BS1F}	=.0
Q_R	=.021	Q_{RF}	=.021

Run 6

C_{A0}	=.1973	C_{A0F}	=.1973
C_B	=.1885	C_{B0F}	=.1066
C_{AS1}	=.0944	C_{AS1F}	=.0944
C_{BS1}	=.0	C_{BS1F}	=.0
F_{A0}	=.050	F_{AF}	=.050
F_{B0}	=.074	F_{BF}	=.074
F_{AS1}	=.022	F_{AS1F}	=.040
F_{BS1}	=.0	F_{BS1F}	=.0
Q_R	=.021	Q_{RF}	=.021

Time (min)	C_A (moles/liter)	Time (min)	C_A (moles/liter)
0.0	0.0566	0.0	0.0356
0.2	0.0560	0.2	0.0376
0.4	0.0523	0.4	0.0411
0.6	0.0397	0.6	0.0527
0.8	0.0387	0.8	0.0536
1.0	0.0382	1.0	0.0539
1.2	0.0378	1.2	0.0544
1.4	0.0372	1.4	0.0551
1.6	0.0367	1.6	0.0556
1.8	0.0363	1.8	0.0558
2.0	0.0361	2.0	0.0560
2.4	0.0359	2.4	0.0562
2.8	0.0358	2.8	0.0567
3.2	0.0357	3.2	0.0566
3.6	0.0357	3.6	0.0565
4.0	0.0356	4.0	0.0567
4.5	0.0356	4.5	0.0567
5.0	0.0356	5.0	0.0567
5.5	0.0356	5.5	0.0567

Table 6

Run 7		Run 8	
C_{A0} =.1973	C_{A0F} =.0944	C_{A0} =.0944	C_{A0F}=.1973
C_{B0} =.1066	C_{B0F} =.1066	C_{B0} =.1066	C_{B0F} =.1066
C_{AS1}=.0944	C_{AS1F} =.0944	C_{AS1} =.0944	C_{AS1F} =.0944
C_{BS1}=.0	C_{BS1F} =.0	C_{BS1} =.0	C_{BS1F} =.0
F_{A0} =.050	F_{AF} =.050	F_{A0} =.050	F_{AF} =.050
F_{B0} =.074	F_{BF} =.074	F_{B0} =.074	F_{BF} =.074
F_{AS1}=.040	F_{AS1F} =.022	F_{AS1} =.022	F_{AS1F} =.040
F_{BS1}=.0	F_{BS1F} =.0	F_{BS1} =.0	F_{BS1F} =.0
Q_R =.021	Q_{RF} =.021	Q_R =.021	Q_{RF} =.021

Time (min)	C_A (moles/liter)	Time (min)	C_A (moles/liter)
0.0	0.0566	0.0	0.0277
0.2	0.0560	0.2	0.0295
0.4	0.0516	0.4	0.0338
0.6	0.0330	0.6	0.0526
0.8	0.0312	0.8	0.0530
1.0	0.0310	1.0	0.0532
1.2	0.0301	1.2	0.0543
1.4	0.0290	1.4	0.0552
1.5	0.0286	1.6	0.0557
1.8	0.0284	1.8	0.0559
2.0	0.0282	2.0	0.0561
2.4	0.0279	2.4	0.0562
2.8	0.0278	2.8	0.0563
3.2	0.0278	3.2	0.0564
3.6	0.0277	3.6	0.0565
4.0	0.0276	4.0	0.0566
4.5	0.0277	4.5	0.0567
5.0	0.0277	5.0	0.0567
5.5	0.0277	5.5	0.0567

Table 7

Run 9			
C_{A0} =.1973	C_{A0F} =.1973		
C_{B0} =.1885	C_{B0F} =.1885		
C_{AS1} =.0944	C_{AS1F} =.0944		
C_{BS1} =.0	C_{BS1F} =.0		
F_{A0} =.044	F_{AF} =.044		
F_{B0} =.074	F_{BF} =.048		
F_{AS1} =.010	F_{AS1F} =.022		
F_{BS1} =.0	F_{BS1F} =.0		
Q_R =.021	Q_{RF} =.021		

Run 10	
C_{A0} =.1973	C_{A0F} =.1973
C_{B0} =.1885	C_{B0F} =.1885
C_{AS1}=.0944	C_{AS1F} =.0944
C_{BS1}=.0	C_{BS1F} =.0
F_{A0} =.044	F_{AF} =.044
F_{B0} =.048	F_{BF} =.074
F_{AS1}=.022	F_{AS1F} =.010
F_{BS1}=.0	F_{BS1F} =.0
Q_R =.021	Q_{RF} =.021

Time (min)	C_A (moles/liter)	Time (min)	C_A (moles/liter)
0.0	0.0260	0.0	0.0447
0.2	0.0257	0.2	0.0449
0.4	0.0292	0.4	0.0412
0.6	0.0314	0.6	0.0310
0.8	0.0407	0.8	0.0282
1.0	0.0411	1.0	0.0280
1.2	0.0414	1.2	0.0278
1.4	0.0422	1.4	0.0271
1.6	0.0427	1.6	0.0266
1.8	0.0432	1.8	0.0264
2.0	0.0436	2.0	0.0263
2.4	0.0439	2.4	0.0263
2.8	0.0441	2.8	0.0262
3.2	0.0443	3.2	0.0262
3.6	0.0445	3.6	0.0261
4.0	0.0446	4.0	0.0260
4.5	0.0447	4.5	0.0260
5.0	0.0447	5.0	0.0260
5.5	0.0447	5.5	0.0260

Table 8

Run 11				Run 12			
C_{A0}	=.0944	C_{A0F}	=.0944	C_{A0}	=.0944	C_{A0F}	=.0944
C_{B0}	=.1066	C_{B0F}	=.1066	C_{B0}	=.1066	C_{B0F}	=.1066
C_{AS1}	=.0944	C_{AS1F}	=.0944	C_{AS1}	=.0944	C_{AS1F}	=.0944
C_{BS1}	=.0	C_{BS1F}	=.0	C_{BS1}	=.0	C_{BS1F}	=.0
F_{A0}	=.044	F_{AF}	=.044	F_{A0}	=.044	F_{AF}	=.044
F_{B0}	=.074	F_{BF}	=.048	F_{B0}	=.048	F_{BF}	=.074
F_{AS1}	=.010	F_{AS1F}	=.022	F_{AS1}	=.022	F_{AS1F}	=.010
F_{BS1}	=.0	F_{BS1F}	=.0	F_{BS1}	=.0	F_{BS1F}	=.0
Q_R	=.021	Q_{RF}	=.021	Q_R	=.021	Q_{RF}	=.021

Time (min)	C_A (moles/liter)	Time (min)	C_A (moles/liter)
0.0	0.0202	0.0	0.0334
0.2	0.0200	0.2	0.0336
0.4	0.0249	0.4	0.0291
0.6	0.0263	0.6	0.0224
0.8	0.0297	0.8	0.0217
1.0	0.0310	1.0	0.0214
1.2	0.0313	1.2	0.0211
1.4	0.0319	1.4	0.0209
1.6	0.0323	1.6	0.0208
1.8	0.0327	1.8	0.0207
2.0	0.0330	2.0	0.0206
2.4	0.0331	2.4	0.0205
2.8	0.0332	2.8	0.0204
3.2	0.0333	3.2	0.0203
3.6	0.0332	3.6	0.0203
4.0	0.0332	4.0	0.0203
4.5	0.0333	4.5	0.0203
5.0	0.0334	5.0	0.0203
5.5	0.0334	5.5	0.0203

Table 9

Run 13				Run 14			
C_{AO}	=.2239	C_{AOF}	=.1121	C_{AO}	=.1121	C_{AOF}	=.2239
C_{BO}	=.1186	C_{BOF}	=.1186	C_{BO}	=.1186	C_{BOF}	=.1186
C_{AS1}	=.1121	C_{AS1F}	=.1121	C_{AS1}	=.1121	C_{AS1F}	=.1121
C_{BS1}	=.0	C_{BS1F}	=.0	C_{BS1}	=.0	C_{BS1F}	=.0
F_{AO}	=.032	F_{AF}	=.032	F_{AO}	=.032	F_{AF}	=.032
F_{BO}	=.048	F_{BF}	=.048	F_{BO}	=.048	F_{BF}	=.048
F_{AS1}	=.022	F_{AS1F}	=.010	F_{AS1}	=.010	F_{AS1F}	=.022
F_{BS1}	=.0	F_{BS1F}	=.0	F_{BS1}	=.0	F_{BS1F}	=.0
Q_R	=.036	Q_{RF}	=.036	Q_R	=.036	Q_{RF}	=.036

Time (min)	C_A (moles/liter)	Time (min)	C_A (moles/liter)
0.0	0.0562	0.0	0.0237
0.2	0.0560	0.2	0.0239
0.4	0.0515	0.4	0.0299
0.6	0.0462	0.6	0.0370
0.8	0.0317	0.8	0.0470
1.0	0.0312	1.0	0.0480
1.2	0.0302	1.2	0.0495
1.4	0.0290	1.4	0.0515
1.6	0.0270	1.6	0.0532
1.8	0.0262	1.8	0.0542
2.0	0.0257	2.0	0.0545
2.4	0.0248	2.4	0.0551
2.8	0.0242	2.8	0.0554
3.2	0.0239	3.2	0.0557
3.6	0.0237	3.6	0.0558
4.0	0.0236	4.0	0.0559
4.5	0.0237	4.5	0.0561
5.0	0.0237	5.0	0.0562
5.5	0.0237	5.5	0.0562

Table 10

Run 15		Run 16	
C_{A0} =.2239	C_{A0F} =.2239	C_{A0} =.2239	C_{A0F} =.2239
C_{B0} =.1186	C_{B0F} =.2090	C_{B0} =.2090	C_{B0F} =.1186
C_{AS1} =.1121	C_{AS1F} =.1121	C_{AS1} =.1121	C_{AS1F} =.1121
C_{BS1} =.0	C_{BS1F} =.0	C_{BS1} =.0	C_{BS1F} =.0
F_{A0} =.032	F_{AF} =.032	F_{A0} =.032	F_{AF} =.032
F_{B0} =.048	F_{BF} =.048	F_{B0} =.048	F_{BF} =.048
F_{AS1} =.022	F_{AS1F} =.010	F_{AS1} =.010	F_{AS1F} =.022
F_{BS1} =.0	F_{BS1F} =.0	F_{BS1} =.0	F_{BS1F} =.0
Q_R =.036	Q_{RF} =.036	Q_R =.036	Q_{RF} =.036

Time (min)	C_A (moles/liter)	Time (min)	C_A (moles/liter)
0.0	0.0562	0.0	0.0285
0.2	0.0561	0.2	0.0287
0.4	0.0515	0.4	0.0342
0.6	0.0485	0.6	0.0385
0.8	0.0362	0.8	0.0462
1.0	0.0350	1.0	0.0477
1.2	0.0344	1.2	0.0490
1.4	0.0333	1.4	0.0507
1.6	0.0314	1.6	0.0525
1.8	0.0305	1.8	0.0533
2.0	0.0299	2.0	0.0538
2.4	0.0294	2.4	0.0550
2.8	0.0291	2.8	0.0557
3.2	0.0288	3.2	0.0557
3.6	0.0287	3.6	0.0558
4.0	0.0286	4.0	0.0559
4.5	0.0284	4.5	0.0560
5.0	0.0285	5.0	0.0561
5.5	0.0285	5.5	0.0561

Table 11

Run 17			
C_{AO}	=.2239	C_{AOF}	=.1121
C_{BO}	=.1186	C_{BOF}	=.1186
C_{AS1}	=.1121	C_{AS1F}	=.1121
C_{BS1}	=.0	C_{BS1F}	=.0
F_{AO}	=.050	F_{AF}	=.050
F_{BO}	=.074	F_{BF}	=.074
F_{AS1}	=.040	F_{AS1F}	=.022
F_{BS1}	=.0	F_{BS1F}	=.0
Q_R	=.036	Q_{RF}	=.036

Run 18			
C_{AO}	=.1121	C_{AOF}	=.2239
C_{BO}	=.1186	C_{BOF}	=.1186
C_{AS1}	=.1121	C_{AS1F}	=.1121
C_{BS1}	=.0	C_{BS1F}	=.0
F_{AO}	=.050	F_{AF}	=.050
F_{BO}	=.074	F_{BF}	=.074
F_{AS1}	=.022	F_{AS1F}	=.040
F_{BS1}	=.0	F_{BS1F}	=.0
Q_R	=.036	Q_{RF}	=.036

Run 17 Time (min)	C_A (moles/liter)	Run 18 Time (min)	C_A (moles/liter)
0.0	0.0644	0.0	0.0322
0.2	0.0635	0.2	0.0348
0.4	0.0588	0.4	0.0410
0.6	0.0373	0.6	0.0592
0.8	0.0367	0.8	0.0598
1.0	0.0360	1.0	0.0610
1.2	0.0342	1.2	0.0623
1.4	0.0335	1.4	0.0631
1.6	0.0332	1.6	0.0634
1.8	0.0330	1.8	0.0638
2.0	0.0328	2.0	0.0640
2.4	0.0326	2.4	0.0643
2.8	0.0324	2.8	0.0642
3.2	0.0324	3.2	0.0641
3.6	0.0323	3.6	0.0643
4.0	0.0322	4.0	0.0644
4.5	0.0323	4.5	0.0644
5.0	0.0322	5.0	0.0644
5.5	0.0322	5.5	0.0644

Table 12

Run 19				Run 20			
C_{A0}	=.2239	C_{A0F}	=.2239	C_{A0}	=.2239	C_{A0F}	=.2239
C_{B0}	=.1186	C_{B0F}	=.2090	C_{B0}	=.2090	C_{B0F}	=.1186
C_{AS1}	=.1121	C_{AS1F}	=.1121	C_{AS1}	=.1121	C_{AS1F}	=.1121
C_{BS1}	=.0	C_{BS1F}	=.0	C_{BS1}	=.0	C_{BS1F}	=.0
F_{A0}	=.050	F_{AF}	=.050	F_{A0}	=.050	F_{AF}	=.050
F_{B0}	=.074	F_{BF}	=.074	F_{B0}	=.074	F_{BF}	=.074
F_{AS1}	=.040	F_{AS1F}	=.022	F_{AS1}	=.022	F_{AS1F}	=.040
F_{BS1}	=.0	F_{BS1F}	=.0	F_{BS1}	=.0	F_{BS1F}	=.0
Q_R	=.036	Q_{RF}	=.036	Q_R	=.036	Q_{RF}	=.036

Time (min)	C_A (moles/liter)	Time (min)	C_A (moles/liter)
0.0	0.0644	0.0	0.0400
0.2	0.0637	0.2	0.0426
0.4	0.0594	0.4	0.0470
0.6	0.0451	0.6	0.0587
0.8	0.0444	0.8	0.0595
1.0	0.0434	1.0	0.0608
1.2	0.0419	1.2	0.0623
1.4	0.0412	1.4	0.0628
1.6	0.0409	1.6	0.0635
1.8	0.0407	1.8	0.0640
2.0	0.0404	2.0	0.0641
2.4	0.0401	2.4	0.0642
2.8	0.0399	2.8	0.0643
3.2	0.0398	3.2	0.0644
3.6	0.0399	3.6	0.0646
4.0	0.0400	4.0	0.0645
4.5	0.0399	4.5	0.0644
5.0	0.0400	5.0	0.0644
5.5	0.0400	5.5	0.0644

Table 13

Run 21		Run 22	
C_{A0} =.2239	C_{A0F} =.2239	C_{A0} =.2239	C_{A0F} =.2239
C_{B0} =.2090	C_{B0F} =.2090	C_{B0} =.2090	C_{B0F} =.2090
C_{AS1} =.1121	C_{AS1F} =.1121	C_{AS1} =.1121	C_{AS1F} =.1121
C_{BS1} =.0	C_{BS1F} =.0	C_{BS1} =.0	C_{BS1F} =.0
F_{A0} =.044	F_{AF} =.044	F_{A0} =.044	F_{AF} =.044
F_{B0} =.048	F_{BF} =.074	F_{B0} =.074	F_{BF} =.048
F_{AS1} =.022	F_{AS1F} =.010	F_{AS1} =.010	F_{AS1F} =.022
F_{BS1} =.0	F_{BS1F} =.0	F_{BS1} =.0	F_{BS1F} =.0
Q_R =.036	Q_{RF} =.036	Q_R =.036	Q_{RF} =.036

Time (min)	C_A (moles/liter)	Time (min)	C_A (moles/liter)
0.0	0.0508	0.0	0.0288
0.2	0.0515	0.2	0.0283
0.4	0.0481	0.4	0.0323
0.6	0.0355	0.6	0.0393
0.8	0.0330	0.8	0.0443
1.0	0.0325	1.0	0.0450
1.2	0.0310	1.2	0.0458
1.4	0.0302	1.4	0.0476
1.6	0.0300	1.6	0.0487
1.8	0.0297	1.8	0.0491
2.0	0.0293	2.0	0.0498
2.4	0.0289	2.4	0.0503
2.8	0.0287	2.8	0.0505
3.2	0.0286	3.2	0.0507
3.6	0.0287	3.6	0.0508
4.0	0.0288	4.0	0.0509
4.5	0.0288	4.5	0.0509
5.0	0.0288	5.0	0.0509
5.5	0.0288	5.5	0.0509

Table 14

Run 23

C_{AO}	=.1121	C_{AOF}	=.1121
C_{BO}	=.1186	C_{BOF}	=.1186
C_{AS1}	=.1121	C_{AS1F}	=.1121
C_{BS1}	=.0	C_{BS1F}	=.0
F_{AO}	=.044	F_{AF}	=.044
F_{BO}	=.048	F_{BF}	=.074
F_{AS1}	=.022	F_{AS1F}	=.010
F_{BS1}	=.0	F_{BS1F}	=.0
Q_R	=.036	Q_{RF}	=.036

Time (min)	C_A (moles/liter)
0.0	0.0393
0.2	0.0394
0.4	0.0343
0.6	0.0270
0.8	0.0268
1.0	0.0257
1.2	0.0245
1.4	0.0240
1.6	0.0239
1.8	0.0237
2.0	0.0236
2.4	0.0234
2.8	0.0233
3.2	0.0233
3.6	0.0233
4.0	0.0232
4.5	0.0232
5.0	0.0232
5.5	0.0232

Run 24

C_{AO}	=.1121	C_{AOF}	=.1121
C_{BO}	=.1186	C_{BOF}	=.1186
C_{AS1}	=.1121	C_{AS1F}	=.1121
C_{BS1}	=.0	C_{BS1F}	=.0
F_{AO}	=.044	F_{AF}	=.044
F_{BO}	=.074	F_{BF}	=.048
F_{AS1}	=.010	F_{AS1F}	=.022
F_{BS1}	=.0	F_{BS1F}	=.0
Q_R	=.036	Q_{RF}	=.036

Time (min)	C_A (moles/liter)
0.0	0.0232
0.2	0.0230
0.4	0.0283
0.6	0.0331
0.8	0.0353
1.0	0.0357
1.2	0.0365
1.4	0.0375
1.6	0.0383
1.8	0.0385
2.0	0.0387
2.4	0.0390
2.8	0.0391
3.2	0.0392
3.6	0.0392
4.0	0.0391
4.5	0.0391
5.0	0.0392
5.5	0.0392

APPENDIX II

Computer Program

Numerical Solution
to Partial Differential Equations
for the Multiple Feed Recycle Reactor

```
      DIMENSION CA(100),CB(100),CAS(100),CBS(100),CAR(100),CBR(100)
      DIMENSION CAF(100),CBF(100),CASF(100),CBSF(100),CARF(100)
      DIMENSION CBRF(100),CAP(100),CBP(100),CASP(100),CBSP(100)
      DIMENSION CARP(100),CBRP(100)
   70 READ(5,222) Z,CA0,CA0F,CB0,CB0F,CAS1,CAS1F,CBS1,CBS1F
      IF (Z) 1000,1000,100
  100 READ(5,444) QR,QRF,R,R1,AL,AL1,N1,N2,M
      READ(5,222)AK,FA0,FAF,FB0,FBF,FAS1,FAS1F,FBS1,FBS1F
  222 FORMAT(9F)
  333 FORMAT(2X,'FA0=',F6.4,4X,'FB0=',F6.4,4X,'FAS1=',
     1F6.4,4X,'FBS1=',F6.4,3X,'QR=',F6.4,/)
  444 FORMAT(6F,3I)
  555 FORMAT(2X,'FAF=',F6.4,4X,'FBF=',F6.4,4X,'FAS1F=',
     1F6.4,3X,'FBS1F=',F6.4,2X,'QRF=',F6.4,/)
  666 FORMAT(2X,'VOL=',F8.5,2X,'VOL1=',F8.5,2X,'V=',
     1F8.6,2X,'VS=',F8.6,2X,'V1=',F8.6,/)
  777 FORMAT(2X,'CA0=',F7.5,3X,'CB0=',F7.5,3X,'CAS1=',F7.5,
     13X,'CBS1=',F7.5,/)
  888 FORMAT(2X,'INITIAL STEADY STATE CONCENTRATION=',F7.5,//)
  999 FORMAT(2X,'CA0F=',F7.5,2X,'CB0F=',F7.5,2X,'CAS1F=',
     1F7.5,2X,'CBS1F=',F7.5,/)
 1111 FORMAT(2X,'FINAL   STEADY STATE CONCENTRATION=',F7.5,//)
 2222 FORMAT(2X,'DT=',F12.10,//)
 3333 FORMAT(3X,'TIME',7X,'CONCENTRATION')
 4444 FORMAT(2X,F5.2,7X,F7.5,2X,F7.4)
 8888 FORMAT(1H1,2X,'TEST RESULTS FOR RUN NO=',F5.2,///)
 9999 FORMAT(2X,6(F10.8,2X))
      WRITE(6,8888)Z
      AREA=3.1416*R*R
      AREA1=3.1416*R1*R1
      VOL=AL*AREA/1000.
      VOL1=AL1*AREA1/1000.
      AN1=N1
      AN2=N2
      AM=M
      V=VOL/(2.*AN1)
      VS=VOL/(2.*AN2)
      V1=VOL1/AM
      WRITE(6,666)VOL,VOL1,V,VS,V1
C
C
C
C     INITIAL STEADY STATE CALCULATIONS
C
      WRITE(6,777)CA0,CB0,CAS1,CBS1
      WRITE(6,333)FA0,FB0,FAS1,FBS1,QR
      Q=FA0+FB0+QR
      QS=Q+FAS1+FBS1
      CA(1)=CA0*FA0/Q
      CB(1)=CB0*FB0/Q
      CL=.0
      C=Q/(AK*V)
      CS=QS/(AK*VS)
      C1S=QR/(AK*V1)
   66 AM0=CB(1)-CA(1)
      B=AM0+C
      DO 11 I=2,N1
      CA(I)=-.5*B+.5*SQRT(B*B+4.*CA(I-1)*C)
   11 CB(I)=AM0+CA(I)
      CAS(1)=(Q*CA(N1)+FAS1*CAS1)/QS
```

```
      CBS(1)=(Q*CB(N1)+FBS1*CBS1)/QS
      AMØ1=CBS(1)-CAS(1)
      BS=AMØ1+CS
      B1S=AMØ1+C1S
      DO 22 I=2,N2
      CAS(I)=-.5*BS+.5*SQRT(BS*BS+4.*CAS(I-1)*CS)
   22 CBS(I)=AMØ1+CAS(I)
      CAR(1)=CAS(N2)
      CBR(1)=CBS(N2)
      DO 33 I=2,M
      CAR(I)=-.5*B1S+.5*SQRT(B1S*B1S+4.*CAR(I-1)*C1S)
   33 CBR(I)=AMØ1+CAR(I)
      IF(ABS(CAS(N2)-CL)-.ØØØØ1)44,44,55
   55 CA(1)=CAØ*FAØ/Q+CAR(M)*QR/Q
      CB(1)=CBØ*FBØ/Q+CBR(M)*QR/Q
      CL=CAS(N2)
      GO TO 66
   44 WRITE(6,888)CAS(N2)
C
C
C
C     FINAL STEADY STATE CALCULATIONS
C
      WRITE(6,999)CAØF,CBØF,CAS1F,CBS1F
      WRITE(6,555)FAF,FBF,FAS1F,FBS1F,QRF
      QF=FAF+FBF+QRF
      QSF=QF+FAS1F+FBS1F
      CAF(1)=CAØF*FAF/QF
      CBF(1)=CBØF*FBF/QF
      CL=.Ø
      CF=QF/(AK*V)
      CSF=QSF/(AK*VS)
      C1SF=QRF/(AK*V1)
  111 AMØF=CBF(1)-CAF(1)
      BF=AMØF+CF
      DO 77 I=2,N1
      CAF(I)=-.5*BF+.5*SQRT(BF*BF+4.*CAF(I-1)*CF)
   77 CBF(I)=AMØF+CAF(I)
      CASF(1)=(QF*CAF(N1)+FAS1F*CAS1F)/QSF
      CBSF(1)=(QF*CBF(N1)+FBS1F*CBS1F)/QSF
      AMØ1F=CBSF(1)-CASF(1)
      BSF=AMØ1F+CSF
      B1SF=AMØ1F+C1SF
      DO 88 I=2,N2
      CASF(I)=-.5*BSF+.5*SQRT(BSF*BSF+4.*CASF(I-1)*CSF)
   88 CBSF(I)=AMØ1F+CASF(I)
      CARF(1)=CASF(N2)
      CBRF(1)=CBSF(N2)
      DO 99 I=2,M
      CARF(I)=-.5*B1SF+.5*SQRT(B1SF*B1SF+4.*CARF(I-1)*C1SF)
   99 CBRF(I)=AMØ1F+CARF(I)
      IF(ABS(CASF(N2)-CL)-.ØØØØ1)1,1,2
    2 CAF(1)=CAØF*FAF/QF+CARF(M)*QRF/QF
      CBF(1)=CBØF*FBF/QF+CBRF(M)*QRF/QF
      CL=CASF(N2)
      GO TO 111
    1 WRITE(6,1111)CASF(N2)
C
C
C
```

```
C      CALCULATIONS FOR THE STABILITY OF THE SYSTEM
C
       K=1
       TETAO=CAS(N2)
       CL=.0
       TA=V*AN1/Q
       TAS=VS*AN2/QS
       TA1=VOL1/QR
       TB=V*AN1/QF
       TBS=VS*AN2/QSF
       TB1=VOL1/QRF
       WRITE(6,9999)TA,TAS,TA1,TB,TBS,TB1
       T=AMIN1(TA,TAS,TA1,TB,TBS,TB1)
       D1=1./(Q/V+AK*CA(2))
       D2=1./(Q/V+AK*CA(N1))
       D3=1./(Q/V+AK*CB(2))
       D4=1./(Q/V+AK*CB(N1))
       D5=1./(QS/VS+AK*CAS(2))
       D6=1./(QS/VS+AK*CAS(N2))
       D7=1./(QS/VS+AK*CBS(2))
       D8=1./(QS/VS+AK*CBS(N2))
       D9=1./(QR/V1+AK*CAR(2))
       D10=1./(QR/V1+AK*CAR(M))
       D11=1./(QR/V1+AK*CBR(2))
       D12=1./(QR/V1+AK*CBR(M))
       WRITE(6,9999)D1,D2,D3,D4,D5,D6
       WRITE(6,9999)D7,D8,D9,D10,D11,D12
       D13=1./(QF/V+AK*CAF(2))
       D14=1./(QF/V+AK*CAF(N1))
       D15=1./(QF/V+AK*CBF(2))
       D16=1./(QF/V+AK*CBF(N1))
       D17=1./(QSF/VS+AK*CASF(2))
       D18=1./(QSF/VS+AK*CASF(N2))
       D19=1./(QSF/VS+AK*CBSF(2))
       D20=1./(QSF/VS+AK*CBSF(N2))
       D21=1./(QRF/V1+AK*CARF(2))
       D22=1./(QRF/V1+AK*CARF(M))
       D23=1./(QRF/V1+AK*CBRF(2))
       D24=1./(QRF/V1+AK*CBRF(M))
       WRITE(6,9999)D13,D14,D15,D16,D17,D18
       WRITE(6,9999)D19,D20,D21,D22,D23,D24
       DD1=AMIN1(D1,D2,D3,D4,D5,D6,D7,D8,D9,D10,D11,D12)
       DD2=AMIN1(D13,D14,D15,D16,D17,D18,D19,D20,D21,D22,D23,D24)
       DT=AMIN1(DD1,DD2)
       DD=T/10.
       DT=.9*DT
       IF(DD.LT.DT)DT=DD
       WRITE(6,2222)DT
C
C
C
C      CALCULATIONS FOR THE TRANSIENT RESPONSE
C
       WRITE(6,3333)
       TIME=.0
       CC1=AK*DT
       CC2=QF*DT/V
       CC3=QSF*DT/VS
       CC4=QRF*DT/V1
       WRITE(6,4444)TIME,CAS(N2),TETAO
```

```
      CA(1)=CA0F*FAF/QF+CAR(M)*QRF/QF
      CB(1)=CB0F*FBF/QF+CBR(M)*QRF/QF
   90 DO 10 I=2,N1
      CAP(I)=CA(I)*(1.-CC2-CC1*CB(I))+CC2*CA(I-1)
   10 CBP(I)=CB(I)*(1.-CC2-CC1*CA(I))+CC2*CB(I-1)
      DO 20 I=2,N1
      CA(I)=CAP(I)
   20 CB(I)=CBP(I)
      CAS(1)=(CA(N1)*QF+CAS1F*FAS1F)/QSF
      CBS(1)=(CB(N1)*QF+CBS1F*FBS1F)/QSF
      DO 30 I=2,N2
      CASP(I)=CAS(I)*(1.-CC3-CC1*CBS(I))+CC3*CAS(I-1)
   30 CBSP(I)=CBS(I)*(1.-CC3-CC1*CAS(I))+CC3*CBS(I-1)
      DO 40 I=2,N2
      CAS(I)=CASP(I)
   40 CBS(I)=CBSP(I)
      DO 50 I=2,M
      CARP(I)=CAR(I)*(1.-CC4-CC1*CBR(I))+CC4*CAR(I-1)
   50 CBRP(I)=CBR(I)*(1.-CC4-CC1*CAR(I))+CC4*CBR(I-1)
      DO 60 I=2,M
      CAR(I)=CARP(I)
   60 CBR(I)=CBRP(I)
      CAR(1)=CAS(N2)
      CBR(1)=CBS(N2)
      TETA=TETA0*(1.-25.*DT)+25.*DT*CAS(N2)
      TETA0=TETA
      IF(8..LT.TIME)GO TO 70
      IF(TIME.LT.K*.1)GO TO 80
      K=K+1
      WRITE(6,4444)TIME,CAS(N2),TETA0
   80 TIME=TIME+DT
      CA(1)=CA0F*FAF/QF+CAR(M)*QRF/QF
      CB(1)=CB0F*FBF/QF+CBR(M)*QRF/QF
      GO TO 90
 1000 STOP
      END
```

APPENDIX III

Notation

NOTATION

$C_A(x,t)$	Concentration of sodium hydroxide in the main reactor before side feed (function of x and t), moles/liter
$C_B(x,t)$	Concentration of methyl acetate in the main reactor before side feed (function of x and t), moles/liter
$C_{AS}(x_S,t)$	Concentration of sodium hydroxide in the main reactor after side feed (function of x_S and t), moles/liter
$C_{BS}(x_S,t)$	Concentration of methyl acetate in the main reactor after side feed (function of x_S and t), moles/liter
$C_{AR}(x',t)$	Concentration of sodium hydroxide in the recycle line (function of x' and t), moles/liter
$C_{BR}(x',t)$	Concentration of methyl acetate in the recycle line (function of x' and t), moles/liter
$C_A(I)$	Concentration of sodium hydroxide at i^{th} tank or position before the side feed, moles/liter
$C_B(I)$	Concentration of methyl acetate at i^{th} tank or posion before the side feed, moles/liter
$C_{AS}(I)$	Concentration of sodium hydroxide at i^{th} tank or position after the side feed, moles/liter
$C_{BS}(I)$	Concentration of methyl acetate at i^{th} tank or position after the side feed, moles/liter
$C_{AR}(I)$	Concentration ofsodium hydroxide at i^{th} tank or position in the recycle line, moles/liter
$C_{BR}(I)$	Concentration of methyl acetate at i^{th} tank or position in the recycle line, moles/liter
C_{AO}	Concentration of sodium hydroxide in stream A before upset, moles/liter
C_{BO}	Concentration of methyl acetate in stream B before upset, moles/liter

C_{AS1}	Concentration of sodium hydroxide in side stream A before upset, moles/liter
C_{BS1}	Concentration of methyl acetate in side stream B before upset, moles/liter
C_{AOF}	Concentration of sodium hydroxide in stream A after upset, moles/liter
C_{BOF}	Concentration of methyl acetate in stream B after upset, moles/liter
C_{AS1F}	Concentration of sodium hydroxide in side stream A after upset, moles/liter
C_{BS1F}	Concentration of methyl acetate in side stream B after upset, moles/liter
F_{AO}	Flow rate of stream A before upset, liter/min.
F_{BO}	Flow rate of stream B before upset, liter/min.
F_{AS1}	Flow rate of side stream A before upset, liter/min.
F_{BS1}	Flow rate of side stream B before upset, liter/min.
Q	Flow rate in the main reactor before side feed before upset, liter/min.
Q_S	Flow rate in the main reactor after side feed before upset, liter/min.
Q_R	Flow rate in the recycle line before upset, liter/min.
F_{AF}	Flow rate of stream A after upset, liter/min.
F_{BF}	Flow rate of stream B after upset, liter/min.
F_{AS1F}	Flow rate of side stream A after upset, liter/min.
F_{BS1F}	Flow rate of side stream B after upset, liter/min.
Q_F	Flow rate in the main reactor before side feed after upset, liter/min.
Q_{SF}	Flow rate in the main reactor after side feed after upset, liter/min,
Q_{RF}	Flow rate in the recycle line after upset, liter/min.
v	Flow velocity in the main reactor before side feed, meters/min.

v_S	Flow velocity in the main reactor after side feed, meters/min.
v'	Flow velocity in the recycle line, meters/min.
V	Volume of element in the main reactor before side feed, liters
V_S	Volume of element in the main reactor after side feed, liters
V'	Volume of element in the recycle line, liters
t	Time variable, min.
x	Length variable of the main reactor before side feed, meters
x_S	Length variable of the main reactor after side feed, meters
x'	Length variable of the recycle line, meters
l	Length of the main reactor before side feed, meters
l_S	Length of the main reactor after side feed, meters
l'	Length of the recycle line, meters
N1	Number of times the main reactor before side feed is divided
N2	Number of times the main reactor after side feed is divided
M	Number of times the recycle line is divided
j	Number of CFSTR's
I	Tank or differential element
M_0	Concentration difference between A and B at entrance of the main reactor, moles/liter
M_{0S}	Concentration difference between A and B at entrance of the main reactor after side feed, moles/liter
k	Reaction rate constant, liter/mole-min.
D_{eff}	Effective dispersion coefficient, meter^2/min.
Δx	Differential length in the main reactor before side feed, meters

Δx_S	Differential length in the main reactor after side feed, meters
$\Delta x'$	Differential length in the recycle line, meters
Δt	Time increment, min.
λ	Flow rate in the recycle line/Flow rate in the main reactor before side feed
τ	Flow rate of side stream A and B/Flow rate in the main reactor after side feed

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