APPENDIX F

CIRCULATION MODEL FOR GAS RESIDENCE TIME DISTRIBUTION IN THREE-PHASE FLUIDIZATION

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APPENDIX F

CIRCULATION MODEL FOR GAS RESIDENCE TIME DISTRIBUTION IN THREE-PHASE FLUIDIZATION

Gas flow in three-phase (gas, liquid, solid) fluidization has been shown to be generally characterized by an upflow of gas bubbles in the center region of the bed and a downflow of gas bubbles near the wall region. In order to describe the various degrees of gas mixing which may occur in each region, a circulation model consisting of n and m completely mixed tanks is proposed. This is shown schematically in Figure F-1.

Mathematical Development

A material balance at the node where the recirculation stream and input stream meet leads to the equation:

$$\nu C_i + \nu_2 C_2 = \nu_1 C_1 \quad (1)$$

To derive the response equation to the system shown in Figure F-1, consider the transfer function in the Laplace domain for the n and m tanks, respectively (55).

$$\frac{C_o(S)}{C_1(S)} = \frac{1}{[S\frac{V_n}{n\nu_1} + 1]^n} \quad (2)$$

$$\frac{C_2(S)}{C_o(S)} = \frac{1}{[S\frac{V_m}{m\nu_2} + 1]^m} \quad (3)$$

Taking the Laplace transform of Equation 1 and rearranging:

$$\frac{\nu}{\nu_1} C_i(S) + \frac{\nu_2}{\nu_1} C_2(S) = C_1(S) \quad (4)$$

Substituting the transfer functions into Equation 4 and rearranging:

$$\frac{C_o(S)}{C_i(S)} = \frac{\frac{\nu}{\nu_1}[s\bar{t}_2 + 1]^m}{\{[s\bar{t}_1 + 1]^n[s\bar{t}_2 + 1]^m - \frac{\nu_2}{\nu_1}\}} \quad (5)$$

where $\bar{t}_1 = V_n/n\nu_1$ and $\bar{t}_2 = V_m/m\nu_2$, assuming equal sized tanks in each stream.

Letting $A = \nu/(\nu_1 \bar{t}_1^{\,n})$ and $B = \nu_2/\nu_1(1/\bar{t}_1^{\,n}\bar{t}_2^{\,m})$ gives a more workable form of Equation 5 as:

$$\frac{C_o(S)}{C_i(S)} = \frac{A(S + 1/\bar{t}_2)^m}{[(S + 1/\bar{t}_1)^n(S + 1/\bar{t}_2)^m - B]} \quad (6)$$

Equation 6 is the general transfer function for the recirculation model shown in Figures F-1 and 36.

Consider now the analytical response equation of the system to an impulse input of tracer.

The first output signal will be for the n tanks alone--i.e., $C_2(S) = 0$:

$$C_1(S) = \frac{\nu}{\nu_1} C_i(S) \tag{7}$$

$$\frac{C_o(S)}{C_1(S)} = \frac{1}{(S\bar{t}_1 + 1)^n} \tag{8}$$

Substituting Equation 7 into Equation 8 gives the transfer function for the first output signal as:

$$\frac{C_o(S)}{C_i(S)} = \frac{\nu/\nu_1}{(S\bar{t}_1 + 1)^n} \tag{9}$$

The second output signal, corresponding to one complete loop, may be obtained by first substituting Equation 9 into Equation 3:

$$\frac{C_2(S)}{C_i(S)} = \frac{\nu/\nu_1}{(S\bar{t}_1 + 1)^n} \left\{\frac{1}{(S\bar{t}_2 + 1)^m}\right\} \tag{10}$$

A material balance at the first node gives, $C_i(S) = 0$,

$$C_1(S) = \frac{\nu_2}{\nu_1} C_2(S) \tag{11}$$

Substituting Equation 11 into Equation 10:

$$\frac{C_1(S)}{C_i(S)} = \frac{\nu/\nu_1}{(S\bar{t}_1 + 1)^n} \left\{\frac{\nu_2/\nu_1}{(S\bar{t}_2 + 1)^m}\right\} \tag{12}$$

Substituting Equation 12 into Equation 2 yields the transfer function for one complete loop as:

$$\frac{C_o(S)}{C_i(S)} = \frac{\nu/\nu_1}{(S\bar{t}_1 + 1)^n} \left\{\frac{\nu_2}{\nu_1} \frac{1}{(S\bar{t}_2 + 1)^m} \frac{1}{(S\bar{t}_1 + 1)^n}\right\} \tag{13}$$

Continuing this procedure, it can easily be shown that the overall transfer function with an impulse input to the system may be generally written:

$$\frac{C_o(S)}{C_i(S)} = \frac{\nu}{\nu_1} \sum_{R=1}^{R^*} \left\{ \left(\frac{\nu_2}{\nu_1}\right)^{R-1} \frac{1}{(S\bar{t}_1 + 1)^{Rn}} \; \frac{1}{(S\bar{t}_2 + 1)^{(R-1)m}} \right\} \tag{14}$$

Letting a = Rn and b = (R-1)m:

$$\frac{C_o(S)}{C_i(S)} = \frac{\nu}{\nu_1} \sum_{R=1}^{R^*} \left\{ \left(\frac{\nu_2}{\nu_1}\right)^{R-1} \frac{1}{\bar{t}_1{}^a \bar{t}_2{}^b} \; \frac{1}{(S + 1/\bar{t}_1)^a (S + 1/\bar{t}_2)^b} \right\} \tag{15}$$

In order to obtain the inverse function, first consider the term

$$\frac{1}{(S - a_1)^a (S - a_2)^b}$$

where $a_1 = -1/\bar{t}_1$

and $a_2 = -1/\bar{t}_2$

Now consider a Heaviside expansion formula for repeated roots (56):

$$f(S) = \frac{1}{(S - a_1)^a (S - a_2)^b}$$

$$= \frac{A_1}{(S - a_1)^a} + \frac{A_2}{(S - a_1)^{a-1}} + \dots\dots + \frac{A_a}{(S - a_1)}$$

$$+ \frac{C_1}{(S - a_2)^b} + \frac{C_2}{(S - a_2)^{b-1}} + \dots\dots + \frac{C_b}{(S - a_2)}$$

$$= \sum_{r=1}^{a} \frac{A_r}{(S - a_1)^{a-r+1}} + \sum_{r=1}^{b} \frac{C_r}{(S - a_2)^{b-r+1}} \tag{16}$$

In order to obtain the values of the coefficients, first multiply both sides of Equation 16 by $(S - a_1)^a$:

$$f(S)(S - a_1)^a = A_1 + A_2(S - a_1) + \dots\dots + A_a(S - a_1)^{a-1}$$

$$+ (S - a_1)^a \left\{ \sum_{r=1}^{b} \frac{C_r}{(S - a_2)^{b-r+1}} \right\}$$

or:

$$f(S)(S - a_1)^a = \sum_{r=1}^{a} (S - a_1)^{r-1} A_r + (S - a_1)^a h_1(S) \tag{17}$$

where $h_1(S) = \sum_{r=1}^{b} \frac{C_r}{(S - a_2)^{b-r+1}}$

Differentiating Equation 17 successively (M - 1) times, where $1 \leq M \leq r$, all terms in the summation from r = 1 to r = M - 1 disappear, leaving:

$$\frac{d^{M-1}}{ds^{M-1}}\left[(S - a_1)^a f(S)\right] = \sum_{r=M}^{a} (r-1)(r-2)\ldots\ldots(r-M+1)$$

$$\left[(S - a_1)^{r-M} A_r\right] + \frac{d^{M-1}}{ds^{M-1}}(S - a_1)^a h_1(S)$$

Setting $S = a_1$, all terms will disappear except that in which r = M. In the remaining term, replace M by r:

$$A_r = \frac{1}{(r-1)!}\frac{d^{r-1}}{ds^{r-1}}\left[(S - a_1)^a f(S)\right]\Big|_{S = a_1} \qquad (18)$$

where $1 \leq r \leq a$.

The coefficients C_r can be determined in a similar fashion as:

$$C_r = \frac{1}{(r-1)!}\frac{d^{r-1}}{ds^{r-1}}\left[(S - a_2)^b f(S)\right]\Big|_{S = a_2} \qquad (19)$$

where $1 \leq r \leq b$.

Making use of the Laplace transform pairs:

$$\mathcal{L}^{-1}\left\{\frac{1}{(S - a_1)^k}\right\} = \frac{t^{k-1}}{(k-1)!}e^{a_1 t}$$

$$\mathcal{L}^{-1}\{f_1(s) + f_2(s)\} = \mathcal{L}^{-1}\{f_1(s)\} + \mathcal{L}^{-1}\{f_2(s)\} = f_1(t) + f_2(t)$$

This leads to:

$$f(t) = \sum_{r=1}^{a} A_r \frac{t^{a-r}}{(a-r)!}e^{a_1 t} + \sum_{r=1}^{b} C_r \frac{t^{b-r}}{(b-r)!}e^{a_2 t}$$

Substituting Equations 18 and 19 into the above gives:

$$f(t) = e^{a_1 t}\sum_{r=1}^{a}\frac{1}{(r-1)!}\frac{d^{r-1}}{ds^{r-1}}\left[(S - a_1)^a f(S)\right]\Big|_{S = a_1}\cdot\frac{t^{a-r}}{(a-r)!}$$

$$+ e^{a_2 t}\sum_{r=1}^{b}\frac{1}{(r-1)!}\frac{d^{r-1}}{ds^{r-1}}\left[(S - a_2)^b f(S)\right]\Big|_{S = a_2}\cdot\frac{t^{b-r}}{(b-r)!}$$

The dimensionless exit age distribution function may now be obtained from the inverse of Equation 15 and by noting that $E(\theta) = \bar{t}E(t)$.

$$E(\theta) = \frac{\nu\bar{t}}{\nu_1} \sum_{R=1}^{R^\dagger} \left\{ \left(\frac{\nu_2}{\nu_1}\right)^{R-1} \frac{1}{\bar{t}_1{}^a \bar{t}_2{}^b} \left[e^{a_1 t} \sum_{r=1}^{a} \frac{1}{(r-1)!} \frac{d^{r-1}}{ds^{r-1}} [(S - a_1)^a f(S)] \Big|_{S = a_1} \cdot \frac{t^{a-r}}{(a-r)!} + e^{a_2 t} \sum_{r=1}^{b} \frac{1}{(r-1)!} \frac{d^{r-1}}{ds^{r-1}} [(S - a_2)^b f(S)] \Big|_{S = a_2} \cdot \frac{t^{b-r}}{(b-r)!} \right] \right\} \quad (20)$$

$$E(\theta) = \left(\frac{\bar{t}}{1+\lambda}\right) \sum_{R=1}^{R^*} \left\{ \left(\frac{\lambda}{1+\lambda}\right)^{R-1} \frac{1}{\bar{t}_1{}^a \bar{t}_2{}^b} \left[e^{-\tau_1 \theta} \sum_{r=1}^{a} \frac{1}{(r-1)!} \frac{d^{r-1}}{ds^{r-1}} [(S - a_1)^a f(S)] \Big|_{S = a_1} \cdot \frac{t^{a-r}}{(a-r)!} + e^{-\tau_2 \theta} \sum_{r=1}^{b} \frac{1}{(r-1)!} \frac{d^{r-1}}{ds^{r-1}} [(S - a_2)^b f(S)] \Big|_{S = a_2} \cdot \frac{t^{b-r}}{(b-r)!} \right] \right\} \quad (21)$$

Method of Solution

Although Equation 20 appears to be somewhat complex, solving the general transfer function, Equation 6, numerically can be even more tedious, time-consuming, and often yields unreliable results (57,58). By making several transformations, the analytical solution developed can be easily programmed:

Consider the term:

$$\sum_{r=1}^{a} \frac{1}{(r-1)!} \frac{d^{r-1}}{ds^{r-1}} [(S - a_1)^a f(S)] \Big|_{S = a_1} \cdot \frac{t^{a-r}}{(a-r)!}$$

Rewrite the derivative term to give:

$$\sum_{r=1}^{a} \frac{1}{(r-1)!} \frac{d^{r-1}}{ds^{r-1}} \left[\frac{1}{(S - a_2)^b} \right] \Big|_{S = a_1} \cdot \frac{t^{a-r}}{(a-r)!}$$

A generalized recursion formula for the derivative term may be readily derived:

Consider the term:

$$\frac{d^{r-1}}{ds^{r-1}} \left[\frac{1}{(s - a_2)^b} \right] \Bigg|_{s = a_1}$$

For r = 2:

$$\frac{d}{ds} \left[\frac{1}{(s - a_2)^b} \right] \Bigg|_{s = a_1} = \frac{(-b)}{(a_1 - a_2)^{b+1}}$$

For r = 3:

$$\frac{d^2}{ds^2} \left[\frac{1}{(s - a_2)^b} \right] \Bigg|_{s = a_1} = \frac{(-b)[(-b + 1)]}{(a_1 - a_2)^{b+2}}$$

For r = 4:

$$\frac{d^3}{ds^3} \left[\frac{1}{(s - a_2)^b} \right] \Bigg|_{s = a_1} = \frac{(-b)[-b + 1)][-(b + 2)]}{(a_1 - a_2)^{b+3}}$$

For r = a, then:

$$\frac{d^{a-1}}{ds^{a-1}} \left[\frac{1}{(s - a_2)^b} \right] \Bigg|_{s = a_1} = \frac{(-b)[-(b + 1)]....[-(b = a - 2)]}{(a_1 - a_2)^{b+a-1}}$$

Generalizing, replacing a by r leads to the general recursion formula.

$$\frac{d^{r - 1}}{ds^{r - 1}} \left[\frac{1}{(S - a_2)^b} \right] \Big|_{S = a_1}$$

$$= \frac{(- b)[- (b + 1)][- (b + 2)].....[- (b + r - 2)]}{(a_1 - a_2)^{b + r - 1}} \quad \text{for } r > 1.$$

A similar equation for the remaining derivative term may be written as:

$$\frac{d^{r - 1}}{ds^{r - 1}} \left[\frac{1}{(S - a_1)^a} \right] \Big|_{S = a_2}$$

$$= \frac{(- a)[- (a + 1)][- (a + 2)].....[- (a + r - 2)]}{(a_2 - a_1)^{a + r - 1}} \quad \text{for } r > 1.$$

For R = 1, corresponding to the first pass through the upflow branch, these formulas are not needed. Equation 15 will collapse to:

$$c(s) = \frac{V}{V_1} \cdot \frac{1}{\bar{t}_1^{\,n}} \cdot \frac{1}{(s + 1/\bar{t}_1)^n}$$

Then:

$$E(\theta) = \frac{V}{V_1} \quad \frac{\bar{t}}{\bar{t}_1^{\,n}} \quad \frac{t^{n-1}}{(n-1)!} \quad e^{-t/\bar{t}_1}$$

which is the response of n CSTR's in series (59), modified for a volume fraction of less than one.

Figure F-2 shows the flow diagram for the computational procedures based on the proposed model. Calculations of the exit age distribution function begin with specifications of n, m, λ, and P_1. Assuming that the n tanks are all of equal size, V_n/n, and that the m tanks are all of equal size, V_m/m, the following relationships can be easily shown to hold:

$$\frac{\bar{t}_1}{\bar{t}_2} = \frac{P_1}{P_2}\left(\frac{m}{n}\right)\left(\frac{\lambda}{1+\lambda}\right)$$

$$\bar{t} = \bar{t}_1 n(1 + \lambda) + \bar{t}_2 m\lambda$$

where: $P_1 = V_n/V$

$P_2 = V_m/V$

$P_2 = 1 - P_1$

The exit age distribution is calculated from Equation 21 and the appropriate recursion formula from the derivatives. Once the exit age distribution for each output has been determined, a summation over all outputs is made to give the final exit age distribution for the specified parameters. The Fortran program used for the calculation appears in Table F-I.

Figures F-3 and F-4 show some typical response curves obtained from the model. For most regions of interest, the initial response of such a system is controlled by the number of tanks in the upflow stream and the upflow volume fraction. The influence of the recycle branch will largely affect the later decay of the response signal.

A comparison may be made between this model and that recently published by Mann, et al. (58). Figure F-5 contrasts the model predictions (note that different definitions of recycle ratio are used). The agreement is excellent, indicating that the two approaches--summation by convolution in the time domain, or Heaviside expansion in the Laplace domain--yield equivalent solutions.

Application to Experimental Radiotracer Data

This model was then used to describe flow patterns observed during the radiotracer tests. Figure F-6 shows the results of two tests conducted with no coal fines present in the kerosene. At low gas rates, the upflow branch consists of five CSTR's in series; this flow regime is intermediate between backmix and plug flow. A small amount of recycle is present through the one downflow CSTR. Increasing the superficial gas velocity from 0.10 ft/sec to 0.20 ft/sec decreased the number of tanks from five to two, and also slightly diminished the volume fraction occupied by the upflow stream.

The addition of fines to the kerosene changed the residence time distribution as indicated in Figure F-7. For the two experiments shown, the behavior is closely represented by one backmix reactor with a small recycle probability (0.05-0.10). The apparent time delay of 0.2 θ (corresponding to 2-3 seconds) may be related to the rise time for a large gas bubble. This is especially probable for Test 15; a better fit to the response curve could be made by assuming the initial peak of $E(\theta)$ to be a bubble leaving the bed; other gas remaining in the bed would then recirculate to produce the dispersed response seen experimentally.

NOMENCLATURE FOR APPENDIX F

a	Rn
a_1	$-1/\bar{t}_1$
a_2	$-1/\bar{t}_2$
A	$\nu/(\nu_1\bar{t}_1^{\,n})$
Ar	First term coefficients in partial fraction expansion
b	(R - 1)m
B	$(\nu_2/\nu_1)(1/\bar{t}_1^{\,n}\bar{t}_2^{\,m})$
C_o	Outlet tracer concentration from system (arbitrary units)
C_1	Inlet tracer concentration to the n tanks (arbitrary units)
C_2	Outlet tracer concentration from the m tanks (arbitrary units)
C_r	Second term coefficients in partial fraction expansion
E(t)	Exit age distribution function (1/time)
E(θ)	Dimensionless exit age distribution function
m	Number of tanks in downflow region
n	Number of tanks in upflow region
P_1	Volume fraction in upflow stream
P_2	Volume fraction in downflow stream
R	Output signal number
R*	Maximum number of cycles
$\bar{t}$	Mean residence time, V/
$\bar{t}_1$	Mean residence time in the nth tank
$\bar{t}_2$	Mean residence time in the mth tank

NOMENCLATURE FOR APPENDIX F
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ν	Total gas volumetric flow rate
ν_1	Gas volumetric flow rate in upflow stream
ν_2	Gas volumetric flow rate in downflow stream
V	Total gas volume in system
V_m	Total volume of the m tanks
V_n	Total volume of the n tanks

Greek

θ	Dimensionless time
λ	Recycle ratio
$\bar{\theta}_P$	Initial delay in plug flow element

TABLE F-I

```
FORTRAN IV G1  RELEASE 2.0          MAIN           DATE = 80032         10/12/00          PAGE 0001

0001               IMPLICIT REAL*8(A-H,O-Z)
0002               DIMENSION Z(15,700)
             C INPUT PARAMETERS FOR CIRCULATION MODEL
0003            99 IFLAG3=1
0004               N=1
0005               M=1
0006               P1=0.7D0
0007               RLAMB=0.1D0
0008               WRITE(6,108) N,M,RLAMB,P1
0009           108 FORMAT(' THE INPUT PARAMETERS ARE '/,' N= ',I3,' M= ',I3,
                  1' LAMBDA= ',F7.4,' P1= ',F7.4)
             C INPUT MEAN RESIDENCE TIME FROM EXPERIMENTS
0010               TBAR=50.D0
             C COMPUTE MODEL PARAMETERS FROM INPUT PARAMETERS
0011               P2=1.0D0-P1
0012               T2BAR=TBAR/(M*RLAMB*((P1/P2)+1.0D0))
0013               T1BAR=T2BAR*(P1/P2)*(FLOAT(M)/FLOAT(N))*(RLAMB/(RLAMB+1.0D0))
0014               RT1=1.0D0/T1BAR
0015               RT2=1.0D0/T2BAR
0016               TAU1=TBAR/T1BAR
0017               TAU2=TBAR/T2BAR
0018               COEF=(1.0D0/(1.0D0+RLAMB))*TBAR
0019               PI=3.14159D0
0020               L=2
             C BEGIN EXTERNAL SUMMATION
0021               DO 6 I=1,L
             C SET THETA
0022               THETA=0.0D0
0023               K=1
0024               INA=N*I
0025               INB=M*(I-1)
0026               IF(I.EQ.1) GO TO 7
0027               Z=((RLAMB/(1.0D0+RLAMB))**(I-1))*(1.0D0/((T1BAR**INA)*(T2BAR**
                  1INB)))
0028               IF(I.GT.1) GO TO 8
0029             7 Z=1.0D0/(T1BAR**INA)
0030             8 U1=1.0D0/DEXP(THETA*TAU1)
             C IF I EQUAL TO 1 SKIP FIRST INTERNAL SUMMATION
0031               IF(I.EQ.1) GO TO 51
             C COMPUTE FIRST INTERNAL SUMMATION
0032               SUM01=0.0D0
0033               NUM10=1
0034               DO 9 J=1,INA
0035               JM1=J-1
0036               IF(J.EQ.1) GO TO 10
0037               CALL IFACT(JM1,JM1F)
0038               IF(J.GT.1) GO TO 11
0039            10 JM1F=1
0040            11 IF(J.EQ.1) GO TO 12
0041               NUM1N=(-(INB+J-2))
0042               NUM1N=NUM1N*NUM10
0043               DERS1=NUM1N/((RT2-RT1)**(INB+J-1))
0044               IF(J.GT.1) GO TO 14
0045            12 NUM1N=1
0046               DERS1=NUM1N/((RT2-RT1)**INB)
0047            14 INAMJ=INA-J
0048               IF(J.EQ.INA) GO TO 15
0049               CALL IFACT(INAMJ,INAMF)
```

TABLE F-I

-2-

FORTRAN IV G1 RELEASE 2.0 MAIN DATE = 80032 10/12/00 PAGE 0002

```
      V1=(THETA*TBAR)**INAMJ
      IF(J.LT.INA) GO TO 16
   15 INAMF=1
      V1=1.0D0
   16 SUMN1=(1.0D0/JM1F)*DERS1*(V1/INAMF)
      SUMN1=SUMN1+SUM01
      SUM01=SUMN1
      NUM10=NUM1N
    9 CONTINUE
C COMPUTE SECOND INTERNAL SUMMATION
      SUM02=0.0D0
      NUM20=1
      DO 17 J=1,INB
      JM1=J-1
      IF(J.EQ.1) GO TO 18
      CALL IFACT(JM1,JM1F)
      IF(J.GT.1) GO TO 19
   18 JM1F=1
   19 IF(J.EQ.1) GO TO 20
      NUM2N=(-(INA+J-2))
      NUM2N=NUM2N*NUM20
      DERS2=NUM2N/((RT1-RT2)**(INA+J-1))
      IF(J.GT.1) GO TO 21
   20 NUM2N=1
      DERS2=NUM2N/((RT1-RT2)**INA)
   21 INBMJ=INB-J
      IF(J.EQ.INB) GO TO 22
      CALL IFACT(INBMJ,INBMF)
      V2=(THETA*TBAR)**INBMJ
      IF(J.LT.INB) GO TO 23
   22 INBMF=1
      V2=1.0D0
   23 SUMN2=(1.0D0/JM1F)*DERS2*(V2/INBMF)
      SUMN2=SUMN2+SUM02
      SUM02=SUMN2
      NUM20=NUM2N
   17 CONTINUE
C COMPUTE EXTERNAL SUMMATION
      U2=1.0D0/DEXP(THETA*TAU2)
      SUMTN=Z*((U1*SUMN1)+(U2*SUMN2))
      IF(I.GT.1) GO TO 52
   51 NM1=N-1
      IF(N.EQ.1) GO TO 66
      CALL IFACT(NM1,NM1F)
      SUMTN=Z*U1*((THETA*TBAR)**NM1)/NM1F
      IF(N.GT.1) GO TO 52
   66 SUMTN=Z*U1
C COMPUTE E(THETA)
   52 E(I,K)=COEF*SUMTN
C INCREMENT THETA
      THETA=THETA+0.01D0
      K=K+1
      IF(THETA.LE.6.0) GO TO 8
C PRINT OUT E(THETA) FOR EACH OUTPUT
      WRITE(6,100) (E(I,K),K=1,600)
  100 FORMAT(15F7.4/,15F7.4)
C GO TO NEXT OUTPUT
    6 CONTINUE
```

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TABLE F-I

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```
FORTRAN IV G1   RELEASE 2.0          MAIN          DATE = 80032        10/12/80          PAGE 0003

                C CALCULATE AND PRINT TOTAL OUTPUT SIGNAL FOR L TERMS AT EACH THETA
0102                  K=1
0103            40    SUMEO=0.000
0104                  DO 33 I=1,L
0105                  SUMEN=E(I,K)
0106                  SUMEN=SUMEN+SUMEO
0107                  SUMEO=SUMEN
0108            33    CONTINUE
0109                  WRITE(6,105)K,SUMEN
0110           105    FORMAT(' FOR TIME INCREMENT ',I3,' THE VALUE OF E(THETA) IS '
                     1,F7.4)
0111                  K=K+1
0112                  IF(K.LE.600) GO TO 40
0113                  STOP
0114                  END
```

TABLE F-1

-4-

FORTRAN IV G1 RELEASE 2.0 IFACT DATE = 80032 10/12/00 PAGE 0001

```
      SUBROUTINE IFACT(IX,IXF)
      IF(IX.EQ.1) IXM=1
      IF(IX.EQ.2) IXM=2
      IF(IX.LT.3) GO TO 96
      IXO=IX
      IXM1=IX-1
      DO 92 I1=1,IXM1
      IXM=IXO*(IX-I1)
      IXO=IXM
   92 CONTINUE
   96 IXF=IXM
      RETURN
      END
```

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Figure F-1
Gas mixing model

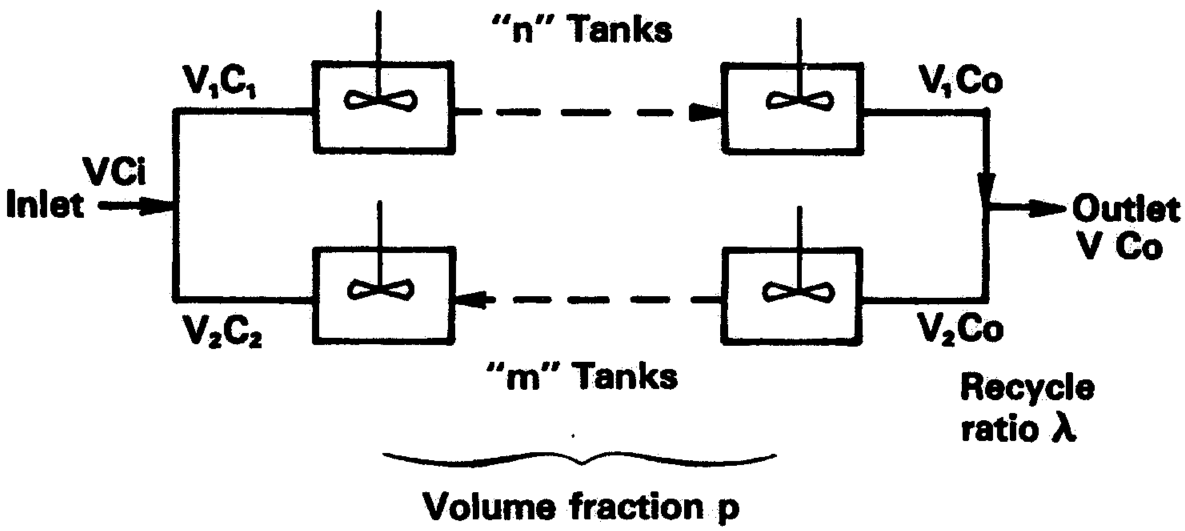

Figure F-2

FLOW DIAGRAM FOR
COMPUTATION PROCEDURE

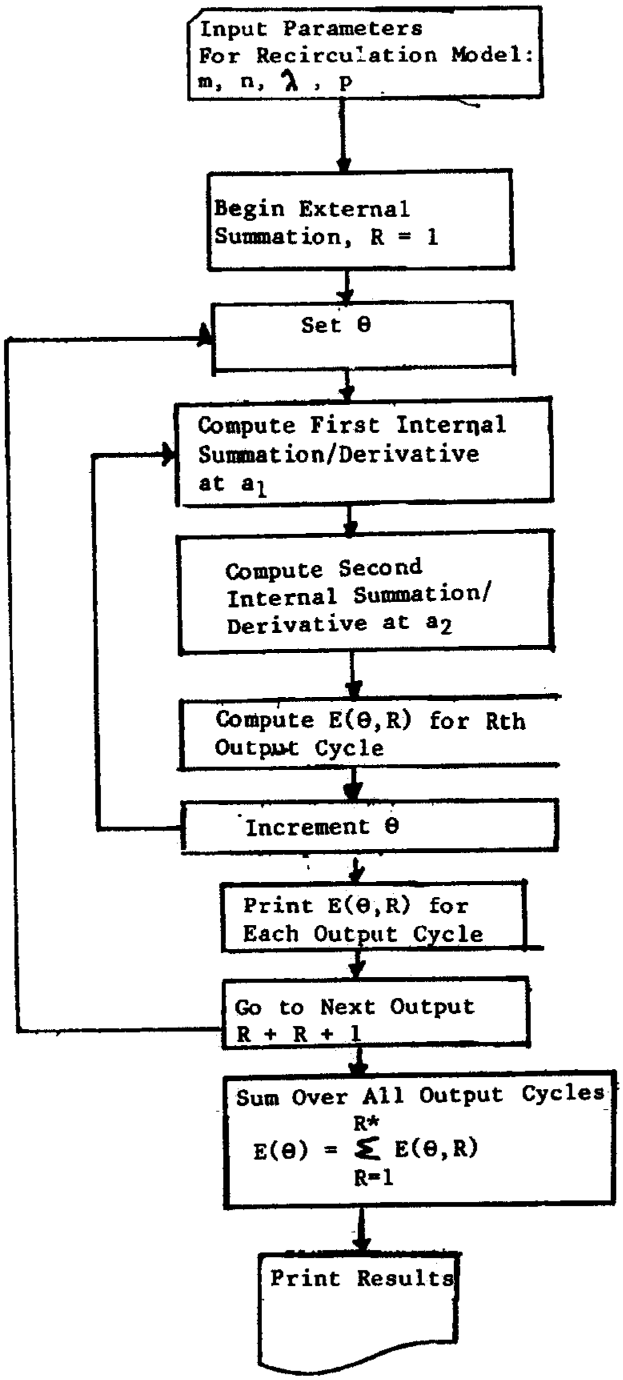

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Figure F-3

Typical response curves based on the proposed model

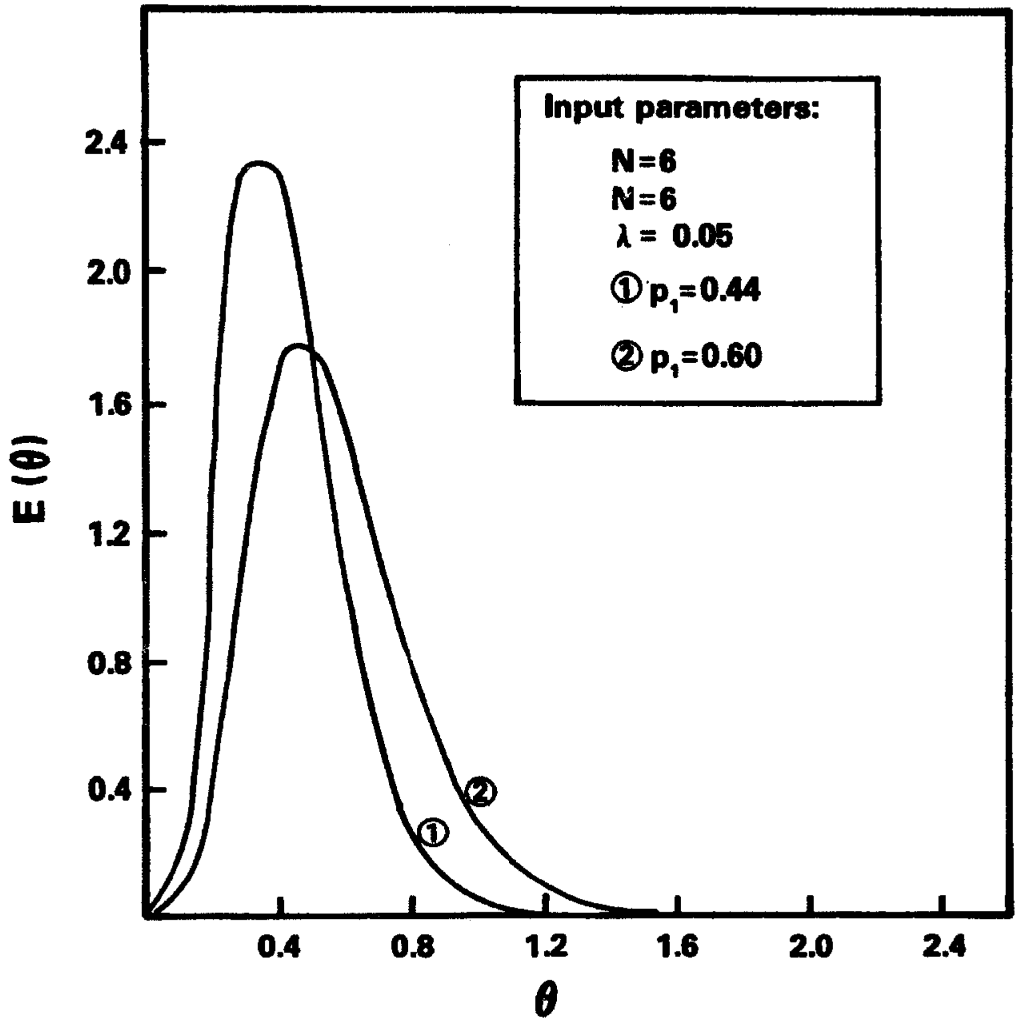

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Figure F-4

Typical response curves based on the proposed model

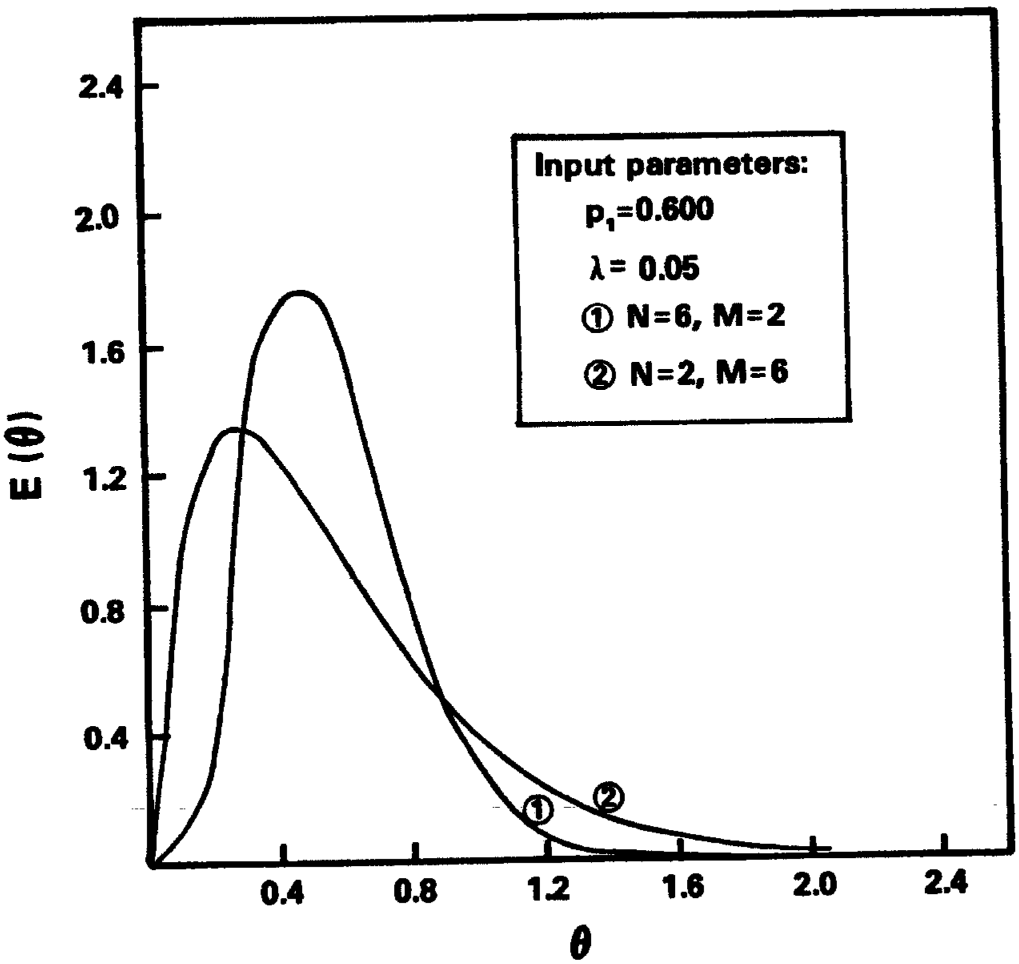

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Figure F-5

Comparison of Laplace transform and integral models

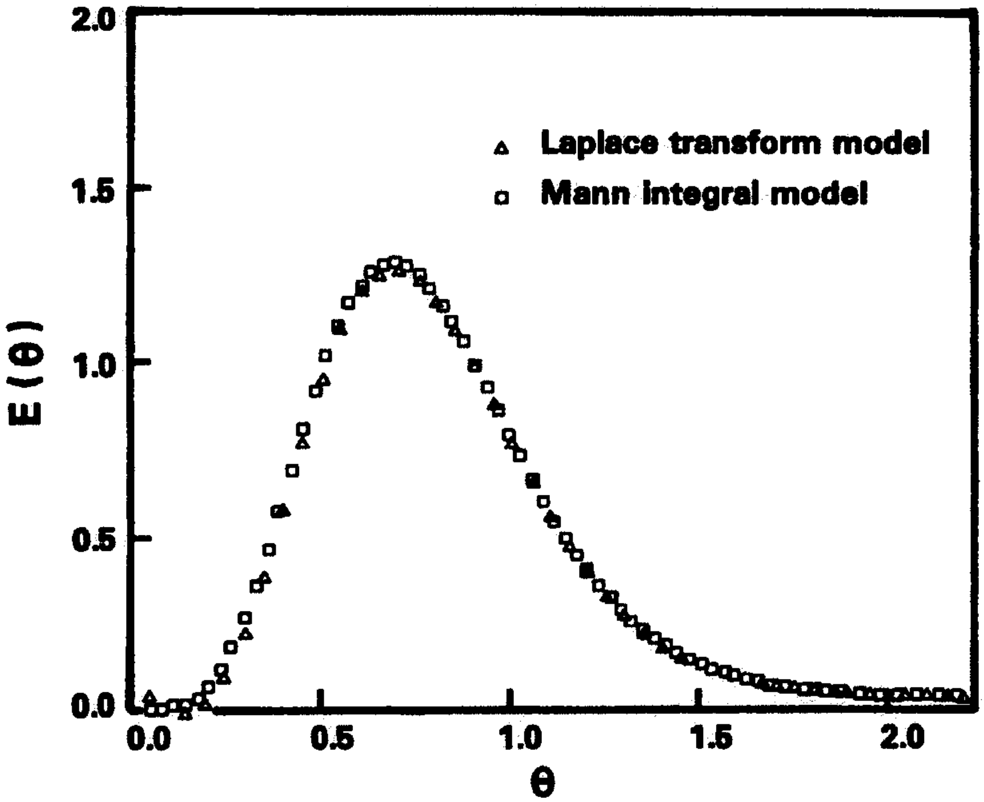

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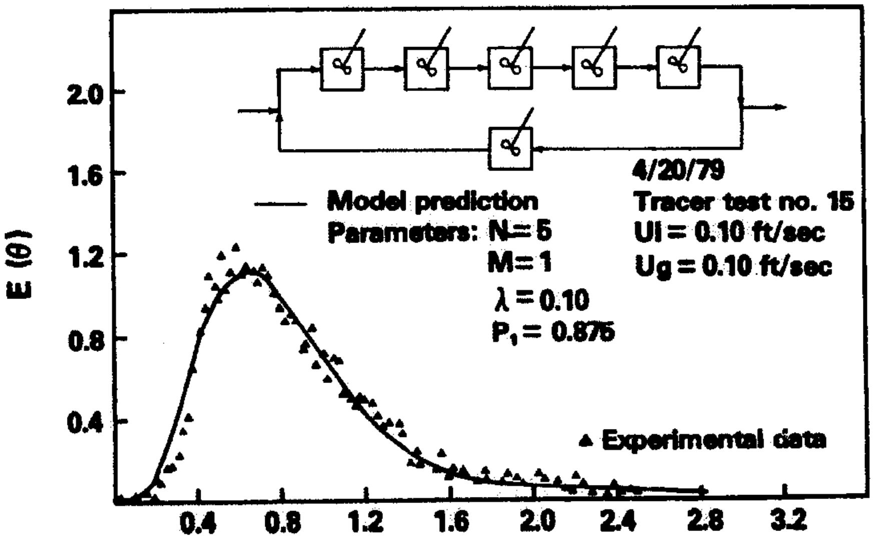
Figure F-6

Comparison of gas mixing model with experiments: Kerosene/catalyst/no fines



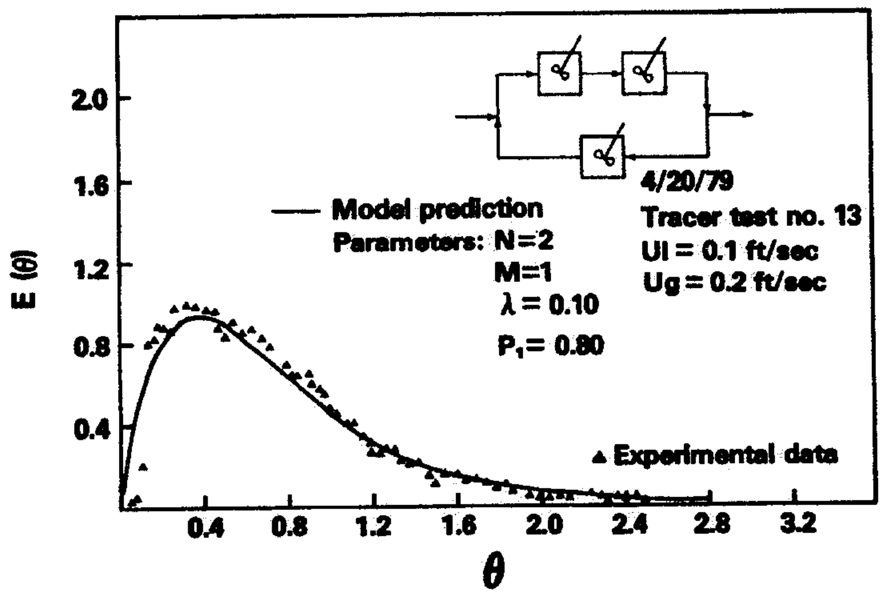


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Figure F-7

Comparison of gas mixing model with experiments: Kerosene/catalyst/15.5 vol % coal fines