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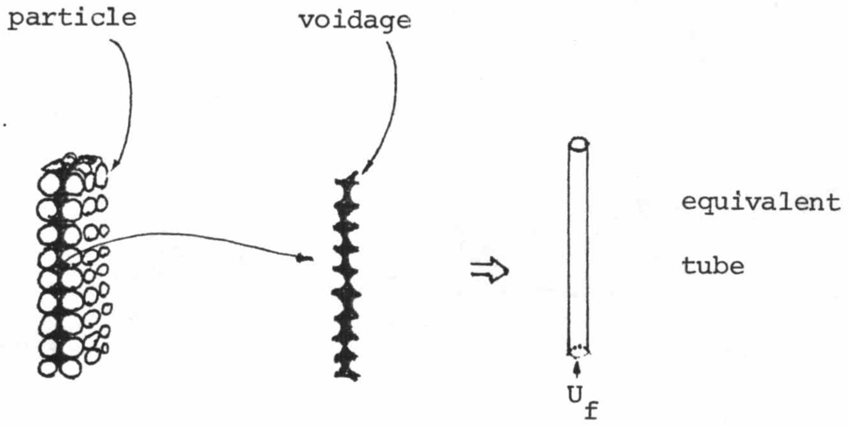
APPENDICES

Apeendix A

Minimum Fluidization Velocity (U_{mf})

The Ergun equation derivation for predicting minimum fluidization velocity (U_{mf}) is shown followingly.

In fixed bed, the particles of the same size are assumed. The small tubes are assumed to be the equivalent tubes for the voidages between particles. The surface area of the equivalent tube is assumed to be equal to the surface area of the particles.



Let the equivalent tube diameter be d_c and U_f is the air velocity passing through the tube.

From the Bernoulli equation

$$\frac{\Delta P}{\rho_g} + \Delta Z \frac{g}{g_c} + \frac{\Delta(\bar{U}_f^{2})}{2g_c} + \Sigma F = W_f \qquad \ldots\ldots \qquad (1)$$

where ΔP = pressure drop across the tube

ρ_g = density of gas

F = force

W_f = work

$$\frac{\Delta P}{\rho_g} + 0 + 0 + F = 0$$

$$\frac{\Delta P}{\rho_g} = F_{friction} + F_{kinetic} \qquad \ldots\ldots \qquad (2)$$

where $F_{friction}$ = friction force

$F_{kinetic}$ = kinetic force

$$F_{friction} = f\frac{L}{d_c}\,\frac{\bar{U}_f^{2}}{2g_c} \qquad \ldots\ldots \qquad (3)$$

$$F_{kinetic} = \frac{k\bar{u}_f^{2}}{2g_c} \qquad \ldots\ldots \qquad (4)$$

where f, k = constant

$$-\frac{\Delta P}{\rho_g} = f\frac{L}{d_c}\cdot\frac{U_f^{2}}{2g_c} + \frac{K\,U_f^{2}}{2g_c} \qquad \ldots\ldots \qquad (5)$$

$$d_c = 2r = 2r \cdot \frac{2\pi r}{2\pi r} = \frac{4\pi r^2}{2\pi r}\cdot\frac{L}{L}\cdot\frac{N_c}{N_c} \qquad \ldots\ldots \qquad (6)$$

where r = radius of the tube

d_c = tube diameter

N_c = numbers of tube

L = length of tube

hence
$$d_c = \frac{4 . \pi r^3 L N_c}{2 \pi r L N_c} = 4 \frac{\text{total void volume}}{\text{total surface of particles}}$$

$$d_c = \frac{4 . N . \frac{4}{3} \frac{\pi d_p^3}{8} . \frac{\epsilon_m}{1-\epsilon_m}}{N . \frac{4 \pi d_p^2}{4}}$$

$$= \frac{2}{3} . \frac{\epsilon_m}{1-\epsilon_m} d_p \qquad \text{......} \qquad (7)$$

where N = numbers of particles

d_p = particle diameter

ϵ_m = void fraction in fixed bed

substitute Eq. (7) in Eq. (5)

$$-\frac{\Delta P}{\rho_g} = f . \frac{3}{2} \frac{(1-\epsilon_m)}{\epsilon_m d_p} . \frac{L \bar{U}_f^2}{2 g_c} + \frac{K \bar{U}_f^2}{2 g_c} \qquad \text{......} \qquad (8)$$

from
$$U_o A_t = \bar{U}_f \epsilon_m A_t \qquad \text{......} \qquad (9)$$

A_t = bed cross section area

U_o = superficial velocity

$$K \propto \frac{L}{d_c} \qquad \text{......} \qquad (10)$$

$$f = \frac{64}{Re} = \frac{64\,\mu}{\rho_g \, \bar{U}_f \, d_c} \qquad \text{......} \qquad (11)$$

where Re = Renolds number

substitute Eq. (9), (10) and (11) into Eq. (8)

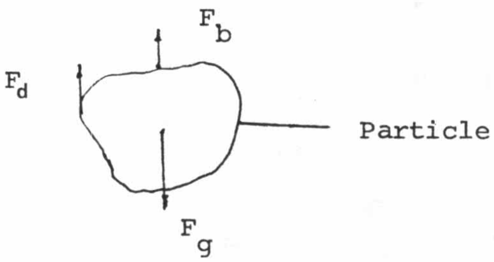
$$\left(-\frac{\Delta P}{L}\right) g_c = \frac{K_1 \, (1-\epsilon_m)^2 \mu \, U_o}{\epsilon_m^3 \, d_p^2} + K_2 \, \frac{(1-\epsilon_m) \, \rho_g \, U_o^2}{d_p \, \epsilon_m^3} \qquad \text{......} \qquad (12)$$

Ergun found that K_1 = 150, K_3 = 1.75

$$\therefore \left(-\frac{\Delta P}{L}\right) g_c = 150 \, \frac{(1-\epsilon_m)^2}{\epsilon_m^3} \cdot \frac{\mu \, U_o}{d_p^2} + 1.75 \, \frac{(1-\epsilon_m) \, \rho_g U_o^2}{d_p \, \epsilon_m^3} \qquad \text{......} \qquad (13)$$

In a fluidized bed, a particle is floating and follows the equation

$$\Sigma F = 0 \qquad \text{......} \qquad (14)$$



$$F_b + F_d = F_g \qquad \ldots\ldots \qquad (15)$$

where F_b = bouyancy force

F_d = drag force

F_g = gravitational force

$$F_g = (1-\epsilon_{mf}) \; A_t \, L \, \rho_s \frac{g}{g_c} \qquad \ldots\ldots \qquad (16)$$

$$F_b = \rho_g \; (1-\epsilon_{mf}) \; A_t \; L \frac{g}{g_c} \qquad \ldots\ldots \qquad (17)$$

$$F_d = \Delta P \; A_t \qquad \ldots\ldots \qquad (18)$$

where ρ_s = solid density

ϵ_{mf} = minimum fluidization void fraction

substitute Eq. (16), (17) and (18) in Eq. (15)

$$(1-\epsilon_{mf}) \; A_t \; L \, \rho_s \frac{g}{g_c} = \rho_g \; (1-\epsilon_{mf}) \; A_t \; L \frac{g}{g_c} + (-\Delta P \; A_t)$$

$$\left(\frac{-\Delta P}{L} \right) g_c = (1-\epsilon_{mf}) (\rho_s - \rho_g) \; g \qquad \ldots\ldots \qquad (19)$$

From Eq. (13) and Eq. (19) and letting $\epsilon_m = \epsilon_{mf}$, $U_o = U_{mf}$

hence $$150 \frac{(1-\epsilon_{mf})^2 \mu \, U_{mf}}{\epsilon_{mf}^3 \, (\varphi d_p)^2} + 1.75 \frac{(1-\epsilon_{mf}) \, \rho_g \, U_{mf}^2}{(\varphi d_p) \, \epsilon_{mf}^3} \quad \ldots\ldots \quad (20)$$

$$= (1-\epsilon_{mf}) \, (\rho_s-\rho_g) \, g$$

or $$G_a = 150 \frac{1-\epsilon_{mf}}{\varphi^2 \epsilon_{mf}^3} Re_{mf} + 1.75 \frac{Re_{mf}^2}{\epsilon_{mf}^3} \quad \ldots\ldots \quad (21)$$

where $Re_{mf} = \frac{U_{mf} \, d_p \, \rho_g}{\mu}$; particle Reynolds number at fluidization velocity

$Ga = g \, d_p^3 \, \rho_g . \, (\rho_s-\rho_g) \, / \mu^2$; Galilei number

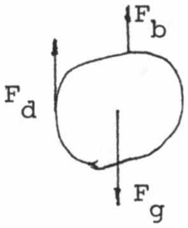
φ = sphericity of particle

Appendix B

Terminal Velocity of Particles (U_t)

The gas flow rate through a fluidized bed is limited on one hand by U_{mf} and on the other by entraiment of solids by the gas. This upper limit to gas flow rate is approximated by the terminal or free-fall velocity of the particles, (U_t).

The derivation of U_t is as follow.



F_d = drag force

F_b = buoyancy force

F_g = gravitational force

$$F = ma$$

$$\therefore a = 0$$

$$F = 0 \qquad \ldots\ldots \qquad (1)$$

$$F_d = F_g - F_b \qquad \ldots\ldots \qquad (2)$$

$$F_d = A_t K C_d$$

where A_t = cross sectional area of bed

C_d = drag coefficient

K = characteristic kinetic energy

$$K = \tfrac{1}{2} \rho_g U_t^2 \qquad \cdots\cdots \qquad (3)$$

$$F_g = \frac{4}{3} \frac{\pi d_p^3}{8} \rho_s \frac{g}{g_c}$$

$$= \frac{\pi d_p^3}{6} \rho_s \frac{g}{g_c} \qquad \cdots\cdots \qquad (4)$$

$$F_b = \frac{\pi d_p^3}{6} \rho_g \frac{g}{g_c} \qquad \cdots\cdots \qquad (5)$$

substitute Eq. (3), (4) and (5) in Eq. (2)

$$\tfrac{1}{2} \rho_g U_t^2 \frac{\pi d_p^2}{4} C_d = \frac{\pi d_p^3}{6} (\rho_s - \rho_g) \frac{g}{g_c}$$

$$U_t = \frac{\frac{4}{3} d_p (\rho_s - \rho_g) \frac{g}{g_c}^{\frac{1}{2}}}{\rho_g C_d} \qquad \cdots\cdots \qquad (6)$$

Eq. (6) is used for spherical particles

An alternate way of finding U_t for spherical particles uses analytic expressions for the drag coefficient C_d. Unfortunately, no single simple expression can represent the experimental findings in the flow regime of interest, so for the particle Reynolds number ranges shown we have

$$C_d, \text{ spherical} = \frac{24}{Re_p} \quad \text{for } Re_p < 0.4 \quad \ldots\ldots \quad (7)$$

$$C_d, \text{ spherical} = \frac{10}{Re_p^{\frac{1}{2}}} \quad \text{for } 0.4 < Re_p < 500 \quad \ldots\ldots \quad (8)$$

$$C_d, \text{ spherical} = 0.43 \quad \text{for } 500 < Re_p < 200{,}000 \quad \ldots\ldots \quad (9)$$

substituting these values of C_d in Eq. (6) gives analytic expressions for U_t, or

$$U_t, \text{ spherical} = \frac{g(\rho_s-\rho_g)\, d_p^{3}}{18} \quad \text{for } Re_p < 0.4 \quad \ldots\ldots \quad (10)$$

$$U_t, \text{ spherical} = \frac{4}{225}\,\frac{(\rho_s-\rho_g)^2 g^2}{\rho_g}^{\frac{1}{3}} d_p \quad \text{for } 0.4 < Re_p < 500$$

$$\ldots\ldots \quad (11)$$

$$U_t, \text{ spherical} = \frac{3.1g\,(\rho_s-\rho_g)\, d_p}{\rho_g}^{\frac{1}{2}} \quad \text{for } 500 < Re_p < 200{,}000$$

$$\ldots\ldots \quad (12)$$

where $Re_p = \dfrac{d_p \rho_g U_t}{\mu}$

For non-spherical particles, Pettyjohn and Christiansen (1948) have proposed that the terminal velocity can be estimated by multiplying the above U_t values by a correction factor.

$$\xi = 0.843 \log \left(\frac{\varphi}{0.065} \right) \qquad \ldots\ldots \qquad (13)$$

where φ = sphericity of particle.

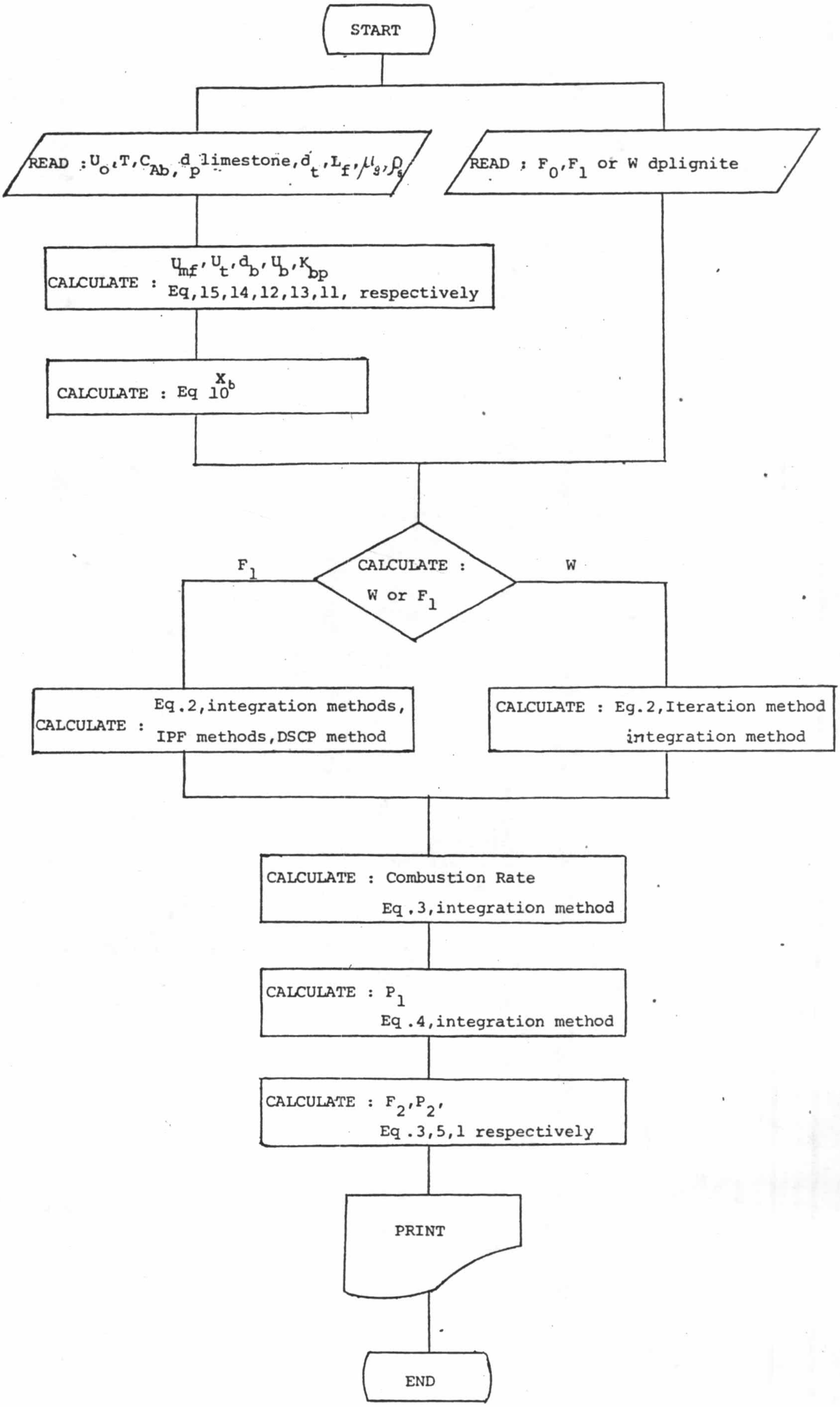
Appendix C

System Model Computation

The system model is computed by a numerical digital computation method.

In computation, the Simpson rule and the Trapezoidal rule are used for integration, an Iteration method is used for finding the weight of Char in bed W, Davies-Swann-Campey and Powell's method (DSCP) for optimization in order to find the value of the overflow rate F_1 Interpolation uses Newton Forward, Newton Backward, Everett method, IPF.

The flow chart and computer programs for system model calculation are shown followingly. The numbers of equations in the flow chart are from section 4.4.8.


START
READ : U_o, T, C_{Ab}, d_p limestone, d_t, L_f, μ_g, ρ_g
READ : F_0, F_1 or W dplignite
CALCULATE : U_{mf}, U_t, d_b, U_b, K_{bp} Eq,15,14,12,13,11, respectively
CALCULATE : Eq 10 X_b
CALCULATE : W or F_1
F_1
W
CALCULATE : Eq.2,integration methods, IPF methods,DSCP method
CALCULATE : Eg.2,Iteration method integration method
CALCULATE : Combustion Rate Eq.3,integration method
CALCULATE : P_1 Eq.4,integration method
CALCULATE : F_2, P_2, Eq.3,5,1 respectively
PRINT
END

```
C THESE PROGRAM WRITTEN BY MR.NUTTAWUT WACHARAKUNDILOKE
C IT IS SYSTEM MODELLING PROGRAM OF COMBUSTION EFFICIENCY
C DEPARTMENT OF CHEMICAL ENGINEERING,FACULTY OF ENGINEERING
C CHULALONGKORN UNIVERSITY
C H=FINITE DIFFERENCE OF PARTICLE DIAMETER
C HZR=FINITE DIFFERENCE OF PARTICLE .LT.DPCMIN
CHF1TR=FINITE DIFFERENCE OF TRIAL FEED RATE
C THE VALUE OF F1STRT IS .LT. F1END,THE VALUE OF F1X IS FROM LARGE TO SMALL
C TK=TEMPERATURE OF AIR IN BED IN KELVIN UNIT
C MC=MOLECULAR WEIGHT OF CARBON,MS=MOLECULARWEIGHT OF SULPHER
C P=ATMOSPHERIC PRESSURE
C R=GAS CONSTANT
C EXC=EXCESS AIR
C PCTCCL=PERCENT OF FIXED CARBON IN COAL
C PCCL=PERCENT OF ALL CARBON IN COAL
C PSCL=PERCENT OF SULPHER IN COAL
C THE PERCENT ABOVE IS NOT THE REAL PERCENT MEANING,OTHERWISE HAVE TO *100.
C DG=DENSITY OF AIR AT 35 C
C N=NUMBERS OF PARTICLE DIAMETER VALUES OF FEED
C EMEU=VISCOUSITY OF AIR
C
C NN=NUMBERS OF SUPERFICIAL VELOCITY(UO)
C LET PCTCCL=PCCL
C
      DIMENSION Y1(999),Y11(999),Y1ZR(999),Y2(999),Y11ZR(999)
      DIMENSION DPC(999),DPC12(999),P0(999),P1(999),P2(999)
      DIMENSION UT(999),II(999),SH(999),RR(999),KK(999)
      DIMENSION ERROR(999),F1XX(999),YSUM2(999),ERUPDN(999)
      DIMENSION UO(50),DAI(50),CAFI(50),DGI(50),EMEUI(50),F1I(50)
      DIMENSION TKI(50)
      DIMENSION UMF1(50)
      DIMENSION FOI(50)
      DIMENSION WI(50)
      INTEGER TRY,KNOWF1
      REAL II,KK,IIX,KKX
      REAL LOWLMT
      READ(5,10) DPCMAX,DPCMIN,H,DCL,G,DT,DCP,N
   10 FORMAT(7F10.4,I10)
C F1STRT IS STARTING POINT OF TRIAL F1,AND IS UPPER LIMIT
C F1END IS END POINT OF TRIAL F1, AND IS LOWER LIMIT
      READ(5,11) F1STRT,F1END,HF1TR,EPS,HZR
   11 FORMAT(5F10.4)
C SPH=SPHERICITY OF COAL PARTICLE
      READ(5,20) PCTCCL,SPH,NN
   20 FORMAT(2F10.4,I10)
      READ(5,21)   (UO(I),I=1,NN)
      READ(5,21)   (DAI(I),I=1,NN)
      READ(5,21) (FOI(I),I=1,NN)
      READ(5,21)   (WI(I),I=1,NN)
      READ(5,21) (F1I(I),I=1,NN)
   21 FORMAT(8F10.4)
```

```
      READ(5,22)   (CAPI(I),I=1,NN)
      READ(5,22)   (DGI(I),I=1,NN)
      READ(5,22)   (EMEUI(I),I=1,NN)
   22 FORMAT(8E10.4)
C FOR BED HEIGHT MORE THAN TDH,A=0.
      READ(5,23) A
   23 FORMAT(F10.4)
C*******
C IF WE KNOW F1,THEN HAVE TO TRY FOR W,LET DATA BELOW IN A READ STATEMENT BE
C W=0.0,WINIT=.....,F1=.....,KNOWF1=1,MAX=.....
C IF WE DON'T KNOW F1,BUT WE KNOW THE VALUE OF W,LET DATA BE
C W=.....,WINIT=0.,F1=0.,KNOWF1=0,MAX=0
C*******
C IF F1 KNOWN,W TO BE FOUND,AND F1 .EQ.0.,W FOUND IS THE MAX. ONE
C THAT MAKES THE CARBON IN COAL COMBUSTED ALL
C*******
      READ(5,25) W,WINIT,KNOWF1,MAX
   25 FORMAT(2F10.4,2I10)
C IF DESIRE TO USE OPTIMIZATION FOR FINDING F1,LET KYDSCP=1
C KYDSCP=KEY TO OPEN TO DSCP METHOD,KYDSCP=1 MEANS 'OPEN',=0 MEANS 'CLOSE'
C IMAX=ALLOWABLE NUMBERS OF ITERATION IN DSCP
C HDSCP=FINITE DIFFERENCE IN DSCP
C XODSCP=THE INITIAL VALUE OF F1 TRIAL FROM WHICH THE SEARCH START
      READ(5,26) KYDSCP,IMAX,HDSCP,XODSCP
   26 FORMAT(2I10,2F10.4)
      READ(5,30) (PC(I),I=1,N)
   30 FORMAT(8F10.4)
      READ(5,32) P,R,PCOL,MC
   32 FORMAT(3F10.4,I10)
      READ(5,33)   (TKI(I),I=1,NN)
      READ(5,33)   (UMFI(I),I=1,NN)
   33 FORMAT(8F10.4)
      DO 100 I=1,N
      DPC(I)=DPCMIN+FLOAT(I-1)*H
  100 CONTINUE
      DPMX=DPCMIN-HZR
      DPZR=HZR
      NL=(DPMX-DPZR)/HZR+1.
C NL NOT BE EQUAL TO ZERO
      NZR=N+NL
C****
C IF KNOWING F1,INSERT THESE PROGRAM(WITHOUT C) ,BUT ALREADY KNOWN W
C     F1=..........
C      KEY=1.
C     IF(KEY.EQ.1.) GOTO 460
C
      DO 1000 ITR=1,NN
      W=WI(ITR)
      F00=F0I(ITR)
      UMF=UMFI(ITR)
      TK=TKI(ITR)
      U00=U0(ITR)
      DA=DAI(ITR)
      CAP=CAPI(ITR)
      DG=DGI(ITR)
      EMEU=EMEUI(ITR)
```

```
      F1=F1I(ITR)
      IF(KNOWF1.EQ.1) GO TO 190
      L=(F1STRT-F1END)/HF1TR+1.1
      WRITE(6,189) L
  189 FORMAT(//T10,'L=',I10)
      GO TO 191
  190 CONTINUE
      W=WINIT
      WO=W
      L=MAX
  191 CONTINUE
      DO 400 TRY=1,L
      IF(KNOWF1.EQ.1) GO TO 192
      Z=TRY-1
      F1X=F1STRT-Z*HF1TR
      GO TO 193
  192 CONTINUE
      F1X=F1
  193  CONTINUE
      DO 200 I=1,N
      N1=N-I+1
      DPCX=DPCMAX-FLOAT(I-1)*H
      CALL IIDP(DPCMAX,H,F1X,IIX,DCL,G,DT,DDP,DA,PCTCCL,SPH,
     *  U00,W,CAP,DG,EMEU,DPCX,UMF,A,UTX,SHX,RRX,KKX)
      Y2(I)=PC(N1)/((DPCX**3)*IIX)
      CALL INTGT(H,I,Y2,SUM2)
      Y11(N1)=(DPCX**3)*IIX/ABS(RRX)
      Y1(N1)=Y11(N1)*SUM2
  200 CONTINUE
      DO 300 I=1,NL
      NL1=NL-I+1
      DPX=DPCMIN-FLOAT(I)*HZR
      CALL IIDP(DPCMAX,HZR,F1X,IIX,DCL,G,DT,DDP,DA,PCTCCL,SPH,
     *  U00,W,CAP,DG,EMEU,DPX,UMF,A,UTX,SHX,RRX,KKX)
      Y11ZR(NL1)=(DPX**3)*IIX/ABS(RRX)
      Y1ZR(NL1)=Y11ZR(NL1)*SUM2
  300 CONTINUE
      CALL INTGT(H,N,Y1,SUM11)
      CALL INTGT(HZR,NL,Y1ZR,SUM12)
      SUM1=SUM11+SUM12
      IF(KNOWF1.EQ.1) GO TO 331
      DIF=(W/FCO)-SUM1
      YDIF=ABS(DIF)
      IF(YDIF.LE.EPS) GO TO 440
      ERRCF(TRY)=YDIF
      F1XX(TRY)=F1X
      GO TO 400
  331 W1=FCO*SUM1
      DIF=ABS(WO-W1)
      IF(DIF.LE.EPS) GO TO 459
      WO=W1
      W=WO
  400 CONTINUE
      IF(KNOWF1.EQ.1) GO TO 451
      DIV=1
      WRITE(6,410)
```

```
  410 FORMAT('1',T10,'TRYING FOR F1 IS DIVERGE'/
     *  T10,'TRY AGAIN BY HAND CHECKING AND THEN GO TO NEXT STEP'/)
      WRITE(6,420)
  420 FORMAT(T10,7('----------')/T25,'F1 TRIAL',T45,'|',
     *  T60,'ERROR'/T10 ,7('----------'))
      WRITE(6,430)(F1XX(I),ERROR(I),I=1,L)
  430 FORMAT(T25,F10.4,T45,'|',T55,F13.8)
      WRITE(6,434)
  434 FORMAT(T10,7('----------'))
      IF(KYDSCP.NE.1) GO TO 437
C FIND F1XX THAT ITS ERROR IS EQUAL TO ZERO BY OPTIMIZATION
C USING DAVIES-SWANN-CAMPEY AND POWELL'S METHOD(DSCP)
      LOWLMT=F1XX(L)
      UPLMT=F1XX(1)
      DO 435  I=1,L
      LI1=L-(I-1)
      ERUPDN(LI1)=ERROR(I)
  435 CONTINUE
      CALL DSCP(HDSCP,XODSCP,F1,ERF1,EPS,IMAX,LOWLMT,HFITR,ERUPDN,L)
      WRITE(6,438) F1,ERF1
  438 FORMAT(1H0/20X,'MINIMIZATION BY DSC-POWELL METHOD'/ 25X,6HX    =    ,
     *  F12.5,25X,6HPM   =  ,F12.5)
      WRITE(6,436) F1,ERF1
  436 FORMAT(//,T10,'BUT AFTER HAND CHECKING AND DESIRING TO USE OPTIMIZ
     *ATION NUMERICAL CALCULATION',/,T10,'OVERFLOW,F1,=',F10.4,
     *  T45,'BUT ERROR FROM CALCULATION =',F10.4)
      GO TO 460
  437 STOP
  440 DIV=0
      F1=F1X
      WRITE(6,450) F1
  450 FORMAT('1',T10,'TRYING FOR F1 IS CONVERGE,',T40,'F1=',F10.4)
      GO TO 460
  451 CONTINUE
      WRITE(6,452) W
  452 FORMAT('1',T10,'FINDING W IS DIVERGE,LAST TRIAL OF W IS',F10.4)
      STOP
  459 CONTINUE
      W=W1
  460 CONTINUE
C****
C FIND TABLE OF DPC(I),PD(I),SH(I),KK(I),RR(I),II(I)
C FROM NEAR ZERO TO DPCMAX
C INPUT F1 FROM HAND CHECKING IF TRYING FOR F1 IS DIVERGE
      DO 480  I=1,NL
      DPC12(I)=HZR*FLOAT(I)
  480 CONTINUE
      DO 490  I=1,N
      NLI=NL+I
      DPC12(NLI)=DPCMIN+FLOAT(I-1)*H
  490 CONTINUE
      DO 500  I=1,NZR
      DPX=DPC12(I)
      IF( I.LE.NL) GO TO 495
      HHZR=H
      GO TO 496
```

```
  495 CONTINUE
      HHZR=HZR
  496 CONTINUE
      CALL IIDP(DPCMAX,HHZR,F1,IIX,DCL,G,DT,DCP,DA,PCTCCL,SPH,
     *  U00,W,CAP,DG,EMEU,DPX,UMF,A,UTX,SHX,RRX,KKX)
      UT(I)=UTX
      II(I)=IIX
      SH(I)=SHX
      RR(I)=RRX
      KK(I)=KKX
  500 CONTINUE
      WRITE(6,510) U00,F1,W
  510 FORMAT('1',T10,'U0 =',F10.4,',',T30,'F1 =',F10.4,',',T50,'W =',
     *  F10.4/)
      WRITE(6,520)
  520 FORMAT(T10,8('----------')/T15,'DPC',T21,'|',T26,'UT',T33,'|',
     * T38,'SH',T44,'|',T52,'KK',T58,'|',T65,'RR',T72,'|',T78,'II'/
     *  T10,8('----------'))
      WRITE(6,530) (DPC12(I),UT(I),SH(I),KK(I),RR(I),II(I),I=1,NZR)
  530 FORMAT(T10,F10.4,T21,'|',T22,F10.4,T33,'|',T34,F10.4,T44,'|',
     *  T45,F10.4,T58,'|',T59,F10.4,T72,'|',T73,F10.4)
      WRITE (6,540)
  540 FORMAT(T10,8('----------'))
C***FIND P1(I)
C***FIND P1(DPC1),SIZE DISTRIBUTION OF COAL PARTICLE IN F1
      DO 600 I=1,N
      N1=N-I+1
       NZR1=NZR-I+1
      YSUM2(I)=PC(N1)/((DPC(N1)**3)*II(NZR1))
      CALL INTGT(H,I,YSUM2,SUM2)
      A=F00*(DPC(N1)**3)*II(NZR1)/(W*ABS(RR(NZR1)))
      P1(NZR1)=A*SUM2
  600 CONTINUE
      DO 700 I=1,NL
      NZR1=NZR1-1
      DPCX=DPCMIN-FLOAT(I)*HZR
      P1(NZR1)=F00*(DPCX**3)*II(NZR1)*SUM2/(W*ABS(RR(NZR1)))
  700 CONTINUE
      DO 701 I=1,NZR
      NT=NZR-(I-1)
      P1T=P1(NT)
      IF(P1T.EQ.0.) GO TO 702
  701 CONTINUE
      GO TO 704
  702 NT1=NT-1
      DO 703 I=1,NT1
      P1(I)=0.
  703 CONTINUE
  704 CONTINUE
      WRITE(6,705)
  705 FORMAT('1',T10,7('----------'))
      WRITE(6,706)
  706 FORMAT(T10,'PARTICLE DIAMETER OF COAL,CM',T40,'|',T51,
     *    'SIZE DISTRIBUTION ,CM**(-1)')
      WRITE(6,707)
  707 FORMAT(T10,7('----------'))
```

```
      WRITE(6,7CE) (DPC(I),P0(I),I=1,N)
  708 FORMAT(T18,F13.4,T40,'|',T51,F13.4)
      WRITE(6,7C7)
      WRITE(6,710) FO0,W,UO0,F1
  710 FORMAT('1',T1C,'F0 =',F10.4,',',T25,'W=',F10.4,',',T40,'UC=',
     * F1C.4/T1C,'F1=',F10.4)
      WRITE(6,72C)
  720 FORMAT(T1C,7('-----------')/
     * T25,'DPC1,CM',T45,'|',T60,'P1,CM**-1'/T10,7('-----------'))
      WRITE(6,730) (DPC12(I),P1(I),I=1,NZR)
  730 FORMAT(T25,F1C.4,T45,'|',T6C,F10.4)
      WRITE(6,74C)
  740 FORMAT(T1C,7('-----------'))
C***
C**FIND ELUTRIATION RATE,F2
      DPCX=HZR
      DO 8C0 I=1,NL
      YSUM2(I)=3.*W*P1(I)*RR(I)/DPCX
      DPCX=DPCX+HZR
  800 CONTINUE
      CALL INTGT(HZR,NL,YSUM2,SMF21)
      DO 850 I=1,N
      NLI=NL+1
      DPCX=DPCMIN+FLOAT(I-1)*H
      YSUM2(I)=3.*W*P1(NLI)*RP(NLI)/DPCX
  850 CONTINUE
      CALL INTGT(H,N,YSUM2,SMF22)
      SMF2=SMF21+SMF22
      WRITE(6,860) SMF2
  860 FORMAT('1',T1C,'RATE OF COAL COMBUSTED=',F10.4)
      F2=FCO-F1-SMF2
C**
C* FIND P2(DPC2),SIZE DISTRIBUTION OF COAL PARTICLE IN F2
      DO 9C0 I=1,NZR
      P2(I)=W*KK(I)*P1(I)/F2
  900 CONTINUE
      WRITE(6,9C5) F2
  905 FORMAT('1',T1C,'F2 =',F10.4)
      WRITE(6,91C)
  910 FORMAT(T1C,7('-----------')/
     * T25,'DPC2,CM',T45,'|',T60,'P2,CM**-1'/T10,7('-----------'))
      WRITE(6,73C) (DPC12(I),P2(I),I=1,NZR)
      WRITE (6,74C)
C*
C CONCLUSION
      EFF=(SMF2/FCC)*100.
      IF(F2.GT.C.) GC TO 915
      F2=C.C
  915 CONTINUE
      WRITE(6,920) SMF2
  920 FORMAT(T1C,'RATE OF COAL COMBUSTED=',F10.4)
      WRITE (6,93C) FO0,F1,F2,EFF
  930 FORMAT(T10,'FC =',F10.4,T25,'F1 =',F1C.4,T40,'F2 =',F1C.4,
     * T55,'EFF =',F10.4)
C FIND PERCENT CF EXCESS AIR IN BED
      AA=0.21*P*(3.1416*(DT+DDP)*(DT-DDP)/4.)*U00

      BB=R*TK*FCC*FCCL/1C
      EXC=AA/BB-1.
      PCTEXC=EXC*1CC.0
      WRITE(6,94C) TK,PCTEXC
  940 FORMAT(//T10,'TEMPERATURE OF AIR IN BED =',F10.4,3X,'K'/
     * T10,'EXCESS AIR=',F10.4)
 1000 CONTINUE
      STOP
      END
```

```
C SUBROUTINE FOR FINDING II,SH,RR,KK
C H= FINITE DIFFERENCE OF COAL DIAMETER
C F1= FEED RATE OF COAL
C DPCMAX=MAXIMUM PARTICLE DIAMETER
C DCL=DENSITY OF COAL PARTICLE
C DT=DIAMETER OF BED
C DDP=DIAMETER OF DRAIN PIPE IN BED
C DA=COEFFICIENT DIFFUSIVITY
C PCTCCL=PERCENT CARBON IN COAL PARTICLE(IN FRACTION)
C SPH=SPHERICITY
C W=WEIGHT OF COAL IN BED
C CAP=CONCENTRATION OF OXYGEN IN PARTICULATE PHASE
C
      SUBROUTINE IIDP(DPCMAX,H,F1,II,DCL,G,DT,DDP,DA,PCTCCL,SPH,
     *  UO,W,CAP,DG,EMEU,DPC,UMF,A,UT,SH,RR,KK)
      DIMENSION Y(1000)
      REAL II,KK,KKX
      N=(DPCMAX-DPC)/H+1.
      DO 10 I=1,N
      DPX=DPC+FLOAT(I-1)*H
      CALL TMV(DCL,G,DPX,DG,EMEU,SPH,UTX)
      CALL SRK(DCL,G,DT,DDP,DA,PCTCCL,UO,W,CAP,DG,EMEU,DPX,UMF,A,
     *  UTX,SHX,RRX,KKX)
      Y(I)=(F1/W+KKX)/RRX
   10 CONTINUE
   30 CALL INTGT(H,N,Y,SUM)
      IF(SUM.GE.70) GO TO 50
   40 II=1./EXP(SUM)
      CALL TMV(DCL,G,DPC,DG,EMEU,SPH,UT)
      CALL SRK(DCL,G,DT,DDP,DA,PCTCCL,UO,W,CAP,DG,EMEU,DPC,UMF,A,
     * UT,SH,RR,KK)
      RETURN
   50 WRITE(6,60) SUM,DPC
   60 FORMAT('1',T10,'SUM IS MORE THAN 70,=',F10.4,'DPC= ',F10.4)
      STOP
      END
```

```
C SUBROUTINE FOR CALCULATING INTEGRATION WITH FINITE DIFFERENCE
C SUBROUTINE INTGT(H,N,Y,SUM)
C H=FINITE DIFFERENCE OF X
C Y=FUNCTION OF X
      SUBROUTINE INTGT(H,N,Y,SUM)
      DIMENSION Y(N)
      REAL ITRAP,ISIMP
      IF(N.GE.7) GO TO 5
      SUM1=0
      DO 3 I=1,N
      SUM1=SUM1+Y(I)*H
    3 CONTINUE
      SUM=SUM1
      GO TO 60
    5 CONTINUE
      KT1=FLOAT(N)/2.+0.6
      KT2=N/2
      IF(KT1-KT2) 10,40,10
C SIMPSON RULE
   10 N1=N-1
      YM1=Y(2)
      DO 20 I=4,N1,2
      YM1=YM1+Y(I)
   20 CONTINUE
      N2=N-2
      YM2=Y(3)
      DO 30 I=5,N2,2
      YM2=YM2+Y(I)
   30 CONTINUE
      ISIMP=(H/3.)*(Y(1)+4.*YM1+2.*YM2+Y(N))
      SUM=ISIMP
      GO TO 60
C TRAPEZOIDAL RULE
   40 YMID=Y(2)
      N1=N-1
      DO 50 I=3,N1
      YMID=YMID+Y(I)
   50 CONTINUE
      ITRAP=(H/2.)*(Y(1)+2.*YMID+Y(N))
      SUM=ITRAP
   60 RETURN
      END
```

```
C SUBROUTINE FOR CALCULATING SHERWOOD NUMBER(SH),
C SHRINKING RATE OF PARTICLE (RR)
C ELUTRIATION CONSTANT (KK)
C CAP=CONCENTRATION OF OXYGEN IN PARTICULATE PHASE,GMMOLE/CM**3
C PCTCC= PERCENT OF CARBON IN COAL
C DCL = DENSITY OF COAL, DPC = DIAMETER OF COAL PARTICLE
C UO USED IN CALCULATING KK NOT BE LESS THAN UMF
      SUBROUTINE SRK(DCL,G,DT,DDP,DA,PCTCCL,UO,W,CAP,DG,EMEU,DPC,UMF,A,
     * UT,SH,RR,KK)
      REAL KK,K,K1
      SH = 2.0+0.6*((UO*DG/EMEU)**0.5)*((EMEU/(DG*DA))**(1./3.))
     *  *(DPC**0.5)
      RR=57.6*CAP*SH*DA/(DPC*PCTCCL*DCL)
      IF(UT.GT.UO) GO TO 10
      K1=130.*EXP(-10.4*((UT/UO)**0.5)*((UMF/(UO-UMF))**0.25))+A
      K=3.1416*(DT-DDP)*(DT+DDP)/4.
      KK=(DG*UO*K/W)*K1
      RETURN
   10 KK=0
      RETURN
      END
```

```
C SUBROUTINE FOR CALCULATING TERMINAL VELOCITY (UT)
C DS= DENSITY OF PARTICLE
~~C G= GRAVITATIONAL ACCELLERATION~~
C DP=PARTICLE DIAMETER
C DG=DENSITY OF GAS
C EMEU=VISCOUSITY OF GAS
C SPH=SPHERICITY
      SUBROUTINE TMV(DS,G,DP,DG,EMEU,SPH,UT)
      ~~ANU=0.843*ALOG10(SPH/0.065)~~
      UTSPHR=0.153*(DP**1.14)*(G**0.71)*((DS-DG)**0.711)/((EMEU**0.43)
     *     *(DG**0.29))
      UT=ANU*UTSPHR
      RETURN
      END
```

```
C DSC POWEL METHOD USING THE COMBINED DAVIES-SWANN CAMPEY AND POWEL
C**************************************************************
C THIS SUBROUTINE USING  THE COMBINED DAVIES-SWANN CAMPEY AND POWELL
C METHOD(DSCP),TO COMPUTE THE MINIMUM OF A CONTINUOUS FUNCTION
C THE FOLLOWING PROVISIONS FOR USERS TO SPECIFY,
C XO-THE INITIAL VALUE OF X FROM WHICH THE SEARCH START
C DX-THE SEARCH STEP SIZE
C EPS-THE PRECISION INDEX
C MAX-THE MAXIMUM ALLOWABLE NUMBER OF ITERATIONS
C XOO,HH,YY,NN ARE ARGUMENTS IN SUBROUTINE SUBPROGRAM IPF,
C LOWER LIMIT ,FINITE DIFFERENCE,VALUES OF Y,NUMBERS OF Y RESPECTIVELY
C ********************************WRITEN BY NUTTAWUT WACHARAKUNDILOK************
      SUBROUTINE DSCP(DX,XO,XM,FM,EPS,MAX,XOO,HH,YY,NN)
      DIMENSION YY(NN)
      DOUBLE PRECISION X1,X2,X3
      DATA ITAP,JTAP/5,6/
       H=DX
    2 CONTINUE
C START THE SEARCH THE BOUND MININUM
      ITR=0.
      M=0
      M1=0
      CALL IPF(XOO,HH,YY,NN,XO,FA)
      X=XO+H
      CALL IPF(XOO,HH,YY,NN,X,FB)
      IF(FB.LE.FA) GO TO 4
C REVERSE THE SEARCH DIRECTION TO OBTAIN DECREASING IN FUNCTION VALUE
C
       X=XO
      H=-2.*H
      GO TO 6
C THE FUNCTION STILL DECREASING ,INCREASE THE STEP SIZE BY DOUBLE
C THE PREVIOUS INCREASE IN STEP SIZE
    4 H=2.*H
    6 CONTINUE
      X=X+H
      CALL IPF(XOO,HH,YY,NN,X,FC)
       IF (FC.GT.FB) GO TO 8
      FB=FC
      ITR=ITR+1
      IF(ITR.GT.MAX) GO TO 38
      GO TO 4
C MINIMUM IS BOUND
    8 CONTINUE
      X2=X-H
      IF(X2.LT.X) GO TO 9
      X1=X
      X3=X2-H/2.
      GO TO 10
    9 CONTINUE
      X3=X
      X1=X2-H/2.
   10 H=-H/2.
```

```
      X=X+H
      X2S=X2
      CALL IPF(X00,HH,YY,NN,X2S,FX2)
      CALL IPF(X00,HH,YY,NN,X,FXX)
      IF(FX2.LT.FXX) GO TO 12
      X1=X2
      X2=X
      GO TO 14
   12 X3=X
   14 CONTINUE
      X1S=X1
      X2S=X2
      X3S=X3
      CALL IPF(X00,HH,YY,NN,X1S,FA)
      CALL IPF(X00,HH,YY,NN,X2S,FB)
      CALL IPF(X00,HH,YY,NN,X3S,FC)
      B=2.*(FA-2.*FB+FC)
      IF(B) 15,24,15
   15 X=X2-ABS(H)*(FA-FC)/B
      WRITE(6,111) X
  111 FORMAT(//,T10,'X=',F10.4)
      ITR=0
   16 CONTINUE
      XX1=X-X1
      XX2=X-X2
      XX3=X-X3
      IF(ABS(XX1).LE.EPS) GO TO 40
      IF(ABS(XX2).LE.EPS) GO TO 40
      IF(ABS(XX3).LE.EPS) GO TO 40
      WRITE(6,222) X
  222 FORMAT(T10,'X1EST=',F10.4)
      ITR=ITR+1
      IF(ITR.GT.MAX) GO TO 38
      CALL IPF(X00,HH,YY,NN,X,FP)
      XP=X
      XP2=XP-X2
      IF(ABS(XP2).LE.EPS) GO TO 40
      IF(FB.LT.FP) GO TO 18
      IF(X.LT.X2) GO TO 17
      X1=X2
      FA=FB
      X2=X
      FB=FP
      GO TO 20
   17 X3=X2
      FC=FB
      X2=X
      FB=FP
      GO TO 20
   18 CONTINUE
      IF(X.LT.X2) GO TO 19
      X3=X
      FC=FP
      GO TO 20
   19 X1=X
      FA=FP
```

```
   20 CONTINUE
C NOW PERFORM THE PARABOLIC INTERPOLATION
      A=(X2-X3)*FA+(X3-X1)*FB+(X1-X2)*FC
      IF(A) 21,28,21
   21 X=(1./2.)*((X2**2-X3**2)*FA+(X3**2-X1**2)*FB+(X1**2+X2**2)*FC)/A
      IF(X.GT.X3) GO TO 22
      IF(X.LT.X1) GO TO 22
      GO TO 23
   22 X312=(X3-X1)/2.
      B=2.*(FA-2.*FB+FC)
      IF(B.EQ.0.) GO TO 24
      X=X2-ABS(X312)*(FA-FC)/B
   23 CONTINUE
      GO TO 16
   24 CONTINUE
      IF(M) 26,26,30
   26 M=M+1
      GO TO 8
   28 CONTINUE
      IF(M1) 29,29,32
   29 M1=M1+1
      GO TO 8
   30 WRITE(JTAP,281)
      GO TO 40
   32 WRITE(JTAP,282)
      GO TO 40
   38 CONTINUE
      WRITE(JTAP,280) ITR
C
   40 CONTINUE
C
      XM=X
      CALL IFF(XCC,HH,YY,NN,XM,FM)
  280 FORMAT(1H0,20X,' SEARCH FAILED WITHIN',I6,' ITERATIONS')
  281 FORMAT(1H0/20X,' THE DSC DIVISOR BEING ZERO SECOND TIME')
  282 FORMAT(1H0/20X,'THE POWELL DIVISOR BEING ZERO SECOND TIME')
C
      RETURN
      END
```

```
C SUBROUTINE IPF(INTERPOLATION) INCLUDES
C NEWTON FORWARD INTERPOLATION FORMULAR
C NEWTON BACKWARD INTERPOLATION FORMULAR
C AND EVERETT INTERPOLATION FORMULAR
C M=DEGREE OF THE INTERPOLATION POLINOMAIL,M=N-1
C N= THE NUMBER OF TABULATED DATA POINTS
C X1=INITIAL VALUE OF X,H=FINITE DIFFERENCE,DY=THE DIFFERENCE OF Y OR ANY DEGRE
C XP=THE POINT OF X WHICH IS USED TO FIND YP OR Y-REQUIRED
C N NOT BE LESS THAN 7
      SUBROUTINE IPF(X1,H,Y,N,XP,YP)
      DIMENSION Y(N)
      DIMENSION DY(200,200)
      DOUBLE PRECISION DY,PP,QQ,A,P,Q
      M=N-1
      N1=N-1
      DO 2 I=1,N1
    2 DY(I,1)=Y(I+1)-Y(I)
      DO 6 K=2,M
      L=N-K
      DO 4 I=1,L
    4 DY(I,K)=DY(I+1,K-1)-DY(I,K-1)
    6 CONTINUE
      XN=X1+H*FLOAT(N1)
      SECT=(XN-X1)/3.
      SECT1=X1+SECT
      SECT2=X1+2*SECT
      IF(XP.GT.SECT2) GO TO 30
      IF(XP.GE.SECT1) GO TO 20
C XP=X1+P*H
C NFIF
   10 P=(XP-X1)/H
      PP=1.
      YP=Y(1)
      DO 12 K=1,4
      K1=K-1
      PP=PP*(P-FLOAT(K1))/FLOAT(K)
   12 YP=YP+PP*DY(1,K)
       RETURN
C XP=XN-P*H
C NBIF
   30 P=(XN-XP)/H
      PP=1.
      YP=Y(N)
      NN=N
      DO 33 K=1,4
      K1=K-1
      PP=-PP*(P-FLOAT(K1))/FLOAT(K)
      NN=NN-1
   33 YP=YP+PP*DY(NN,K)
       RETURN
C EIF
   20 K=FLOAT(N)/2.+0.6
      KI=N/2+0.6
```

```
      XO=X1+(FLOAT(K)-1.)*H
      P=(XP-XO)/H
      Q=1.-P
      A=1.
      PP=P
      QQ=Q
      YP=Q*Y(K)+P*Y(K+1)
      IF(K-KI) 22,21,22
   21 L=M/2
      GO TO 25
   22 L=M/2-1
   25 CONTINUE
      DO 23 I=1,3
      II=2*I
      A=A*II*(II+1)
       QQ=(Q+I)*QQ*(Q-I)
      PP=(P+I)*PP*(P-I)
      KK=K-I
   23 YP=YP+(QQ*DY(KK,II)+PP*DY(KK+1,II))/A
      RETURN
      END
```

```
C SUBROUTINE FOR FINDING CAP,X,KBP
C CAP= CONCENTRATION OF OXYGEN IN PARTICULATE PHASE
C CAB= CONCENTRATION OF OXYGEN IN BUBBLE AT SPECIFIED HEIGHT
C CAO= CONCENTRATION OF OXYGEN IN BUBBLE AT INLET OF BED(GAS INLET)
C UO= SUPERFICIAL VELOCITY, UB= BUBBLE VELOCITY, UMF= MINIMUM FLUIDISATION VEL.
C DB= BUBBLE DIAMETER , LF= HEIGHT OF BED
C G= GRAVITATIONAL ACCELERATION, DA= OXYGEN DIFFUSION COEFFICIENT
C KBP= GAS INTERCHANGE COEFFICIENT FROM BUBBLE TO PARTICULATE PHASE
C X= INTERPHASE CHANGE
C UB NOT EQUAL TO ZERO
C THIS SUBROUTINE DOUBLE PRECISION CAB,CAB,B,C

      SUBROUTINE OXYC(CAB,CAO,UMF,UO,DB,DA,G,LF,UB,KBP,X,CAP)
      DOUBLE PRECISION CAB,CAO,B,C
      REAL LF,KBP
      A=(DA**0.5)*(G**0.25)/(DB**1.25)
      KBP=4.5*(UMF/DB)+5.85*A
      UB=0.711*((G*DB)**0.5)+(UO-UMF)
      X=KBP*LF/UB
      IF(X.GT.50.) GO TO 10
      B=EXP(-X)
      GO TO 20
   10 B=0.0
   20 CONTINUE
      C=1.
      CAP=(CAB-CAO*B)/(C-B)
      RETURN
      END
```

```
C SUBROUTINE FOR FINDING BUBBLE DIAMETER IN FBC
C LF=HEIGHT OF FBC BED
C UO=SUPERFICIAL VELOCITY
C UMF=MINIMUM FLUIDIZATION VELOCITY
C DB= BUBBLE DIAMETER

      SUBROUTINE DBCG(UO,UMF,LF,DB)
      REAL LF
      DB1=0.0326*((UO-UMF)**1.11)*(LF**0.81)
      DB=DB1/1.81
      RETURN
      END
```

An Example of Output from the Computer Simulation

```
UO =   394.2300,      F1 =     0.0259,      W =     8.6584

-------------------------------------------------------------------------------
     CPC    |     UT     |     SH    |      KK       |     RR      |     II
-------------------------------------------------------------------------------
    0.0020  |     5.3542 |    2.3501 |  122.2946     |   0.5239    |   0.0001
    0.0040  |    11.7996 |    2.4951 |   83.3734     |   0.2781    |   0.0001
    0.0060  |    18.7332 |    2.6063 |   61.4450     |   0.1937    |   0.0002
    0.0080  |    26.0041 |    2.7001 |   47.2101     |   0.1505    |   0.0004
    0.0100  |    33.5367 |    2.7827 |   37.2730     |   0.1241    |   0.0007
    0.0120  |    41.2845 |    2.8575 |   30.0110     |   0.1062    |   0.0013
    0.0140  |    49.2160 |    2.9262 |   24.5308     |   0.0932    |   0.0023
    0.0160  |    57.3083 |    2.9901 |   20.2947     |   0.0833    |   0.0037
    0.0180  |    65.5437 |    3.0502 |   16.9581     |   0.0756    |   0.0060
    0.0200  |    73.9086 |    3.1070 |   14.2896     |   0.0693    |   0.0092
    0.0220  |    82.3915 |    3.1610 |   12.1284     |   0.0641    |   0.0137
    0.0240  |    90.9833 |    3.2126 |   10.3591     |   0.0597    |   0.0196
    0.0260  |    99.6760 |    3.2621 |    8.8972     |   0.0559    |   0.0274
    0.0280  |   108.4627 |    3.3098 |    7.6797     |   0.0527    |   0.0371
    0.0300  |   117.3381 |    3.3558 |    6.6584     |   0.0499    |   0.0492
    0.0320  |   126.2966 |    3.4002 |    5.7963     |   0.0474    |   0.0633
    0.0340  |   135.3339 |    3.4433 |    5.0645     |   0.0452    |   0.0803
    0.0360  |   144.4461 |    3.4852 |    4.4400     |   0.0432    |   0.0993
    0.0380  |   153.6292 |    3.5259 |    3.9047     |   0.0414    |   0.1213
    0.0400  |   162.8804 |    3.5655 |    3.4439     |   0.0397    |   0.1449
    0.0420  |   172.1967 |    3.6042 |    3.0456     |   0.0383    |   0.1718
    0.0440  |   181.5752 |    3.6419 |    2.7001     |   0.0369    |   0.1994
    0.0460  |   191.0136 |    3.6788 |    2.3994     |   0.0357    |   0.2304
    0.0480  |   200.5058 |    3.7149 |    2.1369     |   0.0345    |   0.2612
    0.0500  |   210.0615 |    3.7503 |    1.9070     |   0.0334    |   0.2953
    0.0520  |   219.6669 |    3.7849 |    1.7053     |   0.0325    |   0.3283
    0.0540  |   229.3241 |    3.8189 |    1.5276     |   0.0315    |   0.3647
    0.0560  |   239.0313 |    3.8523 |    1.3709     |   0.0307    |   0.3988
    0.0600  |   258.5903 |    3.9173 |    1.1095     |   0.0291    |   0.4990
    0.0700  |   308.2705 |    4.0710 |    0.6707     |   0.0259    |   0.6631
    0.0800  |   358.9575 |    4.2139 |    0.4181     |   0.0235    |   0.8507
    0.0900  |   410.5413 |    4.3482 |    0.0000     |   0.0215    |   0.9040
    0.1000  |   462.9353 |    4.4753 |    0.0000     |   0.0200    |   0.9053
    0.1100  |   516.0693 |    4.5961 |    0.0000     |   0.0186    |   0.9067
    0.1200  |   569.8855 |    4.7115 |    0.0000     |   0.0175    |   0.9082
    0.1300  |   624.3323 |    4.8222 |    0.0000     |   0.0165    |   0.9060
    0.1400  |   679.3696 |    4.9288 |    0.0000     |   0.0157    |   0.9077
    0.1500  |   734.9612 |    5.0316 |    0.0000     |   0.0150    |   0.9095
    0.1600  |   791.0750 |    5.1310 |    0.0000     |   0.0143    |   0.9113
    0.1700  |   847.6821 |    5.2273 |    0.0000     |   0.0137    |   0.9171
    0.1800  |   904.7559 |    5.3209 |    0.0000     |   0.0132    |   0.9191
    0.1900  |   962.2759 |    5.4119 |    0.0000     |   0.0127    |   0.9174
    0.2000  |  1020.2227 |    5.5005 |    0.0000     |   0.0123    |   0.9197
    0.2100  |  1078.5762 |    5.5870 |    0.0000     |   0.0119    |   0.9219
    0.2200  |  1137.3201 |    5.6714 |    0.0000     |   0.0115    |   0.9281
    0.2300  |  1196.4395 |    5.7539 |    0.0000     |   0.0112    |   0.9306
    0.2400  |  1255.9189 |    5.8347 |    0.0000     |   0.0108    |   0.9293
    0.2500  |  1315.7473 |    5.9137 |    0.0000     |   0.0105    |   0.9319
    0.2600  |  1375.9124 |    5.9912 |    0.0000     |   0.0103    |   0.9346
    0.2700  |  1436.4011 |    6.0673 |    0.0000     |   0.0100    |   0.9373
    0.2800  |  1497.2051 |    6.1419 |    0.0000     |   0.0098    |   0.9440
    0.2900  |  1558.3122 |    6.2152 |    0.0000     |   0.0096    |   0.9431
    0.3000  |  1619.7173 |    6.2873 |    0.0000     |   0.0093    |   0.9461
    0.3100  |  1681.4102 |    6.3581 |    0.0000     |   0.0091    |   0.9491
    0.3200  |  1743.3799 |    6.4279 |    0.0000     |   0.0090    |   0.9523
    0.3300  |  1805.6230 |    6.4965 |    0.0000     |   0.0088    |   0.9594
    0.3400  |  1868.1292 |    6.5642 |    0.0000     |   0.0086    |   0.9628
    0.3500  |  1930.8962 |    6.6308 |    0.0000     |   0.0084    |   0.9622
```

DPC	UT	SH	KK	RR	II
0.3600	993.9114	6.6965	0.0000	0.0083	0.9656
0.3700	2057.1723	6.7613	0.0000	0.0081	0.9691
0.3800	2120.6768	6.8252	0.0000	0.0080	0.9767
0.3900	184.4124	6.8882	0.0000	0.0079	0.9766
0.4000	2248.3772	6.9505	0.0000	0.0077	0.9762
0.4100	2312.5674	7.0120	0.0000	0.0076	0.9800
0.4200	2376.9771	7.0728	0.0000	0.0075	0.9838
0.4300	2441.6018	7.1328	0.0000	0.0074	0.9878
0.4400	2506.4380	7.1921	0.0000	0.0073	0.9959
0.4500	2571.4797	7.2508	0.0000	0.0072	0.9958

```
-----------------------------------------------------------------------------
PARTICLE DIAMETER OF COAL,CM   I          SIZE DISTRIBUTION ,CM**( 1)
-----------------+-----------------------------------------------------------
              0.0600           I                 0.0200
              0.0700           I                 0.0400
              0.0800           I                 0.5000
              0.0900           I                 0.1000
              0.1000           I                 0.1500
              0.1100           I                 0.3750
              0.1200           I                 0.7500
              0.1300           I                 1.1200
              0.1400           I                 1.5000
              0.1500           I                 1.8750
              0.1600           I                 2.3500
              0.1700           I                 2.8200
              0.1800           I                 3.3500
              0.1900           I                 3.8800
              0.2000           I                 4.3000
              0.2100           I                 4.9500
              0.2200           I                 5.3200
              0.2300           I                 5.5000
              0.2400           I                 5.6200
              0.2500           I                 5.6500
              0.2600           I                 5.6800
              0.2700           I                 5.6700
              0.2800           I                 5.6300
              0.2900           I                 5.5500
              0.3000           I                 5.3500
              0.3100           I                 4.8000
              0.3200           I                 3.9500
              0.3300           I                 3.0500
              0.3400           I                 2.3000
              0.3500           I                 1.7500
              0.3600           I                 1.4000
              0.3700           I                 1.1000
              0.3800           I                 0.8300
              0.3900           I                 0.4600
              0.4000           I                 0.3500
              0.4100           I                 0.2500
              0.4200           I                 0.1800
              0.4300           I                 0.1200
              0.4400           I                 0.0700
              0.4500           I                 0.0300
-----------------------------------------------------------------------------
```

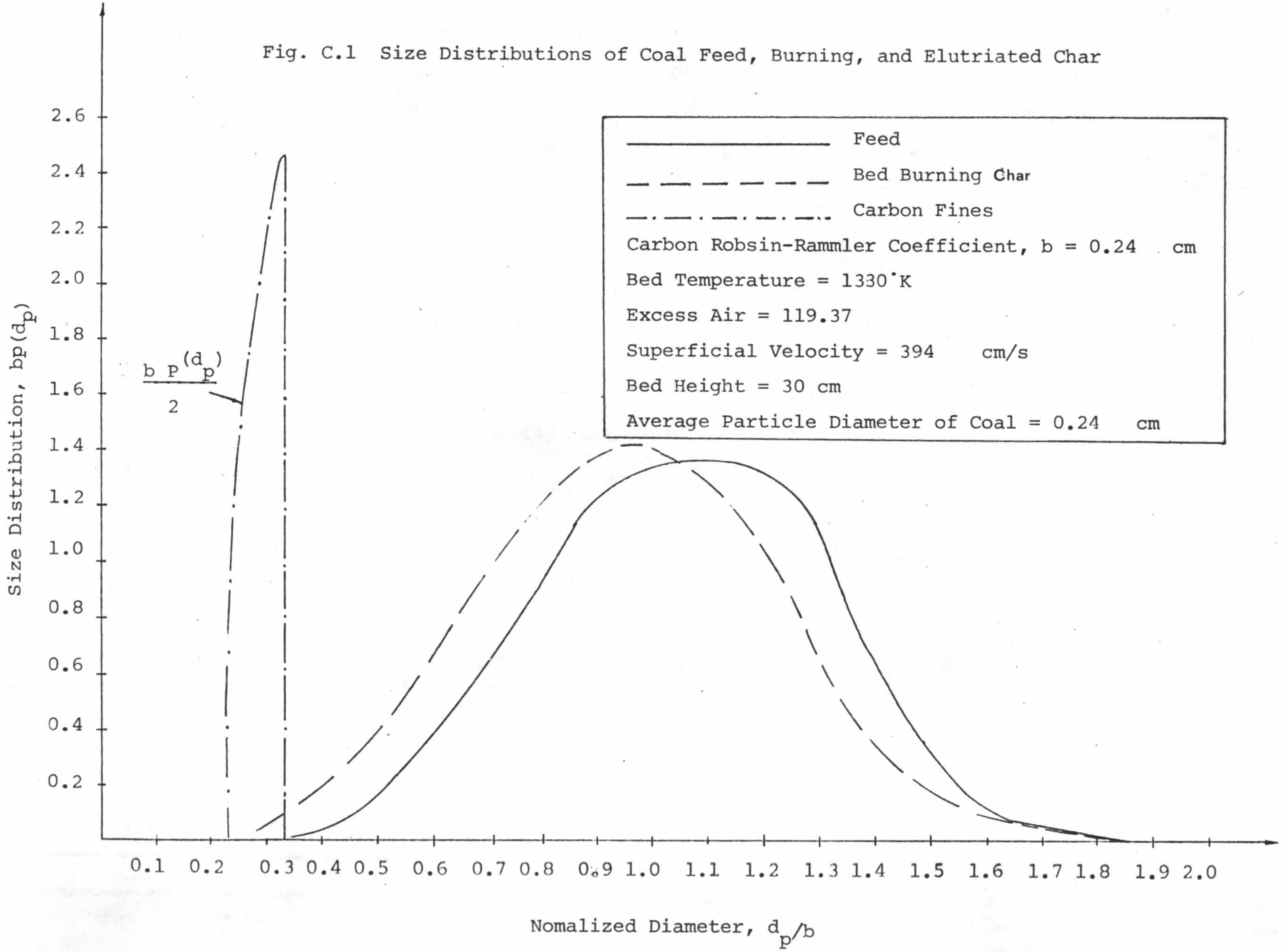
```
F0 =      1.6717,W=      8.6584,   U0=  394.2300
F1=     0.0259
--------------------------------------------------------------
                  DPC1,CM               |               F1,CM** 1
--------------------------------------------------------------
                   0.0020               |                0.0000
                   0.0040               |                0.0000
                   0.0060               |                0.0000
                   0.0080               |                0.0000
                   0.0100               |                0.0000
                   0.0120               |                0.0000
                   0.0140               |                0.0000
                   0.0160               |                0.0000
                   0.0180               |                0.0000
                   0.0200               |                0.0000
                   0.0220               |                0.0000
                   0.0240               |                0.0000
                   0.0260               |                0.0000
                   0.0280               |                0.0000
                   0.0300               |                0.0000
                   0.0320               |                0.0000
                   0.0340               |                0.0000
                   0.0360               |                0.0000
                   0.0380               |                0.0000
                   0.0400               |                0.0000
                   0.0420               |                0.0000
                   0.0440               |                0.0000
                   0.0460               |                0.0000
                   0.0480               |                0.0000
                   0.0500               |                0.0000
                   0.0520               |                0.0000
                   0.0540               |                0.0000
                   0.0560               |                0.0576
                   0.0600               |                0.0841
                   0.0700               |                0.2017
                   0.0800               |                0.3911
                   0.0900               |                0.6065
                   0.1000               |                0.8859
                   0.1100               |                1.2372
                   0.1200               |                1.6409
                   0.1300               |                2.0832
                   0.1400               |                2.5667
                   0.1500               |                3.0791
                   0.1600               |                3.6045
                   0.1700               |                4.1363
                   0.1800               |                4.6311
                   0.1900               |                5.0430
                   0.2000               |                5.4172
                   0.2100               |                5.6884
                   0.2200               |                5.8689
                   0.2300               |                5.9194
                   0.2400               |                5.8615
                   0.2500               |                5.7194
                   0.2600               |                5.5003
                   0.2700               |                5.1653
                   0.2800               |                4.7696
                   0.2900               |                4.2186
                   0.3000               |                3.6099
                   0.3100               |                2.9339
                   0.3200               |                2.3286
                   0.3300               |                1.7944
                   0.3400               |                1.3921
                   0.3500               |                1.0553
```

```
------------------------------------------------------------------------
            DPC1,CM              |              F1,CM**-1
------------------------------------------------------------------------
            0.3600               |               0.7936
            0.3700               |               0.5685
            0.3800               |               0.3873
            0.3900               |               0.2572
            0.4000               |               0.2251
            0.4100               |               0.1514
            0.4200               |               0.0966
            0.4300               |               0.0550
            0.4400               |               0.0260
            0.4500               |               0.0081
------------------------------------------------------------------------


RATE OF COAL COMBUSTED=     1.5768
```

```
F2 =      0.0690
------------------------------------------------------------
           DPC2,CM               |            F2,CM** 1
------------------------------------------------------------
                     0.0020      |                  0.0000
                     0.0040      |                  0.0000
                     0.0060      |                  0.0000
                     0.0080      |                  0.0000
                     0.0100      |                  0.0000
                     0.0120      |                  0.0000
                     0.0140      |                  0.0000
                     0.0160      |                  0.0000
                     0.0180      |                  0.0000
                     0.0200      |                  0.0000
                     0.0220      |                  0.0000
                     0.0240      |                  0.0000
                     0.0260      |                  0.0000
                     0.0280      |                  0.0000
                     0.0300      |                  0.0000
                     0.0320      |                  0.0000
                     0.0340      |                  0.0000
                     0.0360      |                  0.0000
                     0.0380      |                  0.0000
                     0.0400      |                  0.0000
                     0.0420      |                  0.0000
                     0.0440      |                  0.0000
                     0.0460      |                  0.0000
                     0.0480      |                  0.0000
                     0.0500      |                  0.0000
                     0.0520      |                  0.0000
                     0.0540      |                  0.0000
                     0.0560      |                  9.9063
                     0.0600      |                 11.7023
                     0.0700      |                 16.9619
                     0.0800      |                 20.5056
                     0.0900      |                  0.0000
                     0.1000      |                  0.0000
                     0.1100      |                  0.0000
                     0.1200      |                  0.0000
                     0.1300      |                  0.0000
                     0.1400      |                  0.0000
                     0.1500      |                  0.0000
                     0.1600      |                  0.0000
                     0.1700      |                  0.0000
                     0.1800      |                  0.0000
                     0.1900      |                  0.0000
                     0.2000      |                  0.0000
                     0.2100      |                  0.0000
                     0.2200      |                  0.0000
                     0.2300      |                  0.0000
                     0.2400      |                  0.0000
                     0.2500      |                  0.0000
                     0.2600      |                  0.0000
                     0.2700      |                  0.0000
                     0.2800      |                  0.0000
                     0.2900      |                  0.0000
                     0.3000      |                  0.0000
                     0.3100      |                  0.0000
                     0.3200      |                  0.0000
                     0.3300      |                  0.0000
                     0.3400      |                  0.0000
                     0.3500      |                  0.0000
                     0.3600      |                  0.0000
```

```
-----------------------------------------------------------------------------
              DPC2,CM               |               F2,CM**-1
-----------------------------------------------------------------------------
               0.3700               |                0.0000
               0.3800               |                0.0000
               0.3900               |                0.0000
               0.4000               |                0.0000
               0.4100               |                0.0000
               0.4200               |                0.0000
               0.4300               |                0.0000
               0.4400               |                0.0000
               0.4500               |                0.0000
-----------------------------------------------------------------------------
RATE OF COAL COMBUSTED=       1.5766
F0 =      1.6717 F1 =      0.0259 F2 =      0.0690 EFF =      94.3203

TEMPERATURE OF AIR IN BED = 1330.0000    K
EXCESS AIR=  119.3747
```

Fig. C.1 Size Distributions of Coal Feed, Burning, and Elutriated Char



Appendix D

Average Particles Diameter

```
C FIND THE AVERAGE DIAMETER OF LIGNITE PARTICLE
C DBPMAX=MAXIMUM DIAMETER OF BED PARTICLE
C DBPMIN=THE MINIMUM DIAMETER OF BED PARTICLE
C PBP(I)= SIZE DISTRIBUTION OF PARTICLE ,BETWEEN DP AND DP+D(DP)
C NM=(DBPMAX-DBPMIN)/H+1,THE NUMBER OF DATAS TO BE CALCULATE)
C H=FINITE DIFFERENCE OF DBP
      DIMENSION DBP(100),PBP(100),YFB(100)
      DO 200 J =1,2
      READ(5,21) DBPMAX,DBPMIN,H,NM
   21 FORMAT(3F10.4,I10)
      READ(5,31) (PBP(I),J=1,NM)
   31 FORMAT(8F10.4)
      DO 100 I=1,NM
      DBP(I)=DBPMIN+(I-1)*H
      YFB(I)=PBP(I)/DBP(I)
  100 CONTINUE
      CALL INTGT (N,NM,YFB,SUM)
      DPA=1/SUM
      WRITE(5,36)
   36 FORMAT('1',T11,'FIND THE AVERAGE DIAMETER OF LIGNITE PARTICLE')
      WRITE (6,37)
   37 FORMAT('0',T11,7('----------'))
      WRITE(5,38)
   38 FORMAT (T11,'DIAMETER OF LIGNITE PARTICLE ,CM',T45,'|',T51,'SIZE
     *DISTRIBUTION,CM**(-1)')
      WRITE(6,39)
   39 FORMAT(T11,7('----------'))
      WRITE(5,41) (DBP(I),PBP(I),I=1,NM)
   41 FORMAT(T18,F13.4,T45,'|',T58,F13.4)
      WRITE(6,42)
   42 FORMAT(T11,7('----------'))
      WRITE(6,43) DBPMAX,DBPMIN,NM,H,DPA
   43 FORMAT(T11,'MAXIMUM DIAMETER OF BED MATERIAL = ',T51,F13.4/
     *       T11,'MINIMUM DIAMETER OF BED MATERIAL = ',T51,F13.4/
     *       T11,'RANGE NUMBERS OF PARTICLE DIAMETER = ',T51,I4/
     *       T11,'FINITE DIFFERENCE = ',T51,F13.4//
     *       T11,'THE AVERAGE BED PARTICLE DIAMETER =',T51,F13.4)
  200 CONTINUE
      STOP
      END
C SUBROUTINE FOR CALCULATING INTEGRATION WITH FINITE DIFFERENCE
C SUBROUTINE INTGT(H,N,Y,SUM)
C H=FINITE DIFFERENCE OF X
C Y=FUNCTION OF X

      SUBROUTINE INTGT(H,N,Y,SUM)
      DIMENSION Y(N)
      REAL ITRAP,ISIMP
      KT1=FLOAT(N)/2.+0.6
      KT2=N/2
      IF(KT1-KT2) 10,40,10
C SIMPSON RULE
   10 N1=N-1
      YM1=Y(2)
      DO 20 I=4,N1,2
      YM1=YM1+Y(I)
   20 CONTINUE
      N2=N-2
      YM2=Y(3)
      DO 30 I=5,N2,2
      YM2=YM2+Y(I)
   30 CONTINUE
      ISIMP=(H/3.)*(Y(1)+4.*YM1+2.*YM2+Y(N))
      SUM=ISIMP
      GO TO 60
C TRAPEZOIDAL RULE
   40 YMID=Y(2)
      N1=N-1
      DO 50 I=3,N1
      YMID=YMID+Y(I)
   50 CONTINUE
      ITRAP=(H/2.)*(Y(1)+2.*YMID+Y(N))
      SUM=ITRAP
   60 RETURN
      END
```

Appendix E

Estimation of Air-to-fuel Ratio

$$\text{Air-to-fuel Ratio} = \frac{\text{air feed rate (by weight)}}{\text{coal feed rate}}$$

$$= \frac{\frac{PA_tU_o}{RT} M_{air}}{F_o}$$

$$= \frac{PA_tU_o}{RTF_o} M_{air}$$

where P = air pressure

A_t = bed cross section area

U_o = superficial velocity

M_{air} = molecular weight of air

R = gas constant

T = air temperature

F_o = coal feed rate

Appendix F

Estimation of Excess Air

$$\text{Excess Air} = \left(\left(\frac{\text{mole of air used}}{\text{mole of carbon}} \right) \Big/ \left(\frac{\text{mole of air}}{\text{mole of carbon}} \right)_{\text{theory}} - 1 \right) \text{ X } 100$$

$$= \frac{\left(\frac{\text{mole of air used}}{\text{mole of Carbon}} \right)_{\text{actual}}}{\left(\frac{\text{mole of oxygen X } \frac{1}{0.21}}{\text{mole of carbon}} \right)_{\text{theory}}} - 1 \quad \text{X } 100$$

$$= \left(\frac{PV}{RT \text{ X mole of carbon}} \text{ x } 0.21 - 1 \right) \text{ x } 100$$

$$= \left(0.21 \; \frac{PA_tU_o}{RT} \text{ x } \frac{\text{molecular weight of carbon}}{\text{weight of carbon / time}} - 1 \right) \text{ x } 100$$

$$= \left(0.21 \; \frac{PA_tU_oM_c}{RTYF_o} - 1 \right) \text{ x } 100$$

where P = air pressure

A_t = bed cross section area

U_o = superficial velocity

M_c = carbon molecular weight

R = gas constant

T = air temperature

F_o = coal feed rate

Y = percentage of carbon in coal

Appendix G

Fuel Mixture Feed Rate

The fuel mixture in these experiments mentioned before is fed with screw feeder which is controlled by a variable speed motor.

The fuel mixture feed rates and the speed numbers are shown in Table G.1 and Table G.2

Table G.1

Fuel Mixture Feed Rate

Ratio of limestone and lignite in fuel mixture = 1:1 by weight

$\bar{d}_p$ of coal = 1 mm.

$\bar{d}_p$ of limestone = 0.5 mm.

motor speed No.	fuel mixture feed rate	
	gm/sec	gm/min.
1	1.5	87.3
2	2.0	118.1
3	2.7	163.4
4	3.6	214.0
5	4.6	277.1
6	5.2	311.3

$\bar{d}_p$ = average diameter of particles

Table G.2

Fuel Mixture Feed Rate

Ratio of limestone and lignite in fuel mixture = 1:1 by weight

$\bar{d}_p$ of coal = 2.4 mm.

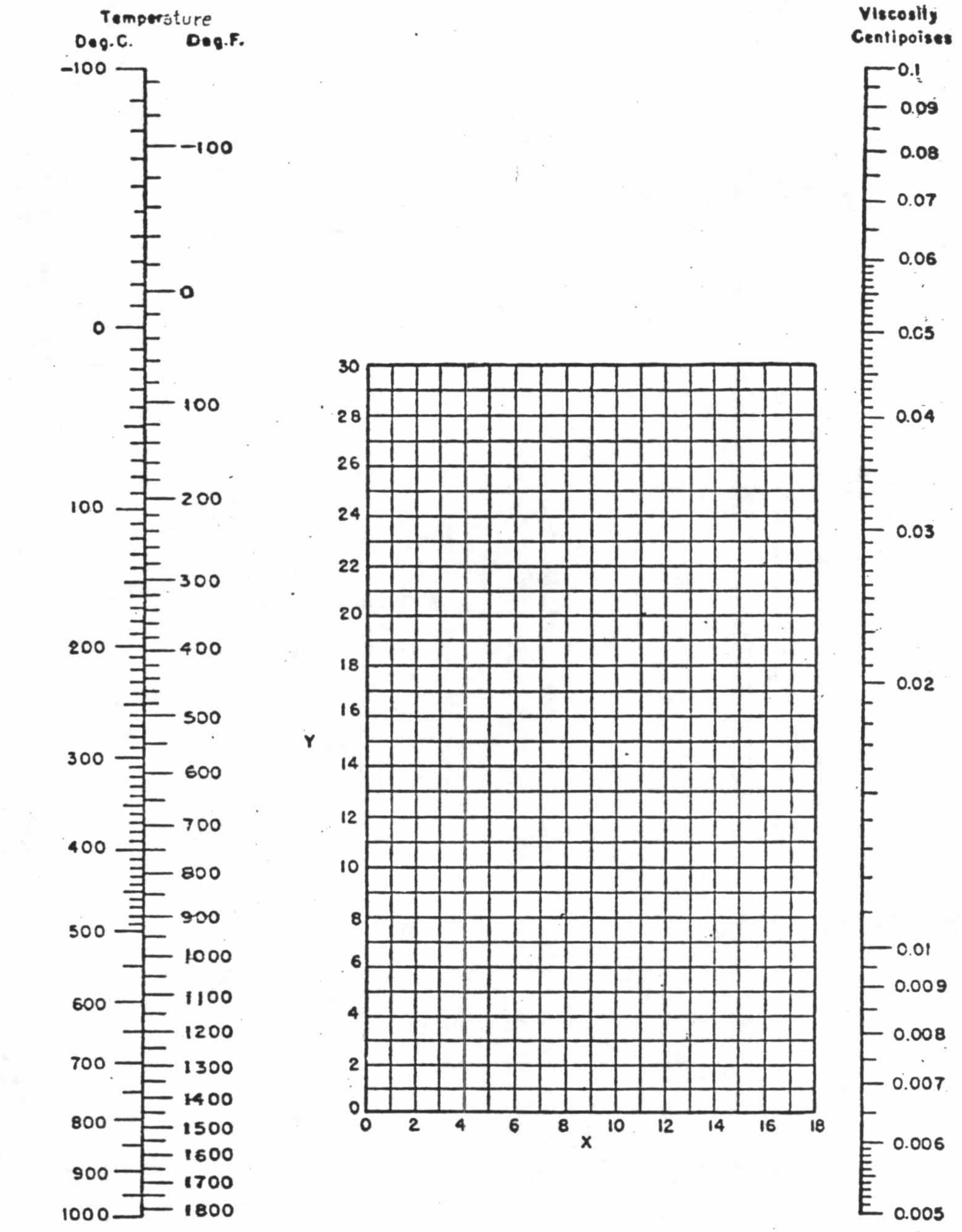
$\bar{d}_p$ of limestone = 1 mm.

motor speed No.	fuel mixture feed rate	
	gm/sec	gm/min.
1	1.2	71.6
2	1.6	98.2
3	2.4	144.6
4	3.3	200.6
5	4.3	259.4
6	5.1	303.3
7	5.4	325.6

$\bar{d}_p$ = the average diameter of particles

Appendix H

Viscousity[37]



Viscosities of gases at 1 atm. For coordinates, see

Coordinates for use with Fig.

No.	Gas	X	Y	No.	Gas	X	Y	No.	Gas	X	Y	No.	Gas	X	Y
1	Acetic acid	7.7	14.3	15	Chloroform	8.9	15.7	29	Freon-113	11.3	14.0	43	Nitric oxide	10.9	20.5
2	Acetone	8.9	13.0	16	Cyanogen	9.2	15.2	30	Helium	10.9	20.5	44	Nitrogen	10.6	20.0
3	Acetylene	9.8	14.9	17	Cyclohexane	9.2	12.0	31	Hexane	8.6	11.8	45	Nitrosyl chloride	8.0	17.6
4	Air	11.0	20.0	18	Ethane	9.1	14.5	32	Hydrogen	11.2	12.4	46	Nitrous oxide	8.8	19.0
5	Ammonia	8.4	16.0	19	Ethyl acetate	8.5	13.2	33	$3H_2 + 1N_2$	11.2	17.2	47	Oxygen	11.0	21.3
6	Argon	10.5	22.4	20	Ethyl alcohol	9.2	14.2	34	Hydrogen bromide	8.8	20.9	48	Pentane	7.0	12.8
7	Benzene	8.5	13.2	21	Ethyl chloride	8.5	15.6	35	Hydrogen chloride	8.8	18.7	49	Propane	9.7	12.9
8	Bromine	8.9	19.2	22	Ethyl ether	8.9	13.0	36	Hydrogen cyanide	9.8	14.9	50	Propyl alcohol	8.4	13.4
9	Butene	9.2	13.7	23	Ethylene	9.5	15.1	37	Hydrogen iodide	9.0	21.3	51	Propylene	9.0	13.8
10	Butylene	8.9	13.0	24	Fluorine	7.3	23.8	38	Hydrogen sulfide	8.6	18.0	52	Sulfur dioxide	9.6	17.0
11	Carbon dioxide	9.5	18.7	25	Freon-11	10.6	15.1	39	Iodine	9.0	18.4	53	Toluene	8.6	12.4
12	Carbon disulfide	8.0	16.0	26	Freon-12	11.1	16.0	40	Mercury	5.3	22.9	54	2, 3, 3-Trimethylbutane	9.5	10.5
13	Carbon monoxide	11.0	20.0	27	Freon-21	10.8	15.3	41	Methane	9.9	15.5	55	Water	8.0	16.0
14	Chlorine	9.0	18.4	28	Freon-22	10.1	17.0	42	Methyl alcohol	8.5	15.6	56	Xenon	9.3	23.0

Fig H.1 Viscousity of Gases

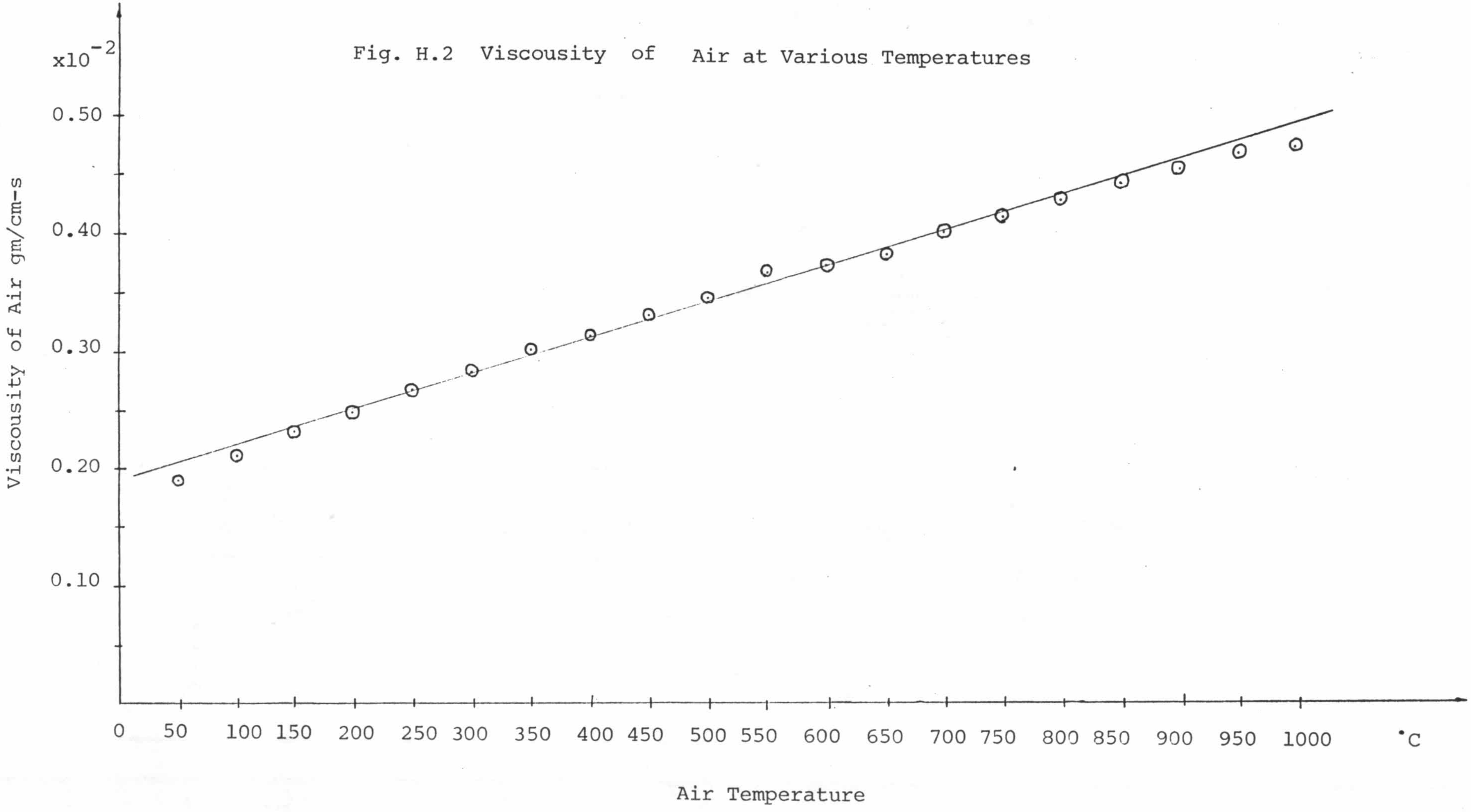


Fig. H.2 Viscousity of Air at Various Temperatures

Appendix I

Diffusivity[38]

For low pressure of binary gas mixture and high temperature, the diffusivity of oxygen in air is expressed in the following equation [32, 33]

$$D_{AB} = \frac{0.001858\ T^{3/2}\ (1/M_A + s/M_B)^{\frac{1}{2}}}{P\ 6_{AB}^{2}\ \Omega_D}\quad cm^3/s \qquad \ldots\ldots\ (1)$$

where D_{AB} = Mutual diffusion coefficient species A in binary of A and B, cm^{2}/s

P = total pressure = 1 atm.

M_A = Molecular weight of A

here, the molecular weight of oxygen = 32

M_B = Molecular weight of B,

here, the molecular weight of air = 28.84

6 = Lennard-Jones potential parameter, °A (see Table

Table 1.1 LENNARD-JONES POTENTIAL PARAMETERS

Molecule	Compound	σ, Å	ϵ/k °K
A	Argon	3.542	93.3
He	Helium†	2.551	10.22
Kr	Krypton	3.655	178.9
Ne	Neon	2.820	32.8
Xe	Xenon	4.082	206.9
Air	Air	3.711	78.6
Br_2	Bromine	4.296	507.9
CCl_4	Carbon tetrachloride	5.947	322.7
CF_4	Carbon tetrafluoride	4.662	134.0
$CHCl_3$	Chloroform	5.389	340.2
CH_2Cl_2	Methylene chloride	4.898	356.3
CH_3Br	Methyl bromide	4.118	449.2
CH_3Cl	Methyl chloride	4.182	350.0
CH_3OH	Methanol	3.626	481.8
CH_4	Methane	3.758	148.6
CO	Carbon monoxide	3.690	91.7
COS	Carbonyl sulfide	4.130	336.0
CO_2	Carbon dioxide	3.941	195.2
CS_2	Carbon disulfide	4.483	467.0
C_2H_2	Acetylene	4.033	231.8
C_2H_4	Ethylene	4.163	224.7
C_2H_6	Ethane	4.443	215.7
C_2H_5Cl	Ethyl chloride	4.898	300.0
C_2H_5OH	Ethanol	4.530	362.6
C_2N_2	Cyanogen	4.361	348.6
CH_3OCH_3	Methyl ether	4.307	395.0
CH_2CHCH_3	Propylene	4.678	298.9
CH_3CCH	Methylacetylene	4.761	251.8
C_3H_6	Cyclopropane	4.807	248.9
C_3H_8	Propane	5.118	237.1
$n\text{-}C_3H_7OH$	*n*-Propyl alcohol	4.549	576.7
CH_3COCH_3	Acetone	4.600	560.2
CH_3COOCH_3	Methyl acetate	4.936	469.8
$n\text{-}C_4H_{10}$	*n*-Butane	4.687	531.4
$iso\text{-}C_4H_{10}$	Isobutane	5.278	330.1
$C_2H_5OC_2H_5$	Ethyl ether	5.678	313.8
$CH_3COOC_2H_5$	Ethyl acetate	5.205	521.3
$n\text{-}C_5H_{12}$	*n*-Pentane	5.784	341.1
$C(CH_3)_4$	2,2-Dimethylpropane	6.464	193.4
C_6H_6	Benzene	5.349	412.3
C_6H_{12}	Cyclohexane	6.182	297.1
$n\text{-}C_6H_{14}$	*n*-Hexane	5.949	399.3
Cl_2	Chlorine	4.217	316.0
F_2	Fluorine	3.357	112.6
HBr	Hydrogen bromide	3.353	449.0
HCN	Hydrogen cyanide	3.630	569.1
HCl	Hydrogen chloride	3.339	344.7
HF	Hydrogen fluoride	3.148	330.0
HI	Hydrogen iodide	4.211	288.7
H_2	Hydrogen	2.827	59.7
H_2O	Water	2.641	809.1
H_2O_2	Hydrogen peroxide	4.196	289.3
H_2S	Hydrogen sulfide	3.623	301.1
Hg	Mercury	2.969	750.0
I_2	Iodine	5.160	474.2
NH_3	Ammonia	2.900	558.3
NO	Nitric oxide	3.492	116.7
NOCl	Nitrosyl chloride	4.112	395.3
N_2	Nitrogen	3.798	71.4
N_2O	Nitrous oxide	3.828	232.4
O_2	Oxygen	3.467	106.7
PH_3	Phosphine	3.981	251.5
SF_6	Sulfur hexafluoride	5.128	222.1
SO_2	Sulfur dioxide	4.112	335.4
$SnBr_4$	Stannic bromide	6.388	563.7
UF_6	Uranium hexafluoride	5.967	236.8

† Calculated from quantum-mechanical formulas.

σ_{AB} = Lennard-Jones potential parameter of the mixture of A and B

Ω_D = collision integral (see Table 1.2 and Fig 1.1)

T = gas temperature

The value of σ_{AB} can be calculated from

$$\sigma_{AB} = \tfrac{1}{2}(\sigma_A+\sigma_B) \quad \ldots\ldots \quad (2)$$

A = oxygen

B = air

hence, $\sigma_{AB} = \tfrac{1}{2}(3.711+3.467)$

$= 3.589$ for binary of oxygen and air ..... (3)

Using the Table 1.1 , the value of ε/k can be found, and the value of ε/k of the binary gas minture can be calculated by

$$\frac{\varepsilon_{AB}}{K} = \left(\frac{\varepsilon_A}{K} \cdot \frac{\varepsilon_B}{K}\right)^{\frac{1}{2}} \quad \ldots\ldots \quad (4)$$

Knowing the value of ε_{AB}/K, the collision integral can be found from Table 1.2

Table 1.2 VALUES OF THE COLLISION INTEGRAL Ω_D BASED ON THE LENNARD-JONES POTENTIAL†

kT/ε	Ω_D‡	kT/ε	Ω_D	kT/ε	Ω_D
0.30	2.662	1.65	1.153	4.0	0.8836
0.35	2.476	1.70	1.140	4.1	0.8788
0.40	2.318	1.75	1.128	4.2	0.8740
0.45	2.184	1.80	1.116	4.3	0.8694
0.50	2.066	1.85	1.105	4.4	0.8652
0.55	1.966	1.90	1.094	4.5	0.8610
0.60	1.877	1.95	1.084	4.6	0.8568
0.65	1.798	2.00	1.075	4.7	0.8530
0.70	1.729	2.1	1.057	4.8	0.8492
0.75	1.667	2.2	1.041	4.9	0.8456
0.80	1.612	2.3	1.026	5.0	0.8422
0.85	1.562	2.4	1.012	6	0.8124
0.90	1.517	2.5	0.9996	7	0.7896
0.95	1.476	2.6	0.9878	8	0.7712
1.00	1.439	2.7	0.9770	9	0.7556
1.05	1.406	2.8	0.9672	10	0.7424
1.10	1.375	2.9	0.9576	20	0.6640
1.15	1.346	3.0	0.9490	30	0.6232
1.20	1.320	3.1	0.9406	40	0.5960
1.25	1.296	3.2	0.9328	50	0.5756
1.30	1.273	3.3	0.9256	60	0.5596
1.35	1.253	3.4	0.9186	70	0.5464
1.40	1.233	3.5	0.9120	80	0.5352
1.45	1.215	3.6	0.9058	90	0.5256
1.50	1.198	3.7	0.8998	100	0.5130
1.55	1.182	3.8	0.8942	200	0.4644
1.60	1.167	3.9	0.8888	400	0.4170

† From J. O. Hirschfelder, C. F. Curtiss, and R. B. Bird, "Molecular Theory of Gases and Liquids," John Wiley & Sons, Inc., New York, 1954

‡ Hirschfelder uses the symbols T^* for kT/ε and $\Omega^{(1,1)*}$ in place of Ω_D.

Now the value of ε_{AB}/K of oxygen in air = ε_{AB}/K

$$= \tfrac{1}{2} \left(\frac{\varepsilon_A}{k} \cdot \frac{\varepsilon_B}{k}\right)^{\frac{1}{2}}$$

$$= \tfrac{1}{2} (78.6+106.7)^{\frac{1}{2}}$$

$$= 91.58 \qquad \ldots\ldots \quad (5)$$

The collision integral is also the function of temperature. The collision integral of oxygen in air as the function of temperature is shown in Fig. I.1

Hence, the diffusion of oxygen in air can be expressed in the following equation

$$D_{AB} = 3.73 \times 10^{-5} \frac{T^{3/2}}{\Omega_{AB}} \qquad \ldots\ldots \quad (6)$$

where A = oxygen

B = air

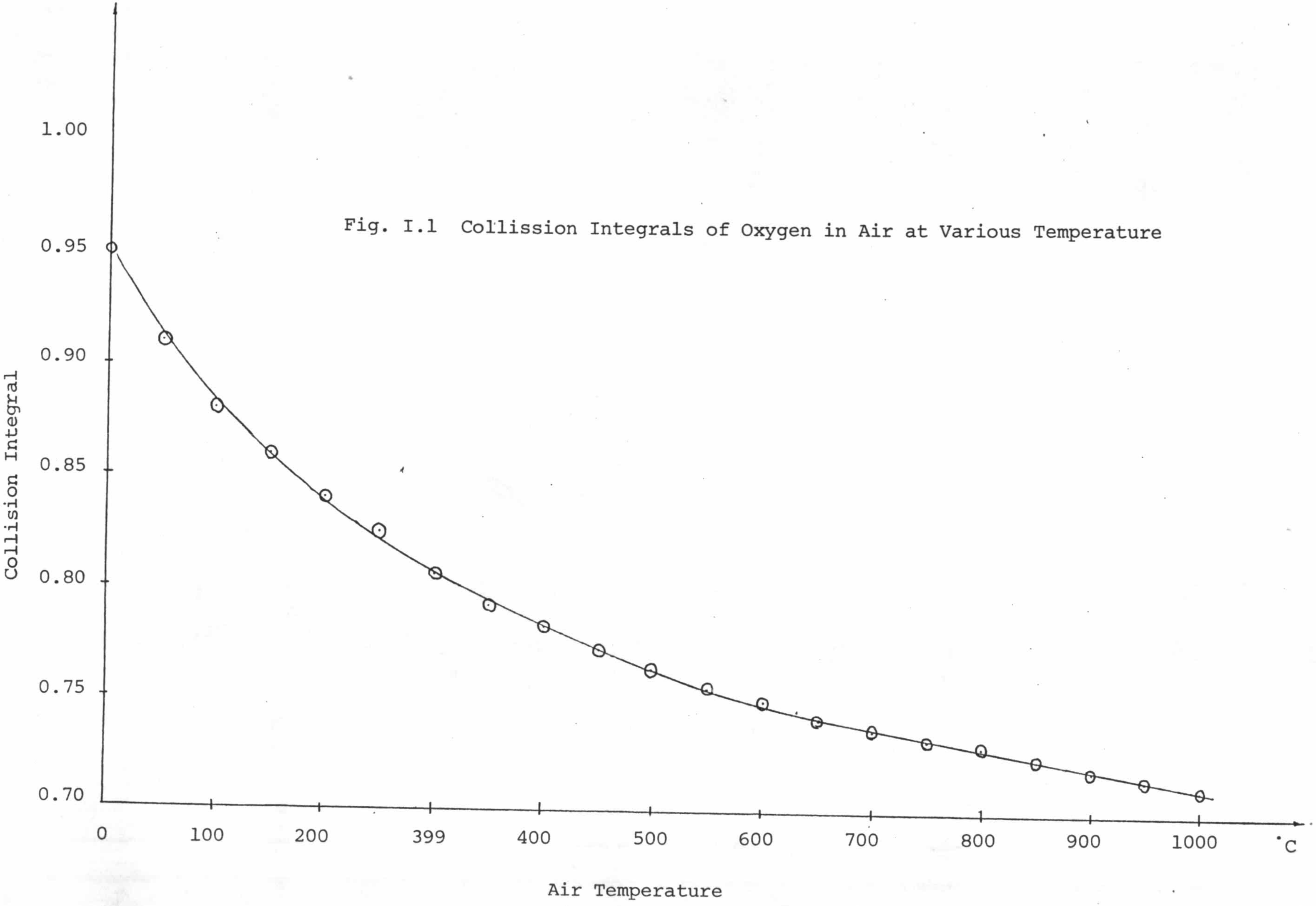


Fig. I.1 Collission Integrals of Oxygen in Air at Various Temperature

Appendix J

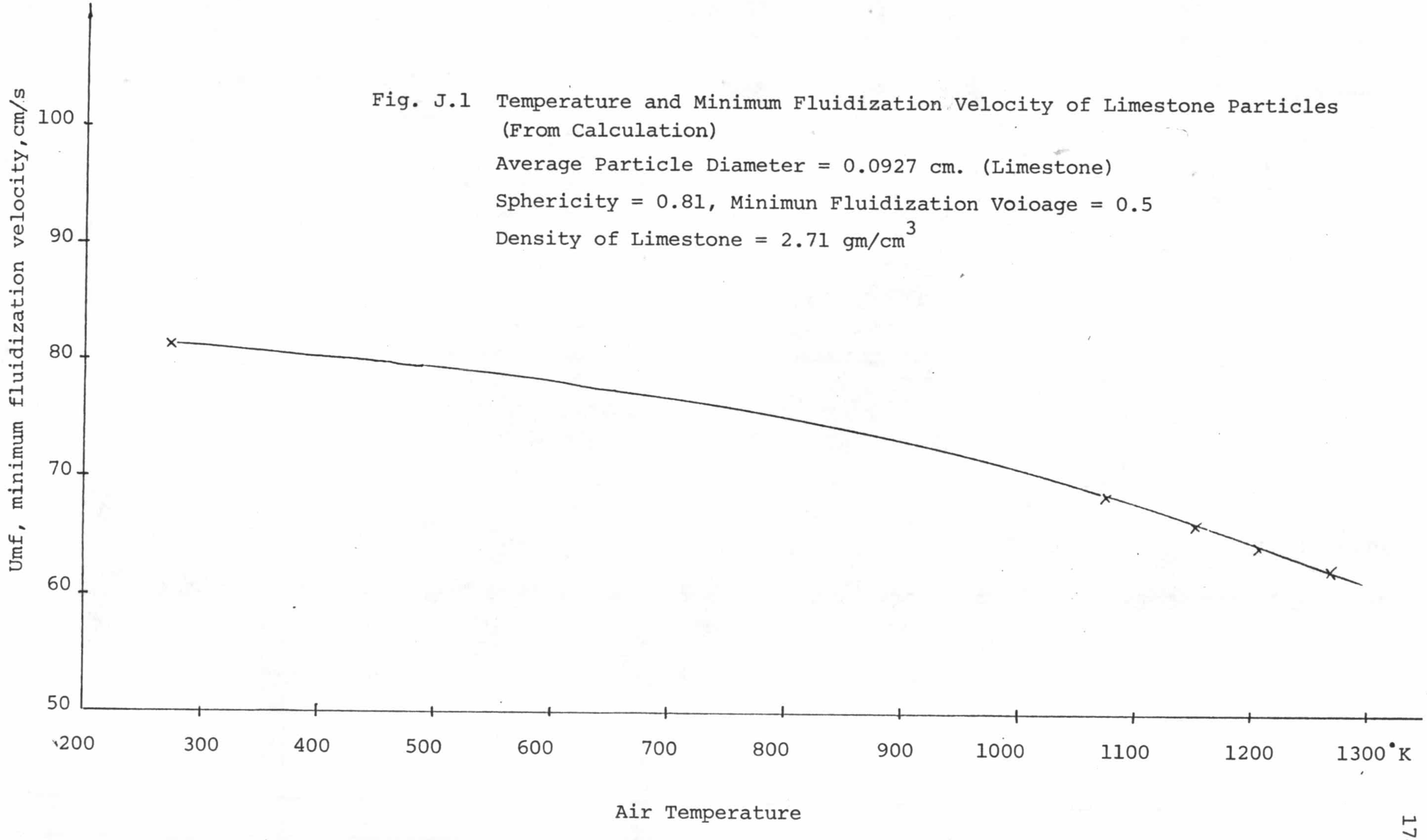


Fig. J.1 Temperature and Minimum Fluidization Velocity of Limestone Particles (From Calculation)

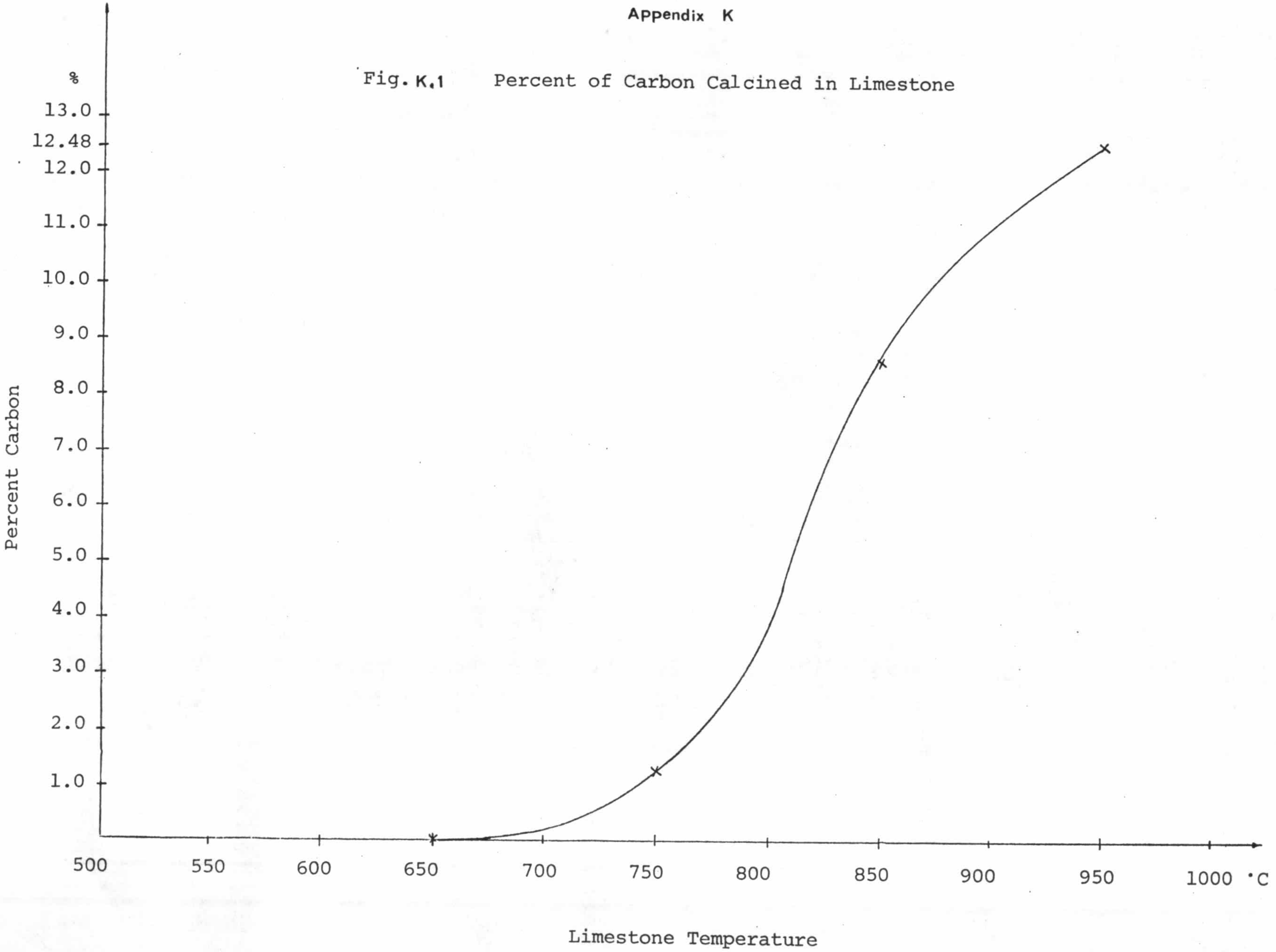
Average Particle Diameter = 0.0927 cm. (Limestone)

Sphericity = 0.81, Minimun Fluidization Voioage = 0.5

Density of Limestone = 2.71 gm/cm^3

Appendix K

Fig. K.1 Percent of Carbon Calcined in Limestone



Appendix L

Approximate Heat Balance in the Combustor

The heat balance in the combustor can be estimated followingly.

Now an example of Calculation is shown

From data No. 3 of Table 6.1

average bed temperature = $\bar{T}_B$ = 995° C

average gas temperature = $\bar{T}_G$ = 418°C

inlet limestone temperature = 36°C

inlet lignite temperature = 30°C

inlet air temperature = 35°C

lignite feed rate = F_{ocl} = 1.13 gm/s

limestone feed rate = F_{ol} = 1.13 gm/s

specific heat of coal ash = 0.31 cal/gm°C

specific heat of limestone = 0.217 cal/gm°C

specific heat of air at $\bar{T}_G$ of 418°C = 0.26 cal/gm°C

heating value of lignite = 4166 cal/gm

air density at STP = ρ_g = 1.293×10^{-3} gm/cm^3

inlet air velocity = 376 an/s

ash content in lignite = 10 %

bed diameter = .15 cm

Inlet

If carbon is all combusted, heat will

be generated = 4166X1.13 cal/s

= 4708 cal/s

Outlet

Due to the specific heat of CO, CO_2, O_2 N_2 and air at the same temperature of 418°C is approximately the same.

Let the specific heat of outlet gas = 0.26 $\frac{cal}{gn^\circ C}$

heat accepted by outlet gas and limestone

$$=(418-35)X1.293X10^{-3}X\frac{273}{(273+418)}X376X\frac{}{4}X15X15$$

$$X0.26+(995-30)X1.13X0.217$$

$$= 3617 \quad cal/s$$

heat accepted by coal ash

$$= 1.13X0.10X(995-30)X0.31$$

$$= 34$$

hence heat accepted by outlet solids and gas

$$= 365 \quad cal/s$$

the calculated outlet heat is less than the inlet potential heat = 4708-3651 = 1057 cal/s

This uncalculated heat can be lost by other way such as the conduction of heat through the refractory and stainless steel of combustor, heat consumed by the endothermic reaction of

$$CO_2+C \longrightarrow 2CO$$

Appendix M

Some Constant Values

density of limestone ± 2.75 gm/cm^3

density of lignite = 1.50 gm/cm^3

density of air at STP = $1.293x10^{-3}$ gm/cm^3

universal gas constant = 82.06 $atm\text{-}cm^3/gmole{\cdot}K$

= 1.987 cal/gmole·K

gravitational accelation = 980 cm/s^2

sphericity of lime = 0.77

void fraction of limestone of 0.5 mm. in average particles diameter

= 0.513

void fraction of limestone of 1.0 mm in average particles diameter

= 0.45

inlet oxygen concentration = $1.28x10^{-3}$ $kmole/m^3$ at 1173·K and 1 atm.

= $2.18x10^{-6}$ $gmole/cm^3$ at 1173·K and 1 atm.

Appendix N

Output from Computer Simulation

From chapter 7 the graphs of effects of operating variables on carbon combustibles loss are plotted from the following data:

N.1 The Effect of Superficial Velocity on Carbon Combustibles Loss

Let $\frac{W}{W_B}$ = 0.1 %, C_{Ab} = 91.3 % C_{Ao}, $\bar{T}_B$ = constant = 1173°K , F_o = constant = 1.13 gm/s

$\bar{d}_{p\ limestone}$ = 0.1 cm, $\bar{d}_{plignite}$ = 0.24 cm, ρ_g =0.28x10^{-3} gm/cm^3, μ_g = 4.6x10^{-4} gm/cm-s

D_A = 2.08 cm^3/s C_{Ao} = 2.18x10^{-6} gmole/cm^3, U_{mf} = 65 cm/s at 1173°K, L_f = 30 cm

d_t = 15 cm, limestone : lignite = 1:1 by weight

NO	U_o cm/s	X	C_{Ap} gmole/cm^3	$\bar{t}$ s	W gm	F_1 gm/s	F_2 gm/s	η %	EXC %
1	200	3.7	1.98x10^{-6}	6.2	7.1	0.17	0.03	82.7	91.5
2	250	2.9	1.97x10^{-6}	6.1	6.9	0.13	0.03	86.2	139.4
3	300	1.8	1.95x10^{-6}	6.0	6.8	0.10	0.03	89.0	187.3
4	350	1.7	1.948x10^{-6}	5.9	6.7	0.05	0.04	92.2	235.1
5	400	1.5	1.94x10^{-6}	5.8	6.7	0.02	0.05	94.2	283.0
6	450	1.4	1.92x10^{-6}	5.7	6.4	0.00	0.07	93.7	330.9

W = weight of burning char in the bed

W_B = weight of bed material

C_{Ab} = concentration of oxygen in bubble

C_{Ao} = concentration of oxygen in inlet air

C_{Ap} = concentration of oxygen in particulate phase

$\bar{T}_B$ = average bed temperature

F_o = coal feed rate

F_1 = overflow rate

F_2 = elutriation rate

U_o = superficial velocity

X = number of transfer unit

$\bar{t}$ = average residence time of burning char particles in bed

η = combustion efficiency

EXC = excess air

$\bar{d}_{p\ limestone}$ = average particles diameter of limestone

$\bar{d}_{p\ coal}$ = average particles diameter of coal

ρ_g = density of air

μ_g = viscousity of air

D_A = diffusivity of oxygen in air

U_{mf} = minimum fluidizing velocity

L_f = expanded bed height

d_t = bed diameter

N. 2 The Effect of Bed Temperature on Carbon Combustibles Loss

Let $\frac{W}{W_B} = 0.1$ %, $C_{Ab} = 91.3$ % C_{Ao}, U_o = constant = 350 cm/s, F_o = 1.13 gm/s

L_f = 30 cm, d_t = 15 cm, $\bar{d}_p$ limestone = 0.1 cm, $\bar{d}_p$ lignite = 0.74 cm

limestone: lignite = 1:1 by weight

NO.	$\bar{T}_B$ °K	D_A cm^3/s	μ_g gm/cm-s	ρ_g gm/cm^3	U_{mf} cm/s	X	C_{Ao} gmole/cm^3	C_{Ab} gmole/cm^3	C_{Ap} gmole/cm^3	W gm	F_1 gm/s	F_2 gm/s	η %	EXC %
1	1273	2.39	4.7×10^{-4}	2.6×10^{-4}	62	1.63	2.0×10^{-6}	1.8×10^{-6}	1.8×10^{-6}	6.6	0.04	0.04	93.3	209
2	1223	2.24	4.7×10^{-4}	2.7×10^{-4}	64	1.67	2.1×10^{-6}	1.9×10^{-6}	1.9×10^{-6}	6.6	0.05	0.04	92.0	221
3.	1173	2.09	4.5×10^{-4}	2.8×10^{-4}	65	1.71	2.2×10^{-6}	2.0×10^{-6}	2.0×10^{-6}	6.5	0.06	0.04	91.0	235
4	1123	1.95	4.4×10^{-4}	2.9×10^{-4}	67	1.76	2.3×10^{-6}	2.1×10^{-6}	2.0×10^{-6}	6.5	0.07	0.04	90.5	250
5	1073	1.81	4.3×10^{-4}	3.1×10^{-4}	68	1.78	2.4×10^{-6}	2.2×10^{-6}	2.1×10^{-6}	6.5	0.09	0.04	89.1	266
6	1023	1.67	4.1×10^{-4}	3.2×10^{-4}	70	1.83	2.5×10^{-6}	2.3×10^{-6}	2.2×10^{-6}	6.4	0.10	0.04	88.4	274

N.3 The Effect of Coal Feed Rate on Carbon Combustibles Loss

Let $\frac{W}{W_B} = 0.1$, $C_{Ab} = 91.3\ \%\ C_{Ao}$, $\bar{T}_B$ = constant = 1173°K , U_o = constant = 400 cm/s

$\bar{d}_p$ limestons = 0.1 cm, $\bar{d}_p$ lignite = 0.24 cm, $\rho_g = 0.28\text{x}10^{-3}$, $\mu_g = 4.6\text{x}10^{-4}$ gm/cm-s, d_t = 15 cm

D_A = 2.08 cm^3/s, $C_{Ao} = 2.18\text{x}10^{-6}$ gmole/cm^3, U_{mf} = 6.5 cm/s at 1173°K, L_f 30 cm

limestone : lignite = 1:1 by weight

NO.	F_o gm/s	X	C_{Ap} gmole/cm^3	W gm	$\bar{t}$ s	F_1 gm/s	F_2 gm/s	η %	EXC %
1	0.5	1.5	$1.94\text{x}10^{-6}$	2.87	13.0	0.00	0.03	94.8	767
2	1.0	"	"	5.77	6.6	0.00	0.05	95.4	333
3	1.5	"	"	6.56	4.4	0.43	0.03	69.3	188
4	2.0	"	"	"	3.3	0.99	0.01	50.4	117
5	2.5	"	"	"	2.6	1.53	0.00	40.0	73
6	3.0	"	"	"	2.2	2.04	0.00	33.5	44

Bibliography

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