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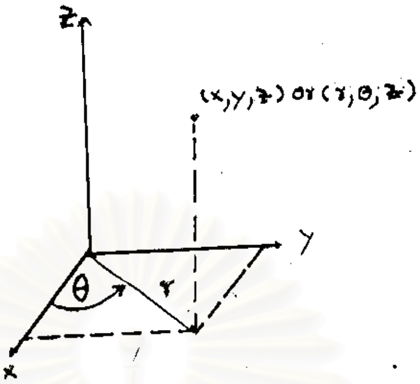
Appendix A1

Cartesian and cylindrical coordinate transformation



FigureA-1
Cylindrical coordinates

In cylindrical coordinates, instead of designating the coordinates of a point by *x, y, z,* we locate the point by giving the values of *r, θ, z.* these coordinates are shown in Fig. A–1. They are related to the rectangular coordinates by

$$x = r\cos\theta \quad (A1.1) \qquad r = +\sqrt{x^2 + y^2} \quad (A1.4)$$

$$y = r\sin\theta \quad (A1.2) \qquad \theta = \arctan(y/x) \quad (A1.5)$$

$$z = z \quad (A1.3) \qquad z = z \quad (A1.6)$$

To convert derivatives of scalars with respect to *x, y, z* into derivatives with respect to *r, θ, z,* the "Chain rule" of partial differentiation[1] is used. The derivative operators are readily found to be related as follows:

$$\frac{\partial}{\partial x} = (\cos\theta)\frac{\partial}{\partial r} + \left(-\frac{\sin\theta}{r}\right)\frac{\partial}{\partial \theta} + (0)\frac{\partial}{\partial z} \qquad (A1.7)$$

$$\frac{\partial}{\partial y} = (\sin\theta)\frac{\partial}{\partial r} + \left(\frac{\cos\theta}{r}\right)\frac{\partial}{\partial \theta} + (0)\frac{\partial}{\partial z} \qquad (A1.8)$$

$$\frac{\partial}{\partial z} = (0)\frac{\partial}{\partial r} + (0)\frac{\partial}{\partial \theta} + (1)\frac{\partial}{\partial z} \qquad (A1.9)$$

---

[1] For example, for a scalar function $\phi(x,y,z) = \Phi(r,\theta,z)$

$$\left(\frac{\partial\phi}{\partial x}\right)_{y,z} = \left(\frac{\partial r}{\partial x}\right)_{y,z}\left(\frac{\partial\Phi}{\partial r}\right)_{\theta,z} + \left(\frac{\partial\theta}{\partial x}\right)_{y,z}\left(\frac{\partial\Phi}{\partial\theta}\right)_{r,z} + \left(\frac{\partial z}{\partial x}\right)_{y,z}\left(\frac{\partial\Phi}{\partial z}\right)_{r,\theta}$$

With these relations, derivatives of any scalar functions (including, of course, components of vectors and tensors) with respect to *x*, *y*, and z can be expressed in terms of derivatives with respect to *r*, *θ*, and *z*.

Having discussed the interrelationship of the coordinates and derivatives in the two coordinate systems, we now turn to the relation between the unit vectors. We begin by noting that the unit vectors $\delta_x, \delta_y, \delta_z$ (or $\delta_1, \delta_2, \delta_3$ as we have been calling them) are independent of position—that is, independent of *x*, *y*, *z*. In cylindrical coordinates the unit vectors δ_r and δ_θ will depend on position. The unit vector δ_r is a vector of unit length in the direction of increasing *r*; the unit vector δ_θ is a vector of unit length in the direction of increasing *θ*. Clearly as the point *P* is moved around on the *xy*-plane, the directions of δ_r and δ_θ change. Elementary trigonometrical arguments lead to the following relations:

$$\delta_r = (\cos\theta)\delta_x + (\sin\theta)\delta_y + (0)\delta_z \qquad \text{(A1.10)}$$

$$\delta_\theta = (-\sin\theta)\delta_x + (\cos\theta)\delta_y + (0)\delta_z \qquad \text{(A1.11)}$$

$$\delta_z = (0)\delta_x + (0)\delta_y + (1)\delta_z \qquad \text{(A1.12)}$$

These may be solved for δ_x, δ_y, and δ_z to give:

$$\delta_x = (\cos\theta)\delta_r + (-\sin\theta)\delta_\theta + (0)\delta_z \qquad \text{(A1.13)}$$

$$\delta_x = (\sin\theta)\delta_r + (\cos\theta)\delta_\theta + (0)\delta_z \qquad \text{(A1.14)}$$

$$\delta_z = (0)\delta_r + (0)\delta_\theta + (1)\delta_z \qquad \text{(A1.15)}$$

APPENDIX A2
Thomas's Algorithm (TriDiagonal Metrix Algorithm (TDMA))

Consider a system of M linear, simulteneous algebraic equations with M unknowns, $u_1, u_2, u_3 \ldots, u_M$ given in the form below.

$$d_1u_1 + a_1u_2 = c_1 \qquad (A2.1)$$

$$b_2u_1 + d_2u_2 + a_2u_3 = c_2 \qquad (A2.2)$$

$$b_3u_2 + d_3u_3 + a_3u_4 = c_3 \qquad (A2.3)$$

$$\ddots \quad \ddots \quad \ddots$$

$$b_{M-1}u_{M-2} + d_{M-1}u_{M-1} + a_{M-1}u_M = c_{M-1} \qquad (A2.4)$$

$$b_Mu_{M-1} + d_Mu_M = c_M \qquad (A2.5)$$

This is tridiagonal system ,i.e., a system of equations with finite coefficients only on the main diagonal (the d_i's), the lower diagonal (the b_i's), and the upper diagonal (the a_i's).

A standard method for solving a system of linear , algebraic equations is gaussian elimination. Thomas' algorithm is essentially the result of applying gaussian eliminarion to the tridiagonal system of equations. Specifically, we wish to eliminate the lower-diagonal term (the b_i's), as follows. Multiply Equation (A2.1) by b_2.

$$b_2d_1u_1 + b_2a_1u_2 = c_1b_2 \qquad (A2.6)$$

Multiply equation (A2.2) by d_1

$$d_1b_2u_1 + d_1d_2u_2 + d_1a_2u_3 = c_2d_1 \qquad (A2.7)$$

Subtract Equation (A2.6) from (A2.7)

$$\left(d_1d_2 - b_2a_1\right)u_2 + d_1a_2u_3 = c_2d_1 - c_1b_2 \qquad (A2.8)$$

Divide equation (A2.8) by d1.

$$\left(d_2 - \frac{b_2a_1}{d_1}\right)u_2 + a_2u_3 = c_2 - \frac{c_2b_2}{d_1} \qquad (A2.9)$$

Note that equation (A2.9) no longer has a lower-diagonal term - it has been eliminated by the multiplication and subtraction process above. Denoting some of the coefficients in equation (A2.9) as follows:

$$d_2' = \left(d_2 - \frac{b_2a_1}{d_1}\right) \qquad (A2.10)$$

and

$$c_2' = c_2 - \frac{c_2 b_2}{d_1} \tag{A2.11}$$

Then equation (A2.9) can be written in the simpler form as

$$d_2' u_2 + a_2 u_3 = c_2' \tag{A2.12}$$

Continue further elimination process by multiplying (A2.12) by b_3 :

$$b_3 d_2' u_2 + b_3 a_2 u_3 = b_3 c' \tag{A2.13}$$

Multiply equation (A2.3) by d_2'

$$d_2' b_3 u_2 + d_2' d_3 u_3 + d_2' a_3 u_4 = d_2' c_3 \tag{A2.14}$$

Subtract Equation (A2.13) from (A2.14)

$$\left(d_2' d_3 - b_3 a_2\right) u_3 + d_2' a_3 u_4 = d_2' c_3 - b_3 c_2' \tag{A2.15}$$

Divided equation (A2.15) by d'_2

$$\left(d_3 - \frac{b_3 a_2}{d_2'}\right) u_3 + a_3 u_4 = c_3 - \frac{b_3 c_2'}{d_2'} \tag{A2.16}$$

Note that equation (A2.16) no longer has a lower -diagonal term ; it has been eliminated in the same fashion as was the case for equation (A2.9)

It should be noted that equation (A2.9) can be viewed as obtained from equation (A2. 2) bby dropping the first term (the term involving u_1), replacing the main-diagonal coefficient with

$$d_2 - \frac{b_2 a_1}{d_1} \tag{A2.17}$$

instead of d_2, keeping the third term unchanged ($a_2 u_3$), and replacing the term on the right hand side of equation by

$$c_2 - \frac{b_2 a_1}{d_1} \tag{A2.18}$$

instead of c_2. The exactly same pattern can be seen if comparing equation (A2.16) and (A2.3), where in equation (A2.3) the first term is dropped ($b_3 u_2$), the diagonal coefficient is replaced by

$$d_3 - \frac{b_3 a_2}{d_2'} \tag{A2.19}$$

The third term remains unchanged (a_3u_4), and right hand side is replaced by

$$c_3 - \frac{c_2' b_3}{d_2'} \tag{A2.20}$$

The pattern is clear. Compare the form given by (A2.17) and (A2.19); they are the same. Compare the forms given by (A2.18) and (A2.20); they are the same. Starting at the top of equation system represented by equation (A2.1) through (A2.5), leaving equation (A2.1) alone and drop the first term of the following equation, replace the coefficient of main-diagonal term by

$$d_i' = d_i - \frac{b_i a_{i-1}}{d_{i-1}'} \qquad i = 2,3,\ldots,M \tag{A2.21}$$

and replace the term on the right hand side of the equation by

$$c_i' = c_i - \frac{c_{i-1}' b_i}{d_{i-1}'} \qquad i = 2,3,\ldots,M \tag{A2.22}$$

$$\begin{array}{lllll}
d_1u_1 + a_1u_2 & & & & = c_1 \\
 & d_2'u_2 + a_2u_3 & & & = c_2' \\
 & & d_3'u_3 + a_3u_4 & & = c_3' \\
 & & \ddots \quad \ddots & & \\
 & & & d_{M-1}'u_{M-1} + a_{M-1}u_M & = c_{M-1}' \qquad (A2.23) \\
 & & & d_M'u_M & = c_M' \qquad (A2.24)
\end{array}$$

Examining the above system of equation, it can be seen that the last equation (A2.24) contain only one unknown, namely, u_M; hence

$$u_M = \frac{c_M'}{d_M'} \tag{A2.25}$$

The solution of the remaining unknown is obtained by working upward in the above system. For example, after u_M is obtained from equation (A2.25), the value of u_{M-1} can be found from equation (A2.23) as

$$u_{M-1} = \frac{c_{M-1}' - a_{M-1}u_M}{d_{M-1}'} \tag{A2.26}$$

Indeed, the equation (A2.26) can be replaced by the general formula

$$u_i = \frac{c_i' - a_i u_{i+1}}{d_i'} \qquad \text{(A2.27)}$$

for the calculation of u_i where u_{i+1} has already calculated from the previous application of equation (A2.27).

In summary, Thomas' algorithm is as follows. Given a system of linear, simulteneous, algebraic equations in tridiagonal form represented by equation (A2.1), the first step is to change this system into an upper bidiagonal form by dropping the first term in each equation (involving b_i's), replacing the coefficient of the main diagonal term by equation (A2.21), and replacing the right hand side with equation (A2.22). This will result in last equation in the equation in the system in having only one unknown , namely, u_M. Solve for u_M from equation (A2.25). Then, all other unknowns are found in sequence from equation(A2.27), starting with $u_i = u_{M-1}$ and ending with $u_i = u_1$.

Appendix A3
Partial Elimination Algorithm (PEA)

Partial Elimination Algorithm (PEA) is a device for accelerating convergence in situation inwhich sets of multiphase finite volume equation are tightly coupled.

Consider two phase flow equation for v_1 and v_2 velocity of the two phases at the same grid point, can be written:

$$a_1u_1 = b(v_2 - v_1) + c_1 \qquad (A3.1)$$

$$a_2u_2 = b(v_1 - v_2) + c_2 \qquad (A3.2)$$

Where b express interphase momentum transfer and a's and c's express all other terms.

If arranged in usual form for numerical solution, these equations appear as

$$v_1 = bv_2 + \frac{c_1}{(b + a_1)} \qquad (A3.3)$$

$$v_2 = bv_1 + \frac{c_2}{(b + a_2)} \qquad (A3.4)$$

If successive iteration -substitution is employed for solution.

1. v_2 is guessed
2. v_1 is computed from equation (A3.3) and put in equation (A3.4)
3. v_2 is computed from equation (A3.4) and put in equation (A3.3)
4. v_1 is computed from equation (A3.3) and put in equation (A3.4)

and so on until convergence

Suppose b is very large as when particle is small, then the equation become $v_1=v_2$; $v_2=v_1$. So, succesive iteration leave the value unchanged. Even in moderate value of b ,when this procedure is employed, may entailed very slow convergence and therefore excessive computer time.

The first step of PEA operation is elimination of v_2 from equation (A3.3) by substitute right-hand side term of equation (A3.4) in to (A3.3), and v_1 is then eliminated from equation (A3.4) by substitute right-hand side term of equation (A3.4) in to (A3.3) there results:

$$v_1 = \frac{\left(c_1 + \frac{\left(c_1 + c_2\right)b}{a_2}\right)}{\left(a_1 + \frac{\left(a_1 + a_2\right)b}{a_1}\right)} \tag{A3.5}$$

$$v_2 = \frac{\left(c_2 + \frac{\left(c_1 + c_2\right)b}{a_1}\right)}{\left(a_2 + \frac{\left(a_1 + a_2\right)b}{a_1}\right)} \tag{A3.6}$$

If now b become very large, these reduce to

$$v_1 = \frac{\left(c_1 + c_2\right)}{\left(a_1 + a_2\right)} \tag{A3.7}$$

$$v2 = \frac{\left(c_1 + c_2\right)}{\left(a_1 + a_2\right)} \tag{A3.8}$$

v_1 and v_2 tend to have the same value but not to each other previous value. Convergence now proceed rapidly .

Appendix B1

Q1 file of particle shear stress excluded of 200 μm particle in fully developed flow

```
 TALK=T;RUN( 1, 1);VDU=VGAMOUSE

TEXT(2-PHASE TURBULENT AIR-SOLIDS PIPE FLOW
TITLE
 DISPLAY
  The case considered is 2-phase solids-laden turbulent vertical
  flow of air in a pipe, as studied experimentally by Tsuji et
  al [J.Fluid Mech, Vol.139, p417, 1984]. The calculation is
  performed with the parabolic option, and for testing purposes
  the calculation is terminated after 10 forward steps. However,
  for comparison with data the calculation should be carried out
  until the flow is fully developed, i.e. 70 diameters downstream.
  The calculation may be made with the standard k-e model, or
  alternatively with the Chen-Wood or Mostafa-Mongia k-e variants
  which allow for gas turbulence modulation due to the presence of
  particles. The pipe Reynolds number is 3E4, the density ratio
  is 866, the particle mass-flow loading may be 1.0 or 2.1, and
  the particle diameter is 200 microns. The task is to calculate
  the fully-developed vertical velocity profiles for comparison
  with the measured profiles.
 ENDDIS
CHAR(CTURB);INTEGER(JRUN,NSTEP)
MESG( Enter the required turbulence-modulation option;
MESG( default NONE
MESG( The options are:
MESG(  MOST  - Mostafa-Mongia k-e modulation sources
MESG(  CHEN  - Chen-Wood      k-e modulation sources
MESG(  NONE  - Standard k-e model
MESG(
IF(:CTURB:.NE.MOST.AND.:CTURB:.NE.CHEN.AND.:CTURB:.NE.NONE)THEN
READVDU(CTURB,CHAR,NONE)
ENDIF
REAL(RHOS,RHOG,EMUGAS,RGAS,RSOL,TKEIN,EPSIN,FLOWG,FLOWS)
REAL(VGAS,VSOL,DIAM,GRAD,PLEN,DIAMS,REY,GRAVAC,MLOAD)
RHOS=1020.;GRAVAC=-9.81;DIAM=0.0305;RHOG=1.178;GRAD=0.5*DIAM
MESG( Enter JRUN: default =1
MESG(        =1 solids-to-air mass-flow ratio=1.0
MESG(        =2 solids-to-air mass-flow ratio=2.1
READVDU(JRUN,INT,1)
IF(JRUN.EQ.1) THEN
 + MLOAD=1.0;REY=3.E4;PLEN=70.*DIAM;NSTEP=70
ELSE
+ MLOAD=2.1;REY=2.9427E4;PLEN=70.*DIAM;NSTEP=70
ENDIF
```

```
RSOL=MLOAD*RHOG/RHOS;RGAS=1.0-RSOL;EMUGAS=1.868E-5
VGAS=REY*EMUGAS/(RHOG*DIAM);VSOL=VGAS
  *** specify mean particle diameter
DIAMS=200.E-6
   GROUP 1. Run title and other preliminaries
   GROUP 2. Transience; time-step specification
PARAB=T
   GROUP 3. X-direction grid specification
CARTES=F;XULAST=0.1;NX=1
   GROUP 4. Y-direction grid specification
GRDPWR(Y,25,GRAD,1.0)
   GROUP 5. Z-direction grid specification
NZ=70
  NZ=NSTEP
GRDPWR(Z,NZ,NZ*PLEN/NSTEP,1.0)
   GROUP 6. Body-fitted coordinates or grid distortion
   GROUP 7. Variables stored, solved & named
ONEPHS=F;SOLVE(P1,V1,V2,W1,W2,R1,R2);TURMOD(KEMODL)
STORE(CFIP,ENUT,CD,REYN)
   GROUP 8. Terms (in differential equations) & devices
   GROUP 9. Properties of the medium (or media)
RHO1=RHOG;RHO2=RHOS
FLOWG=RHOG*RGAS*VGAS;FLOWS=RHOS*RSOL*VSOL;ENUL=EMUGAS/R
HOG
TKEIN=(0.05*VGAS)**2;EPSIN=0.1643*TKEIN**1.5/(0.1*GRAD)
PRNDTL(V2)=1.E10;PRNDTL(W2)=1.E10;PRT(V2)=1.E10;PRT(W2)=1.E10
   GROUP 10. Inter-phase-transfer processes and properties
CFIPS=GRND7;CFIPA=1.E-3;RLOLIM=1.E-6;CFIPB=DIAMS
   GROUP 11. Initialization of variable or porosity fields
FIINIT(W1)=VGAS;FIINIT(W2)=VSOL;FIINIT(R1)=RGAS;FIINIT(R2)=RSOL
   GROUP 12. Unused
   GROUP 13. Boundary conditions and special sources
  ** inlet boundary
INLET(IN,LOW,1,NX,1,NY,1,1,1,1)
VALUE(IN,P1,FLOWG);VALUE(IN,W1,VGAS)
VALUE(IN,P2,FLOWS);VALUE(IN,W2,VSOL)
VALUE(IN,KE,TKEIN);VALUE(IN,EP,EPSIN)
  ** gravity
PATCH(GRAVITY,PHASEM,1,NX,1,NY,1,NZ,1,1)
COVAL(GRAVITY,W1,FIXFLU,GRAVAC);COVAL(GRAVITY,W2,FIXFLU,GRA
VAC)
  ** wall boundary
WALL(NWALL,NORTH,1,NX,NY,NY,1,NZ,1,1)
  ** turbulence-modulation sources
CASE :CTURB: OF
WHEN NONE,4
+ MESG(No turbulence modulation sources
WHEN MOST,4
+ MESG(Mostafa-Mongia turbulence-modulation sources
```

```
+ PATCH(KEDISP,CELL,1,NX,1,NY,1,NZ,1,LSTEP);STORE(TE,TP)
+ COVAL(KEDISP,KE,GRND1,ZERO);COVAL(KEDISP,EP,GRND1,ZERO)
WHEN CHEN,4
+ MESG(Chen-Wood turbulence-modulation sources
+ PATCH(KEDISP,CELL,1,NX,1,NY,1,NZ,1,LSTEP);STORE(TE,TP)
+ COVAL(KEDISP,KE,GRND2,ZERO);COVAL(KEDISP,EP,GRND2,ZERO)
ENDCASE
   GROUP 14. Downstream pressure for PARAB=.TRUE.
   GROUP 15. Termination of sweeps
LITHYD=16;SELREF=T;RESFAC=0.01
   GROUP 16. Termination of iterations
   GROUP 17. Under-relaxation devices
RELAX(V1,LINRLX,0.4);RELAX(V2,LINRLX,0.4)
RELAX(W1,LINRLX,0.5);RELAX(W2,LINRLX,0.5)
RELAX(R1,LINRLX,0.3);RELAX(R2,LINRLX,0.3)
RELAX(KE,LINRLX,0.3);RELAX(EP,LINRLX,0.3)
   GROUP 18. Limits on variables or increments to them
VARMIN(W1)=1.E-10;VARMIN(W2)=1.E-10
VARMIN(R1)=1.E-10;VARMIN(R2)=1.E-10
   GROUP 19. Data communicated by satellite to GROUND
   GROUP 20. Preliminary print-out
   GROUP 21. Print-out of variables
NYPRIN=1;NZPRIN=70;ITABL=3
   GROUP 22. Spot-value print-out
IYMON=NY-2;TSTSWP=LITHYD;NPLT=4;IDISPA=NSTEP
   GROUP 23. Field print-out and plot control
   GROUP 24. Dumps for restarts
 LIBREF=219
STOP
```

Appendix B2

Q1 file of Particle shear stress term included 500 μm fully developed flow

```
TALK=T;RUN( 1, 1);VDU=VGAMOUSE

TEXT(2-PHASE TURBULENT AIR-SOLIDS PIPE FLOW
TITLE
 DISPLAY
  Particle shear stress term is included via PRT (W2) = 1.697
  The pipe Reynolds number is1.53E4, the density ratio
  is 866, the particle mass-flow loading may be 1.1 or 2.0, and
  the particle diameter is 500 microns. The task is to calculate
  the fully-developed vertical velocity profiles for comparison
  with the measured profiles.In order to be sure that the fully
  developed is obtained,the particle inlet velocity is assume
  to be equal to air velocity.

 ENDDIS
CHAR(CTURB);INTEGER(JRUN,NSTEP)
MESG( Enter the required turbulence-modulation option;
MESG( default NONE
MESG( The options are:
MESG(  MOST  - Mostafa-Mongia k-e modulation sources
MESG(  CHEN  - Chen-Wood     k-e modulation sources
MESG(  NONE  - Standard k-e model
MESG(
IF(:CTURB:.NE.MOST.AND.:CTURB:.NE.CHEN.AND.:CTURB:.NE.NONE)THEN
READVDU(CTURB,CHAR,NONE)
ENDIF
REAL(RHOS,RHOG,EMUGAS,RGAS,RSOL,TKEIN,EPSIN,FLOWG,FLOWS)
REAL(VGAS,VSOL,DIAM,GRAD,PLEN,DIAMS,REY,GRAVAC,MLOAD)
RHOS=1020.;GRAVAC=-9.81;DIAM=0.0305;RHOG=1.178;GRAD=0.5*DIAM
MESG( Enter JRUN: default =1
MESG(          =1 solids-to-air mass-flow ratio=1.1
MESG(          =2 solids-to-air mass-flow ratio=2.0
READVDU(JRUN,INT,1)
IF(JRUN.EQ.1) THEN
 + MLOAD=1.1;REY=1.531E4;PLEN=70.*DIAM;NSTEP=70
ELSE
 + MLOAD=2.0;REY=1.538E4;PLEN=70.*DIAM;NSTEP=70
ENDIF
RSOL=MLOAD*RHOG/RHOS;RGAS=1.0-RSOL;EMUGAS=1.868E-5
VGAS=REY*EMUGAS/(RHOG*DIAM);VSOL=VGAS
  *** specify mean particle diameter
DIAMS=500.E-6
   GROUP 1. Run title and other preliminaries
   GROUP 2. Transience; time-step specification
PARAB=T
   GROUP 3. X-direction grid specification
```

```
CARTES=F;XULAST=0.1;NX=1
   GROUP 4. Y-direction grid specification
GRDPWR(Y,25,GRAD,1.0)
   GROUP 5. Z-direction grid specification
NZ=70
  NZ=NSTEP
GRDPWR(Z,NZ,NZ*PLEN/NSTEP,1.0)
   GROUP 6. Body-fitted coordinates or grid distortion
   GROUP 7. Variables stored, solved & named
ONEPHS=F;SOLVE(P1,V1,V2,W1,W2,R1,R2);TURMOD(KEMODL)
STORE(CFIP,ENUT,CD,REYN)
   GROUP 8. Terms (in differential equations) & devices
   GROUP 9. Properties of the medium (or media)
RHO1=RHOG;RHO2=RHOS
FLOWG=RHOG*RGAS*VGAS;FLOWS=RHOS*RSOL*VSOL;ENUL=EMUGAS/R
HOG
TKEIN=(0.05*VGAS)**2;EPSIN=0.1643*TKEIN**1.5/(0.1*GRAD)
PRNDTL(V2)=1.E10;PRNDTL(W2)=1.E10;PRT(V2)=1.697;PRT(W2)=1.697
   GROUP 10. Inter-phase-transfer processes and properties
CFIPS=GRND7;CFIPA=1.E-3;RLOLIM=1.E-6;CFIPB=DIAMS
   GROUP 11. Initialization of variable or porosity fields
FIINIT(W1)=VGAS;FIINIT(W2)=VSOL;FIINIT(R1)=RGAS;FIINIT(R2)=RSOL
   GROUP 12. Unused
   GROUP 13. Boundary conditions and special sources
 ** inlet boundary
INLET(IN,LOW,1,NX,1,NY,1,1,1,1)
VALUE(IN,P1,FLOWG);VALUE(IN,W1,VGAS)
VALUE(IN,P2,FLOWS);VALUE(IN,W2,VSOL)
VALUE(IN,KE,TKEIN);VALUE(IN,EP,EPSIN)
 ** gravity
PATCH(GRAVITY,PHASEM,1,NX,1,NY,1,NZ,1,1)
COVAL(GRAVITY,W1,FIXFLU,GRAVAC);COVAL(GRAVITY,W2,FIXFLU,GRA
VAC)
 ** wall boundary
WALL(NWALL,NORTH,1,NX,NY,NY,1,NZ,1,1)
 ** turbulence-modulation sources
CASE :CTURB: OF
WHEN NONE,4
+ MESG(No turbulence modulation sources
WHEN MOST,4
+ MESG(Mostafa-Mongia turbulence-modulation sources
+ PATCH(KEDISP,CELL,1,NX,1,NY,1,NZ,1,LSTEP);STORE(TE,TP)
+ COVAL(KEDISP,KE,GRND1,ZERO);COVAL(KEDISP,EP,GRND1,ZERO)
WHEN CHEN,4
+ MESG(Chen-Wood turbulence-modulation sources
+ PATCH(KEDISP,CELL,1,NX,1,NY,1,NZ,1,LSTEP);STORE(TE,TP)
+ COVAL(KEDISP,KE,GRND2,ZERO);COVAL(KEDISP,EP,GRND2,ZERO)
ENDCASE
   GROUP 14. Downstream pressure for PARAB=.TRUE.
```

```
   GROUP 15. Termination of sweeps
LITHYD=16;SELREF=T;RESFAC=0.01
   GROUP 16. Termination of iterations
   GROUP 17. Under-relaxation devices
RELAX(V1,LINRLX,0.4);RELAX(V2,LINRLX,0.4)
RELAX(W1,LINRLX,0.5);RELAX(W2,LINRLX,0.5)
RELAX(R1,LINRLX,0.3);RELAX(R2,LINRLX,0.3)
RELAX(KE,LINRLX,0.3);RELAX(EP,LINRLX,0.3)
   GROUP 18. Limits on variables or increments to them
VARMIN(W1)=1.E-10;VARMIN(W2)=1.E-10
VARMIN(R1)=1.E-10;VARMIN(R2)=1.E-10
   GROUP 19. Data communicated by satellite to GROUND
   GROUP 20. Preliminary print-out
   GROUP 21. Print-out of variables
NYPRIN=1;NZPRIN=70;ITABL=3
   GROUP 22. Spot-value print-out
IYMON=NY-2;TSTSWP=LITHYD;NPLT=4;IDISPA=NSTEP
   GROUP 23. Field print-out and plot control
   GROUP 24. Dumps for restarts
 LIBREF=219
STOP
```

Appendix B3

Q1 file of pressure drop simulation of Tsuji et al. [1984]'s experiment

```
TALK=T;RUN( 1, 1);VDU=VGAMOUSE
TEXT(2-PHASE TURBULENT AIR-SOLIDS PIPE FLOW
TITLE
 DISPLAY
  Particle shear stress term is included via PRT (U2) = 1.697
  The pipe Reynolds number is 3E4,  the density ratio is 866,
  the particle mass-flow loading may be 3.00  ,for gas mean
  velocity 11.59. The particle diameter is 500 microns.The task
  is to calculate the vertical pressure profiles for comparison
  with the measured profiles.
 ENDDIS
CHAR(CTURB);INTEGER(JRUN,NSTEP)
MESG( Enter the required turbulence-modulation option;
MESG( default NONE
MESG( The options are:
MESG(  MOST  - Mostafa-Mongia k-e modulation sources
MESG(  CHEN  - Chen-Wood      k-e modulation sources
MESG(  NONE  - Standard k-e model
MESG(
IF(:CTURB:.NE.MOST.AND.:CTURB:.NE.CHEN.AND.:CTURB:.NE.NONE)THEN
READVDU(CTURB,CHAR,NONE)
ENDIF
REAL(RHOS,RHOG,EMUGAS,RGAS,RSOL,TKEIN,EPSIN,FLOWG,FLOWS)
REAL(VGAS,VSOL,VSLIP,DIAM,GRAD,PLEN,DIAMS,REY,GRAVAC,MLOAD)
RHOS=1020.;GRAVAC=-9.81;DIAM=0.0305;RHOG=1.178;GRAD=0.5*DIAM
MESG( Enter JRUN: default =1
MESG(          =1 solids-to-air mass-flow ratio=3.00
MESG(          =2 solids-to-air mass-flow ratio=3.00
READVDU(JRUN,INT,1)
IF(JRUN.EQ.1) THEN
 ** forward step-size is 1.0*diameter
+ MLOAD=3.00;REY=2.2292E4;PLEN=100.*DIAM;NSTEP=100
ELSE
 ** forward step-size is 1.0*diameter
+ MLOAD=3.00;REY=2.2292E4;PLEN=100.*DIAM;NSTEP=100
ENDIF
EMUGAS=1.868E-5
VGAS=REY*EMUGAS/(RHOG*DIAM);VSLIP=5.04
VSOL=VGAS-VSLIP
RSOL=MLOAD*(RHOG/RHOS)*(VGAS/VSOL);RGAS=1.0-RSOL
 *** specify mean particle diameter
DIAMS=500.E-6
  GROUP 1. Run title and other preliminaries
  GROUP 2. Transience; time-step specification
PARAB=T
  GROUP 3. X-direction grid specification
```

```
CARTES=F;XULAST=0.1;NX=1
   GROUP 4. Y-direction grid specification
GRDPWR(Y,25,GRAD,1.0)
   GROUP 5. Z-direction grid specification
NZ=100
  NZ=NSTEP
GRDPWR(Z,NZ,NZ*PLEN/NSTEP,1.0)
   GROUP 6. Body-fitted coordinates or grid distortion
   GROUP 7. Variables stored, solved & named
ONEPHS=F;SOLVE(P1,V1,V2,W1,W2,R1,R2);TURMOD(KEMODL)
STORE(CFIP,ENUT,CD,REYN)
   GROUP 8. Terms (in differential equations) & devices
   GROUP 9. Properties of the medium (or media)
RHO1=RHOG;RHO2=RHOS
FLOWG=RHOG*RGAS*VGAS;FLOWS=RHOS*RSOL*VSOL;ENUL=EMUGAS/R
HOG
TKEIN=(0.05*VGAS)**2;EPSIN=0.1643*TKEIN**1.5/(0.1*GRAD)
PRNDTL(V2)=1.E10;PRNDTL(W2)=1.E10;PRT(V2)=1.697;PRT(W2)=1.697
   GROUP 10. Inter-phase-transfer processes and properties
CFIPS=GRND7;CFIPA=1.E-3;RLOLIM=1.E-6;CFIPB=DIAMS
   GROUP 11. Initialization of variable or porosity fields
FIINIT(W1)=VGAS;FIINIT(W2)=VSOL;FIINIT(R1)=RGAS;FIINIT(R2)=RSOL
   GROUP 12. Unused
   GROUP 13. Boundary conditions and special sources
 ** inlet boundary
INLET(IN,LOW,1,NX,1,NY,1,1,1,1)
VALUE(IN,P1,FLOWG);VALUE(IN,W1,VGAS)
VALUE(IN,P2,FLOWS);VALUE(IN,W2,VSOL)
VALUE(IN,KE,TKEIN);VALUE(IN,EP,EPSIN)
 ** gravity
PATCH(GRAVITY,PHASEM,1,NX,1,NY,1,NZ,1,1)
COVAL(GRAVITY,W1,FIXFLU,GRAVAC);COVAL(GRAVITY,W2,FIXFLU,GRA
VAC)
 ** wall boundary
WALL(NWALL,NORTH,1,NX,NY,NY,1,NZ,1,1)
 ** turbulence-modulation sources
CASE :CTURB: OF
WHEN NONE,4
+ MESG(No turbulence modulation sources
WHEN MOST,4
+ MESG(Mostafa-Mongia turbulence-modulation sources
+ PATCH(KEDISP,CELL,1,NX,1,NY,1,NZ,1,LSTEP);STORE(TE,TP)
+ COVAL(KEDISP,KE,GRND1,ZERO);COVAL(KEDISP,EP,GRND1,ZERO)
WHEN CHEN,4
+ MESG(Chen-Wood turbulence-modulation sources
+ PATCH(KEDISP,CELL,1,NX,1,NY,1,NZ,1,LSTEP);STORE(TE,TP)
+ COVAL(KEDISP,KE,GRND2,ZERO);COVAL(KEDISP,EP,GRND2,ZERO)
ENDCASE
   GROUP 14. Downstream pressure for PARAB=.TRUE.
```

```
   GROUP 15. Termination of sweeps
LITHYD=16;SELREF=T;RESFAC=0.01
   GROUP 16. Termination of iterations
   GROUP 17. Under-relaxation devices
RELAX(V1,LINRLX,0.4);RELAX(V2,LINRLX,0.4)
RELAX(W1,LINRLX,0.5);RELAX(W2,LINRLX,0.5)
RELAX(R1,LINRLX,0.3);RELAX(R2,LINRLX,0.3)
RELAX(KE,LINRLX,0.3);RELAX(EP,LINRLX,0.3)
   GROUP 18. Limits on variables or increments to them
VARMIN(W1)=1.E-10;VARMIN(W2)=1.E-10
VARMIN(R1)=1.E-10;VARMIN(R2)=1.E-10
   GROUP 19. Data communicated by satellite to GROUND
   GROUP 20. Preliminary print-out
   GROUP 21. Print-out of variables
   GROUP 22. Spot-value print-out
IYMON=NY-2;TSTSWP=-1;
PATCH(DPDZ,PROFIL,1,1,1,1,1,NZ,1,1);PLOT(DPDZ,P1,0.0,1000.0)
IPROF=0;NCOLPF=4

   GROUP 23. Field print-out and plot control
   GROUP 24. Dumps for restarts
 LIBREF=219
STOP
```

Appendix B4

Q1 file of Uniform inlet configuration (Case A) simulation

```
 TALK=T;RUN( 1, 1);VDU=VGAMOUSE
TEXT(2-PHASE AIR-SOLIDS UNIFORM INLET AIRLIFT )
TITLE
 DISPLAY

   UNIFORM INLET AIRLIFT IS SIMULATED.Gas velocity is 16 m/s
   therefore pipe Reynold number is 201798.Particle diameter is
   500 micron enter into pipe at particle velocity=10.5 m/s and
   density ratio is (825/1.17).Solid loading ratio is 1.2.
   Particle shear stress term is included via PRT (U2) = 1.697
   PRT(R2)=0.7 is activated to include phase mass diffusion effect.
   Acceleration zone pressure,velocity and concentration is
   investigated.Elliptic computation is activated to determine
   result in acceleration domain.
 ENDDIS
REAL(RHOS,RHOG,EMUGAS,RGAS,RSOL,IRSOL,IRGAS,TKEIN,EPSIN,
FLOWG, FLOWS)
REAL(VGAS,VSOL,DIAM,GRAD,DIAMS,REY,GRAVAC,MLOAD)
RHOS=825.;GRAVAC=-9.81;DIAM=0.2;RHOG=1.178;GRAD=0.5*DIAM
 ** forward step-size is 1.0*diameter
MLOAD=1.25
EMUGAS=1.868E-5
VGAS=16.0
VSOL=10.5
REY=RHOG*DIAM*VGAS/EMUGAS
RSOL=MLOAD*(RHOG/RHOS)*(VGAS/VSOL);RGAS=(1.0-RSOL)
IRSOL=1.0*rsol;Irgas=1.0-Irsol
 ***mean particle diameter
DIAMS=500.E-6
   GROUP 1. Run title and other preliminaries
   GROUP 2. Transience; time-step specification
   GROUP 3. X-direction grid specification
CARTES=F;XULAST=0.1;NX=1
   GROUP 4. Y-direction grid specification
GRDPWR(Y,40,GRAD,0.40)
   GROUP 5. Z-direction grid specification
NZ=70
GRDPWR(Z,NZ,NZ*GRAD,1.0)
   GROUP 6. Body-fitted coordinates or grid distortion
   GROUP 7. Variables stored, solved & named
ONEPHS=F;SOLVE(P1,V1,V2,W1,W2,R2);TURMOD(KEMODL)
STORE(R1,CFIP,ENUT,CD,REYN)
   GROUP 8. Terms (in differential equations) & devices
   GROUP 9. Properties of the medium (or media)
RHO1=RHOG;RHO2=RHOS
```

```
TKEIN=(0.05*VGAS)**2;EPSIN=0.1643*TKEIN**1.5/(0.1*GRAD)
PRNDTL(V2)=1.E10;PRNDTL(W2)=1.E10;PRT(V2)=1.697;PRT(W2)=1.697
PRT(R2)=0.7
  GROUP 10. Inter-phase-transfer processes and properties
CFIPS=GRND7;CFIPA=1.E-3;RLOLIM=1.E-6;CFIPB=DIAMS
  GROUP 11. Initialization of variable or porosity fields
FIINIT(W1)=VGAS;FIINIT(W2)=VSOL
FIINIT(R1)=IRGAS;FIINIT(R2)=IRSOL
FIINIT(V2)=-1.e-3
  GROUP 12. Unused
  GROUP 13. Boundary conditions and special sources
 ** inlet boundary
INLET(IN,LOW,1,NX,1,NY,1,1,1,1)
VALUE(IN,P1,FLOWG);VALUE(IN,W1,VGAS)
VALUE(IN,P2,FLOWS);VALUE(IN,W2,VSOL)
 ** Outlet boundary
PATCH(OUTLET,HIGH,1,NX,1,NY,NZ,NZ,1,1)
COVAL(OUTLET,P1,1.0,0.0);COVAL(OUTLET,P2,1.0*RHOS/RHOG,0.0)
COVAL(OUTLET,V1,ONLYMS,0.0);COVAL(OUTLET,W1,ONLYMS,0.0)
COVAL(OUTLET,V2,ONLYMS,0.0);COVAL(OUTLET,W2,ONLYMS,0.0)
COVAL(OUTLET,KE,ONLYMS,0.0);COVAL(OUTLET,EP,ONLYMS,0.0)
 ** gravity
PATCH(GRAVITY,PHASEM,1,NX,1,NY,1,NZ,1,1)
COVAL(GRAVITY,W1,FIXFLU,GRAVAC);COVAL(GRAVITY,W2,FIXFLU,GRA
VAC)
 ** wall boundary
WALL(NWALL,NORTH,1,NX,NY,NY,1,NZ,1,1)
  GROUP 14. Downstream pressure for PARAB=.TRUE.
  GROUP 15. Termination of sweeps
LITHYD=20;LSWEEP=18
 **selref=t;resfac=0.00001
  GROUP 16. Termination of iterations
  GROUP 17. Under-relaxation devices
RELAX(V1,falsdt,3.E-2);RELAX(V2,falsdt,3.E-2)
RELAX(W1,falsdt,0.5);RELAX(W2,falsdt,0.5)
KELIN=3
RELAX(KE,linrlx,0.5);RELAX(EP,linrlx,0.5)
RELAX(P2,LINRLX,0.5)
  GROUP 18. Limits on variables or increments to them
VARMIN(W1)=1.E-10;VARMIN(W2)=1.E-10
VARMIN(R1)=1.E-10;VARMIN(R2)=1.E-10
  GROUP 19. Data communicated by satellite to GROUND
  GROUP 20. Preliminary print-out
echo=f
  GROUP 21. Print-out of variables
NYPRIN=1;NZPRIN=NZ/14;ITABL=2
  GROUP 22. Spot-value print-out
iymon=ny-2;IZMON=20;TSTSWP=-1.
 **PATCH(DPDZ,PROFIL,1,1,1,1,1,NZ,1,1);PLOT(DPDZ,P1,0.0,1000.0)
```

```
iymon=ny-2;IZMON=20;TSTSWP=-1.
 **PATCH(DPDZ,PROFIL,1,1,1,1,1,NZ,1,1);PLOT(DPDZ,P1,0.0,1000.0)
 **IPROF=0;NCOLPF=4

  GROUP 23. Field print-out and plot control
  GROUP 24. Dumps for restarts
 **RESTRT(ALL)
STOP
```

Appendix B5

Q1 file of mixture-annulus inlet configuration (Case B) simulation

```
TALK=T;RUN( 1, 1);VDU=VGAMOUSE
TEXT(MIXTURE-ANNULUS INLET AIRLIFT :CASE B)
TITLE
 DISPLAY
  MIXTURE-ANNULUS INLET AIRLIFT IS SIMULATED.Gas-solid  flow
  in pipe annulus(NY=5 to 40) and gas only flow in core(NY=1 to 5)
  Gas velocity is 16 m/s therefore pipe Reynold number is 201798.
  Particle diameter is 500 micron enter into pipe at particle
  velocity=10.5 m/s and density ratio is (825/1.17).Solid loading
  ratio is 1.2 calculated from totalflow and annulus solid loading
  is 1.4807.Particle shear stress term is included via PRT (U2)=1.
  PRT(R2)=0.7 is activated to include phase mass diffusion effect.
  Acceleration zone pressure,velocity and concentration is
  investigated.
 ENDDIS
REAL(RHOS,RHOG,EMUGAS,TKEIN,EPSIN,FLOWG,FLOWS,MLOAD,RGAS,RS
OL)
REAL(VGAS,VSOL,VSLIP,DIAM,GRAD,DIAMS,REY,GRAVAC)
RHOS=825.;GRAVAC=-9.81;DIAM=0.200;RHOG=1.178;GRAD=0.5*DIAM
 **Average velocity
MLOAD=1.2
EMUGAS=1.868E-5
VGAS=16.0
VSOL=10.5
RSOL=MLOAD*(RHOG/RHOS)*(VGAS/VSOL);RGAS=(1.0-RSOL)
REY=RHOG*VGAS*DIAM/EMUGAS
 **Annulus volume fraction
REAL(MANUL,RANS,RANG)
 *** MANUL=ANNULUS SOLID LOADING RATIO,RAN=ANNULUS VOL.
FRACTION
MANUL=1.4807;RANS=MANUL*(RHOG/RHOS)*(VGAS/VSOL);RANG=1.0-
RANS
 *** specify mean particle diameter
DIAMS=500.E-6
   GROUP 1. Run title and other preliminaries
   GROUP 2. Transience; time-step specification
   GROUP 3. X-direction grid specification
CARTES=F;XULAST=0.1;NX=1
   GROUP 4. Y-direction grid specification
GRDPWR(Y,40,GRAD,0.40)
   GROUP 5. Z-direction grid specification
NZ=70
GRDPWR(Z,NZ,NZ*GRAD,1.0)
   GROUP 6. Body-fitted coordinates or grid distortion
   GROUP 7. Variables stored, solved & named
ONEPHS=F;SOLVE(P1,V1,V2,W1,W2,R1,R2);TURMOD(KEMODL)
```

```
STORE(CFIP,ENUT,CD,REYN)
   GROUP 8. Terms (in differential equations) & devices
   GROUP 9. Properties of the medium (or media)
RHO1=RHOG;RHO2=RHOS
FLOWG=RHOG*RANG*VGAS;FLOWS=RHOS*RANS*VSOL;ENUL=EMUGAS/
RHOG
TKEIN=(0.05*VGAS)**2;EPSIN=0.1643*TKEIN**1.5/(0.1*GRAD)
PRNDTL(V2)=1.E10;PRNDTL(W2)=1.E10;PRT(V2)=1.697;PRT(W2)=1.697
PRT(R2)=0.7
   GROUP 10. Inter-phase-transfer processes and properties
CFIPS=GRND7;CFIPA=1.E-3;RLOLIM=1.E-6;CFIPB=DIAMS
   GROUP 11. Initialization of variable or porosity fields
FIINIT(W1)=VGAS;FIINIT(W2)=VSOL;FIINIT(V2)=-1.E-4;FIINIT(R1)=RGAS
FIINIT(R2)=RSOL
   GROUP 12. Unused
   GROUP 13. Boundary conditions and special sources
  ** inlet boundary
INLET(ANNULUS,LOW,1,NX,6,40,1,1,1,1)
VALUE(ANNULUS,P1,FLOWG);VALUE(ANNULUS,W1,VGAS)
VALUE(ANNULUS,P2,FLOWS);VALUE(ANNULUS,W2,VSOL)
VALUE(ANNULUS,KE,TKEIN);VALUE(ANNULUS,EP,EPSIN)
INLET(CORE,LOW,1,NX,1,5,1,1,1,1)
VALUE(CORE,P1,RHOG*VGAS);VALUE(CORE,W1,VGAS)
VALUE(CORE,P2,0.0);VALUE(CORE,W2,0.0)
VALUE(CORE,KE,TKEIN);VALUE(CORE,EP,EPSIN)
  **Outlet boundary
PATCH(OUTLET,HIGH,1,NX,1,NY,NZ,NZ,1,1)
COVAL(OUTLET,P1,1.0,0.0);COVAL(OUTLET,P2,1.0*RHOS/RHOG,0.0)
COVAL(OUTLET,V1,ONLYMS,0.0);COVAL(OUTLET,W1,ONLYMS,0.0)
COVAL(OUTLET,V2,ONLYMS,0.0);COVAL(OUTLET,W2,ONLYMS,0.0)
COVAL(OUTLET,KE,ONLYMS,0.0);COVAL(OUTLET,EP,ONLYMS,0.0)
  ** gravity
PATCH(GRAVITY,PHASEM,1,NX,1,NY,1,NZ,1,1)
COVAL(GRAVITY,W1,FIXFLU,GRAVAC);COVAL(GRAVITY,W2,FIXFLU,GRA
VAC)
  ** wall boundary
WALL(NWALL,NORTH,1,NX,NY,NY,1,NZ,1,1)
   GROUP 14. Downstream pressure for PARAB=.TRUE.
   GROUP 15. Termination of sweeps
LSWEEP=18;LITHYD=20
   GROUP 16. Termination of iterations
   GROUP 17. Under-relaxation devices
RELAX(V1,FALSDT,4.E-2);RELAX(V2,FALSDT,4.E-2)
RELAX(W1,LINRLX,0.5);RELAX(W2,LINRLX,0.5)
RELAX(R1,LINRLX,0.4);RELAX(R2,LINRLX,0.4)
KELIN=3
RELAX(KE,LINRLX,0.5);RELAX(EP,LINRLX,0.5)
RELAX(P2,LINRLX,0.5)
   GROUP 18. Limits on variables or increments to them
```

```
VARMIN(W1)=1.E-10;VARMIN(W2)=1.E-10
VARMIN(R1)=1.E-10;VARMIN(R2)=1.E-10
   GROUP 19. Data communicated by satellite to GROUND
   GROUP 20. Preliminary print-out
echo=f
   GROUP 21. Print-out of variables
NYPRIN=1;NZPRIN=NZ/14;ITABL=2
   GROUP 22. Spot-value print-out
iymon=18;IZMON=10;TSTSWP=-1.
   GROUP 23. Field print-out and plot control
   GROUP 24. Dumps for restarts
STOP
```

Appendix B6
Q1 file of Mixture-core inlet configuration (Case C) simulation

```
TALK=T;RUN( 1, 1);VDU=VGAMOUSE
TEXT(MIXTURE-CORE INLET AIRLIFT :Case C)
TITLE
 DISPLAY
  MIXTURE-CORE INLET AIRLIFT IS SIMULATED.Gas-solid flow
  in pipe (NY=1 to 30) and gas only flow in annulus(NY=31 to 40)
  Gas velocity is 16 m/s therefore pipe Reynold number is 201798.
  Particle diameter is 500 micron enter into pipe at particle
  velocity=10.5 m/s and density ratio is (825/1.17).Solid loading
  ratio is 1.2 calculated from totalflow and core solid loading
  is 1.507.Particle shear stress term is included via PRT (U2) =
  1.697, PRT(R2)=0.7 is activated to include phase mass diffusion
  effect.Acceleration zone pressure,velocity and concentration is
  investigated.
 ENDDIS
REAL(RHOS,RHOG,EMUGAS,TKEIN,EPSIN,FLOWG,FLOWS,MLOAD,RGAS,RS
OL)
REAL(VGAS,VSOL,VSLIP,DIAM,GRAD,DIAMS,REY,GRAVAC)
RHOS=825.;GRAVAC=-9.81;DIAM=0.200;RHOG=1.178;GRAD=0.5*DIAM
 **Average velocity
MLOAD=1.2
EMUGAS=1.868E-5
VGAS=16.0
VSOL=10.5
RSOL=MLOAD*(RHOG/RHOS)*(VGAS/VSOL);RGAS=(1.0-RSOL)
REY=RHOG*VGAS*DIAM/EMUGAS
 **Annulus volume fraction
REAL(MANUL,RANS,RANG)
 *** MANUL=ANNULUS SOLID LOADING RATIO,RAN=ANNULUS VOL.
FRACTION
MANUL=1.507;RANS=MANUL*(RHOG/RHOS)*(VGAS/VSOL);RANG=1.0-
RANS
  *** specify mean particle diameter
DIAMS=500.E-6
  GROUP 1. Run title and other preliminaries
  GROUP 2. Transience; time-step specification
  GROUP 3. X-direction grid specification
CARTES=F;XULAST=0.1;NX=1
  GROUP 4. Y-direction grid specification
GRDPWR(Y,40,GRAD,0.4)
  GROUP 5. Z-direction grid specification
NZ=70
GRDPWR(Z,NZ,NZ*GRAD,1.0)
  GROUP 6. Body-fitted coordinates or grid distortion
  GROUP 7. Variables stored, solved & named
ONEPHS=F;SOLVE(P1,V1,V2,W1,W2,R1,R2);TURMOD(KEMODL)
```

```
STORE(CFIP,ENUT,CD,REYN)
   GROUP 8. Terms (in differential equations) & devices
   GROUP 9. Properties of the medium (or media)
RHO1=RHOG;RHO2=RHOS
FLOWG=RHOG*RANG*VGAS;FLOWS=RHOS*RANS*VSOL;ENUL=EMUGAS/
RHOG
TKEIN=(0.05*VGAS)**2;EPSIN=0.1643*TKEIN**1.5/(0.1*GRAD)
PRNDTL(V2)=1.E10;PRNDTL(W2)=1.E10;PRT(V2)=1.697;PRT(W2)=1.697
PRT(R2)=0.7
   GROUP 10. Inter-phase-transfer processes and properties
CFIPS=GRND7;CFIPA=1.E-3;RLOLIM=1.E-6;CFIPB=DIAMS
   GROUP 11. Initialization of variable or porosity fields
FIINIT(W1)=VGAS;FIINIT(W2)=VSOL;FIINIT(V2)=-1.E-4;FIINIT(R1)=RGAS
FIINIT(R2)=RSOL
   GROUP 12. Unused
   GROUP 13. Boundary conditions and special sources
 ** inlet boundary
INLET(CORE,LOW,1,NX,1,30,1,1,1,1)
VALUE(CORE,P1,FLOWG);VALUE(CORE,W1,VGAS)
VALUE(CORE,P2,FLOWS);VALUE(CORE,W2,VSOL)
VALUE(CORE,KE,TKEIN);VALUE(CORE,EP,EPSIN)
INLET(ANNULUS,LOW,1,NX,31,40,1,1,1,1)
VALUE(ANNULUS,P1,RHOG*VGAS);VALUE(ANNULUS,W1,VGAS)
VALUE(ANNULUS,P2,0.0);VALUE(ANNULUS,W2,0.0)
VALUE(ANNULUS,KE,TKEIN);VALUE(ANNULUS,EP,EPSIN)
 **Outlet boundary
PATCH(OUTLET,HIGH,1,NX,1,NY,NZ,NZ,1,1)
COVAL(OUTLET,P1,1.0,0.0);COVAL(OUTLET,P2,1.0*RHOS/RHOG,0.0)
COVAL(OUTLET,V1,ONLYMS,0.0);COVAL(OUTLET,W1,ONLYMS,0.0)
COVAL(OUTLET,V2,ONLYMS,0.0);COVAL(OUTLET,W2,ONLYMS,0.0)
COVAL(OUTLET,KE,ONLYMS,0.0);COVAL(OUTLET,EP,ONLYMS,0.0)
 ** gravity
PATCH(GRAVITY,PHASEM,1,NX,1,NY,1,NZ,1,1)
COVAL(GRAVITY,W1,FIXFLU,GRAVAC);COVAL(GRAVITY,W2,FIXFLU,GRA
VAC)
 ** wall boundary
WALL(NWALL,NORTH,1,NX,NY,NY,1,NZ,1,1)
   GROUP 14. Downstream pressure for PARAB=.TRUE.
   GROUP 15. Termination of sweeps
LSWEEP=18;LITHYD=20
   GROUP 16. Termination of iterations
   GROUP 17. Under-relaxation devices
RELAX(V1,FALSDT,4.E-2);RELAX(V2,FALSDT,4.E-2)
RELAX(W1,LINRLX,0.5);RELAX(W2,LINRLX,0.5)
RELAX(R1,LINRLX,0.4);RELAX(R2,LINRLX,0.4)
KELIN=3
RELAX(KE,LINRLX,0.5);RELAX(EP,LINRLX,0.5)
RELAX(P2,LINRLX,0.5)
   GROUP 18. Limits on variables or increments to them
```

```
VARMIN(W1)=1.E-10;VARMIN(W2)=1.E-10
VARMIN(R1)=1.E-10;VARMIN(R2)=1.E-10
   GROUP 19. Data communicated by satellite to GROUND
   GROUP 20. Preliminary print-out
echo=f
   GROUP 21. Print-out of variables
NYPRIN=1;NZPRIN=NZ/14;ITABL=2
   GROUP 22. Spot-value print-out
iymon=5;IZMON=10;TSTSWP=-1.
   GROUP 23. Field print-out and plot control
   GROUP 24. Dumps for restarts
STOP
```

Appendix B7

Q1 file for varied area Mixture-core inlet configuration (Case C+) simulation

```
TALK=T;RUN( 1, 1);VDU=VGAMOUSE
TEXT(AIR-SOLIDS 2ndMIXTURE-CORE INLET AIRLIFT:CASE C+)
TITLE
 DISPLAY
  2nd MIXTURE-CORE INLET AIRLIFT IS SIMULATED.Gas-solid flow
  in CORE (NY=1 to 23) and gas only flow in annulus(NY=24 to 40)
  Gas velocity is 16 m/s therefore pipe Reynold number is 201798.
  Particle diameter is 500 micron enter into pipe at particle
  velocity=10.5 m/s and density ratio is (825/1.17).Solid loading
  ratio is 1.2 calculated from totalflow and core solid loading
  is 1.866.Particle shear stress term is included via PRT (U2) =
  1.697, PRT(R2)=0.7 is activated to include phase mass diffusion
  effect.Acceleration zone pressure,velocity and concentration is
  investigated.
 ENDDIS
REAL(RHOS,RHOG,EMUGAS,TKEIN,EPSIN,FLOWG,FLOWS,MLOAD,RGAS,RS
OL)
REAL(VGAS,VSOL,VSLIP,DIAM,GRAD,DIAMS,REY,GRAVAC)
RHOS=825.;GRAVAC=-9.81;DIAM=0.200;RHOG=1.178;GRAD=0.5*DIAM
 **Average velocity
MLOAD=1.2;
EMUGAS=1.868E-5
VGAS=16.0
VSOL=10.5
REY=RHOG*DIAM*VGAS/EMUGAS
RSOL=MLOAD*(RHOG/RHOS)*(VGAS/VSOL);RGAS=(1.0-RSOL)
 **Annulus volume fraction
REAL(MANUL,RANS,RANG)
 *** MANUL=ANNULUS SOLID LOADING RATIO,RAN=ANNULUS VOL.
FRACTION
MANUL=1.866;RANS=MANUL*(RHOG/RHOS)*(VGAS/VSOL);RANG=1.0-
RANS
 *** specify mean particle diameter
DIAMS=500.E-6
  GROUP 1. Run title and other preliminaries
  GROUP 2. Transience; time-step specification
  GROUP 3. X-direction grid specification
CARTES=F;XULAST=0.1;NX=1
  GROUP 4. Y-direction grid specification
GRDPWR(Y,40,GRAD,0.4)
  GROUP 5. Z-direction grid specification
NZ=70
GRDPWR(Z,NZ,NZ*GRAD,1.0)
  GROUP 6. Body-fitted coordinates or grid distortion
  GROUP 7. Variables stored, solved & named
ONEPHS=F;SOLVE(P1,V1,V2,W1,W2,R1,R2);TURMOD(KEMODL)
```

```
STORE(CFIP,ENUT,CD,REYN)
   GROUP 8. Terms (in differential equations) & devices
   GROUP 9. Properties of the medium (or media)
RHO1=RHOG;RHO2=RHOS
FLOWG=RHOG*RANG*VGAS;FLOWS=RHOS*RANS*VSOL;ENUL=EMUGAS/
RHOG
TKEIN=(0.05*VGAS)**2;EPSIN=0.1643*TKEIN**1.5/(0.1*GRAD)
PRNDTL(V2)=1.E10;PRNDTL(W2)=1.E10;PRT(V2)=1.697;PRT(W2)=1.697
PRT(R2)=0.7
   GROUP 10. Inter-phase-transfer processes and properties
CFIPS=GRND7;CFIPA=1.E-3;RLOLIM=1.E-6;CFIPB=DIAMS
   GROUP 11. Initialization of variable or porosity fields
FIINIT(W1)=VGAS;FIINIT(W2)=VSOL;FIINIT(V2)=-1.E-4;FIINIT(R1)=RGAS
FIINIT(R2)=RSOL
   GROUP 12. Unused
   GROUP 13. Boundary conditions and special sources
 ** inlet boundary
INLET(CORE,LOW,1,NX,1,23,1,1,1,1)
VALUE(CORE,P1,FLOWG);VALUE(CORE,W1,VGAS)
VALUE(CORE,P2,FLOWS);VALUE(CORE,W2,VSOL)
VALUE(CORE,KE,TKEIN);VALUE(CORE,EP,EPSIN)
INLET(ANNULUS,LOW,1,NX,24,40,1,1,1,1)
VALUE(ANNULUS,P1,RHOG*VGAS);VALUE(ANNULUS,W1,VGAS)
VALUE(ANNULUS,P2,0.0);VALUE(ANNULUS,W2,0.0)
VALUE(ANNULUS,KE,TKEIN);VALUE(ANNULUS,EP,EPSIN)
 **Outlet boundary
PATCH(OUTLET,HIGH,1,NX,1,NY,NZ,NZ,1,1)
COVAL(OUTLET,P1,1.0,0.0);COVAL(OUTLET,P2,1.0*RHOS/RHOG,0.0)
COVAL(OUTLET,V1,ONLYMS,0.0);COVAL(OUTLET,W1,ONLYMS,0.0)
COVAL(OUTLET,V2,ONLYMS,0.0);COVAL(OUTLET,W2,ONLYMS,0.0)
COVAL(OUTLET,KE,ONLYMS,0.0);COVAL(OUTLET,EP,ONLYMS,0.0)
 ** gravity
PATCH(GRAVITY,PHASEM,1,NX,1,NY,1,NZ,1,1)
COVAL(GRAVITY,W1,FIXFLU,GRAVAC);COVAL(GRAVITY,W2,FIXFLU,GRA
VAC)
 ** wall boundary
WALL(NWALL,NORTH,1,NX,NY,NY,1,NZ,1,1)
   GROUP 14. Downstream pressure for PARAB=.TRUE.
   GROUP 15. Termination of sweeps
LSWEEP=18;LITHYD=20
   GROUP 16. Termination of iterations
   GROUP 17. Under-relaxation devices
RELAX(V1,LINRLX,4.E-1);RELAX(V2,LINRLX,4.E-1)
RELAX(W1,LINRLX,0.5);RELAX(W2,LINRLX,0.5)
KELIN=3
RELAX(KE,LINRLX,0.5);RELAX(EP,LINRLX,0.5)
RELAX(P2,LINRLX,0.5)
   GROUP 18. Limits on variables or increments to them
VARMIN(W1)=1.E-10;VARMIN(W2)=1.E-10
```

```
VARMIN(R1)=1.E-10;VARMIN(R2)=1.E-10
   GROUP 19. Data communicated by satellite to GROUND
   GROUP 20. Preliminary print-out
echo=f
   GROUP 21. Print-out of variables
NYPRIN=1;NZPRIN=NZ/14;ITABL=2
   GROUP 22. Spot-value print-out
iymon=5;IZMON=10;TSTSWP=-1.
   GROUP 23. Field print-out and plot control
   GROUP 24. Dumps for restarts
STOP
```

VITA

Nithi Nikornprakorn was born on October 25, 1965 in Cholburi, Thailand. He recieved his Bechelor Degree of Industrial Engineering from Khon Khaen University. He has studied Chemical Engineering at Chulalongkorn university since 1994.