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APPENDICES

Appendix A Calculation Algorithm Method of Tray (IFP's Method)

1. Calculate liquid flow on tray by Francis Weir Formula (equation 3.15).
2. Calculate accumulate and composition on tray by equation E.3 and equation E.6
3. Calculate temperature tray by bubble point equation (appendix B).
4. Calculate vapor flow by E.8 (energy equation, steady-state assumption).

Appendix B Calculation Temperature from Bubble Point Equation

1. Assume a value of temperature
2. Calculate vapor pressure from Antoine's equation
3. Calculate vapor composition and sum value of all vapor composition.
4. Calculate new temperature by use Newton's method
5. Go back to step 2 until new temperature convergence.

Appendix C Response Curves of Tuning Parameter

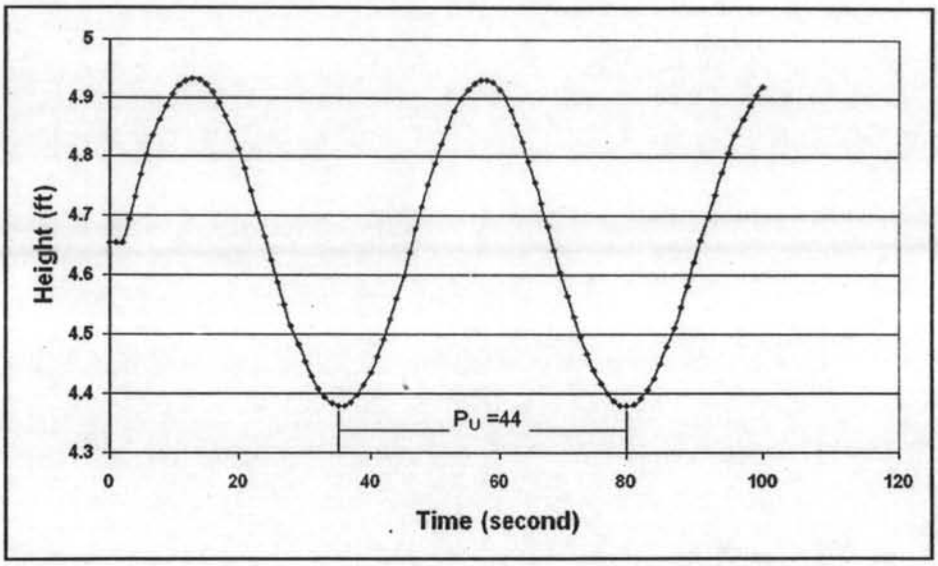

Figure C.1 Response curve of height of gravitational flow tank using feed back control with at K=0.0193 with disturbance of changing input volumetric flow rate per tank area from 0.311 to 0.35 ft/s.

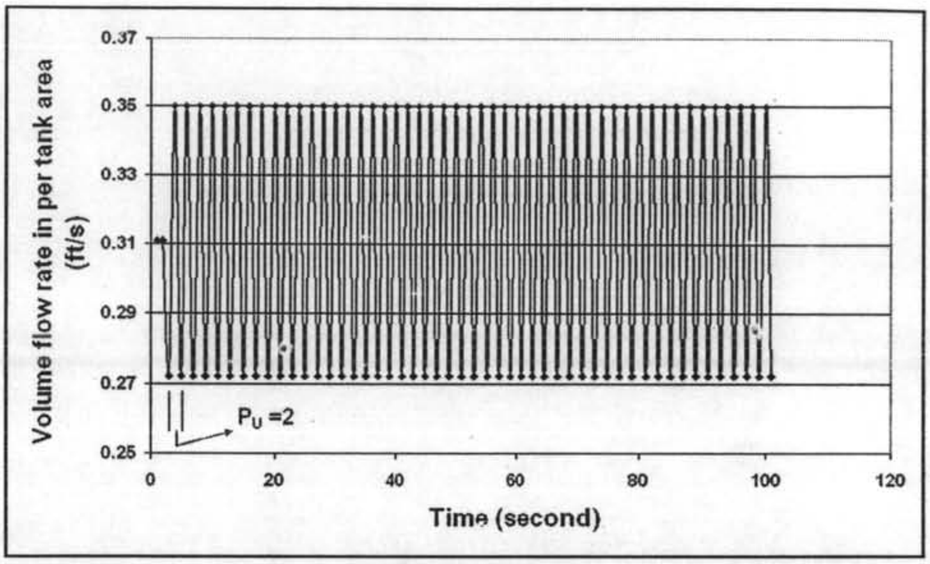

Figure C.2 Response curve of input volumetric flow rate in per tank area of gravitational flow tank with feed forward control at K=2 with disturbance of changing input volumetric flow rate per tank area from 0.311 to 0.35 ft/s.

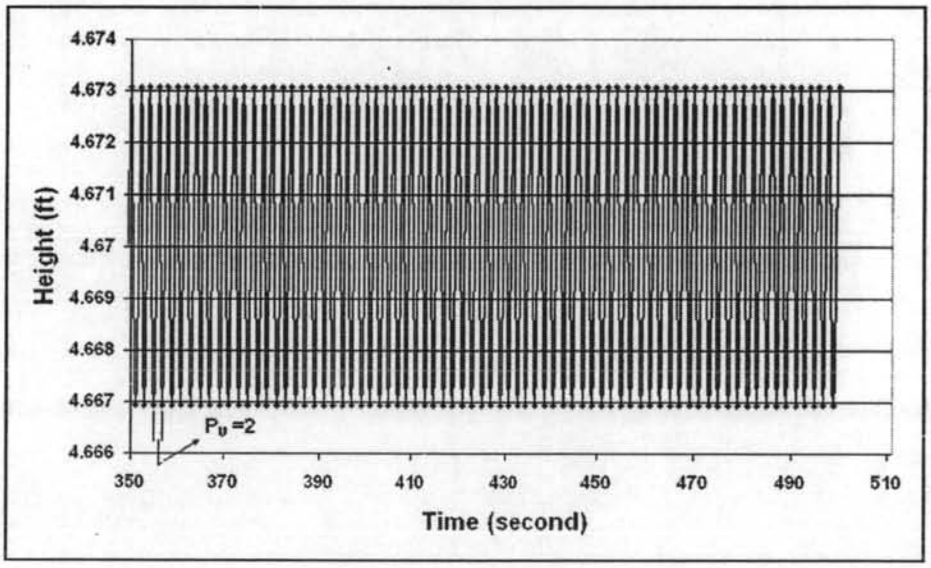

Figure C.3 Response curve of height of gravitational flow tank with cascade control at K of primary controller=0.33339 with disturbance of changing set point from 4.6546 to 4.67 ft/s.

Secondary controller uses the value from feed forward control.

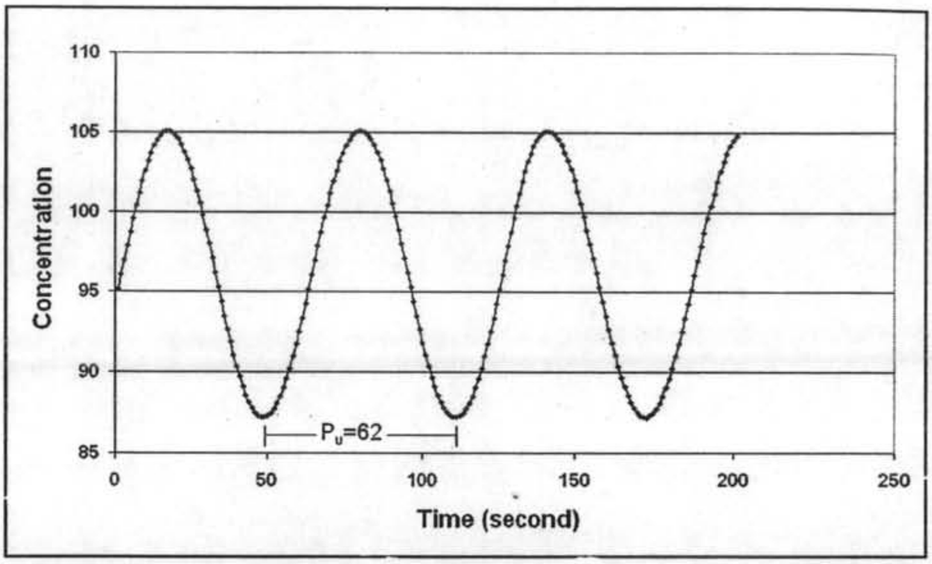

Figure C.4 Response curve of concentration of plug-flow plus CSTR with feedback control at K of controller = 0.1048 after changing feed flowrate from 4 to 5 kmol/s.

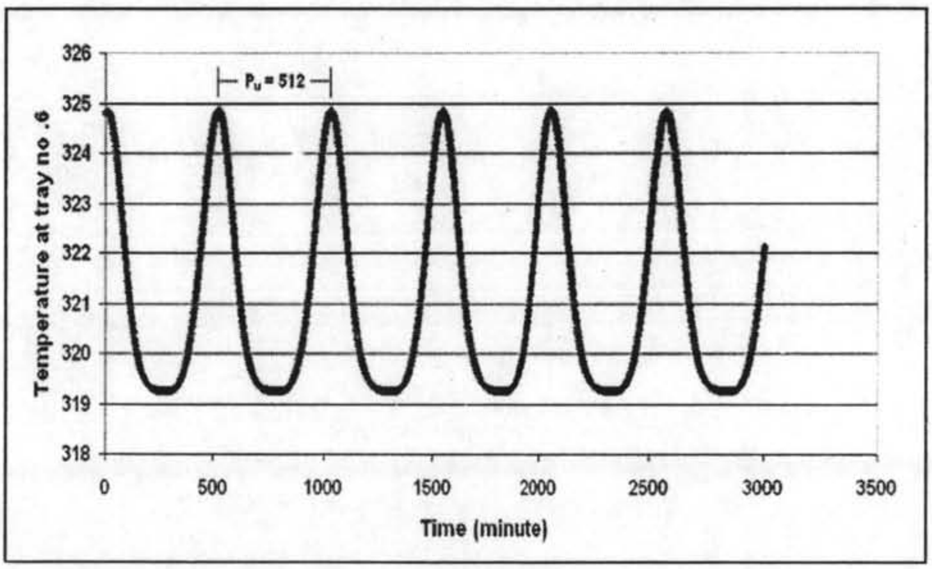

Figure C.5 Response curve of temperature of tray no.6 of top cascade control at K = 0.00002 with disturbance of changing disturbance from 0.5:0.5 to 0.3:0.7 (propane:butane).

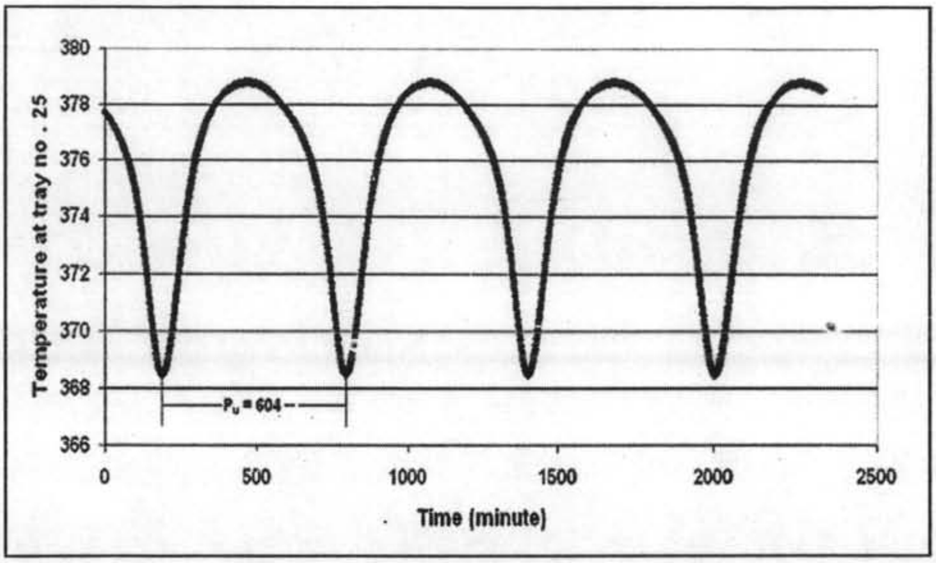

Figure C.6 Response curve of temperature of tray no.6 of bottom cascade control at K = 0.00001 with disturbance of changing disturbance from 0.5:0.5 to 0.3:0.7 (propane:butane).

Appendix D Liquid and Vapor Enthalpy

Liquid and vapor enthalpy are calculated from data in table D.1 and D.2 by used cubic splines function in digital visual fortran program.

Table D.1 Liquid enthalpy

Temperature(K)	Propane(Kcal/Kmol)	Butane(Kcal/Kmol)
273.15	902.24	1125.79
273.15	1221.82	1481.22
273.15	1564.33	1847.22
273.15	1938.14	2227.85
273.15	2360.87	2623.56
273.15	2887.39	3036.26
273.15	3675.48	3468.77
273.15	3937.55	3925.29
273.15	4204.17	4412.81
273.15	4475.33	4944.49

Table D.2 Vapor enthalpy

Temperature(K)	Pressure(Bar)	Propane(Kcal/Kmol)	Butane(Kcal/Kmol)
313.15	1	4653.41	6128.56
323.15	1	4840.63	6381.99
333.15	1	5032.22	6641.07
343.15	1	5228.2	6905.82
353.15	1	5428.62	7176.25
363.15	1	5633.48	7452.38
373.15	1	5842.8	7734.19
383.15	1	6056.6	8021.67
393.15	1	6274.86	8314.8

Table D.2 (Con'd) Vapor enthalpy

403.15	1	6497.6	8613.56
313.15	5	4539.02	5966.78
323.15	5	4735.51	6165.19
333.15	5	4935.2	6455.61
343.15	5	5138.41	6740.21
353.15	5	5345.35	7025.55
363.15	5	5556.17	7313.81
373.15	5	5770.99	7605.95
383.15	5	5989.88	7902.47
393.15	5	6212.92	8203.68
403.15	5	6440.13	8509.75
313.15	10	4366.94	5966.78
323.15	10	4580.95	6165.19
333.15	10	4793.92	6361.11
343.15	10	5008.23	6553.18
353.15	10	5224.93	6764.9
363.15	10	5444.61	7097.64
373.15	10	5667.64	7411.93
383.15	10	5894.24	7724.62
393.15	10	6124.6	8039.06
403.15	10	6538.82	8356.61
313.15	15	4175.28	5966.78
323.15	15	4386.16	6165.19
333.15	15	4623.34	6361.12
343.15	15	4853.6	6553.18
353.15	15	5083.22	6739.61
363.15	15	5314.25	6917.97
373.15	15	5547.67	7142.29

Table D.2 (Con'd) Vapor enthalpy

383.15	15	5784.04	7500.3
393.15	15	6023.71	7837.22
403.15	15	6266.9	8171.6
313.15	20	4175.29	5966.78
323.15	20	4246.78	6165.19
333.15	20	4405.16	6361.11
343.15	20	4667.77	6553.18
353.15	20	4916.29	6739.61
363.15	20	5162.5	6917.97
373.15	20	5409.37	7084.84
383.15	20	5658.19	7235.06
393.15	20	5909.66	7578.38
403.15	20	6164.23	7945.05

Appendix E Numerical Method Of Depropanizer Column

Mole balance

$$\frac{d(AM_j)}{dt} = A_j + V_{j+1} + L_{j-1} - V_j - L_j \quad (E.1)$$

Applying implicit Euler method to equation E.1

$$AM_{j,k+1} = AM_{j,k} + (A_{j,k+1} + V_{j+1,k+1} + L_{j-1,k+1} - V_{j,k+1} - L_{j,k+1})dt \quad (E.2)$$

Applying BALL hypothesis (1961) which is $V_{j+1,k+1} = V_{j+1,k}$ and $V_{j,k+1} = V_{j,k}$ to equation E.2 and $y_{j+1,k+1} = y_{j+1,k}$ and $y_{j,k+1} = y_{j,k}$ to equation E.5.

$$AM_{j,k+1} = AM_{j,k} + (A_{j,k+1} + V_{j+1,k} + L_{j-1,k+1} - V_{j,k} - L_{j,k+1})dt \quad (E.3)$$

Composition balance

$$\frac{dx_j AM_j}{dt} = A_j z_j + L_{j-1}x_{j-1} + V_{j+1}y_{j+1} - V_j y_j - L_j x_j \quad (E.4)$$

Use implicit Euler method and BALL hypothesis on equation E.4

$$x_{j,k+1}AM_{j,k+1} = x_{j,k}AM_{j,k} + \left(A_{j,k+1}z_{j,k+1} + L_{j-1,k+1}x_{j-1,k+1} + V_{j+1,k}y_{j+1,k} - V_{j,k}y_{j,k} - L_{j,k+1}x_{j,k+1}\right)dt \quad (E.5)$$

Rearrange equation E.5

$$x_{j,k+1} = \frac{x_{j,k}AM_{j,k} + \left(A_{j,k+1}z_{j,k+1} + L_{j-1,k+1}x_{j-1,k+1} + V_{j+1,k}y_{j+1,k} - V_{j,k}y_{j,k}\right)dt}{AM_{j,k+1} + L_{j,k+1}dt} \quad (E.6)$$

Energy balance (steady state assumption)

$$0 = h_{A,k+1}A_{j,k+1} + h^L_{j+1,k+1}L_{j+1,k+1} + h^V_{j-1,k}V_{j-1,k} - h^L_{j,k+1}L_{j,k+1} - h^V_{j,k+1}V_{j,k+1} \quad (E.7)$$

Rearrange equation E.7

$$V_{j,k+1} = \frac{h_{A,k+1}A_{j,k+1} + h^L_{j+1,k+1}L_{j+1,k+1} + h^V_{j-1,k}V_{j-1,k} - h^L_{j,k+1}L_{j,k+1}}{h^V_{j,k+1}} \quad (E.8)$$

Where

j is the tray index.

k is the time index

A is the feed flowrate.

AM is the accumulate on tray.

dt is the time step.

h_A is the enthalpy of feed flowrate.

h^L is the enthalpy of liquid.

h^V is the enthalpy of vapor.

L is the liquid flowrate.

V is the vapor flowrate.

x is the liquid composition.

y is the vapor composition.

z is the feed composition.

Appendix F Numerical Methods

F.1 Explicit Euler's method

In the model, Euler's method is used for explicit calculation. This method is used for replacing integration of some equation. For example, material, mass, and component balance equation.

$$y_{i+1} = y_i + f(x_i, y_i) * h \tag{F.1}$$

Where

y_{i+1} is the value at new time step.

y_i is the value at previous time step.

$f(x_i, y_i)$ is the function at previous time step.

h is the step time.

There are many methods of root finding in numerical method. For instant, bisection, regular falsi. In this work, Root finding method used in distillation model is Newton-Raphson convergence.

$$x_{i+1} = x_i - \frac{f_i}{f_i'} \tag{F.2}$$

Where

x_{i+1} is the value at new step time.

x_i is the value at old step time.

f_i is the function.

f_i' is the first derivative of function.

F.2 Implicit Euler's method

Implicit method is faster than explicit method. Implicit method gives stable and converge solution with larger time step compared to explicit method.

$$y_{i+1} = y_i + f'(x_{i+1}, y_{i+1}) * h \tag{F.3}$$

Where

y_{i+1} is the value at new step time.

y_i is the value at old step time.

$f'(x_{i+1}, y_{i+1})$ is the first derivative at new step time.

h is the step time.

F.3 Integral Absolute Error (IAE)

IAE is calculated by equation F.4.

$$IAE = \int_0^\infty abs(error)dt \tag{F.4}$$

Appendix G Response Curves of Step Response for DMC

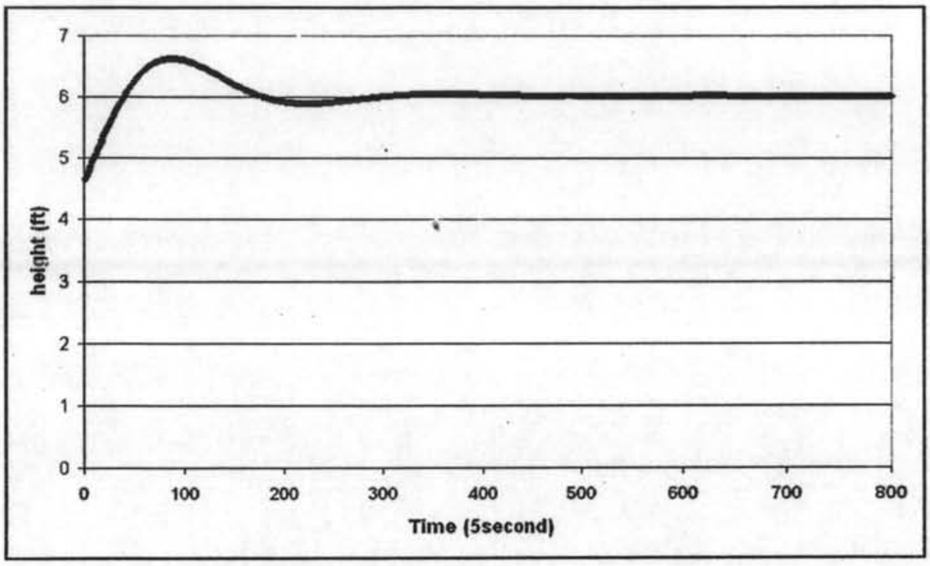

Figure G.1 Response curve of liquid level in gravitational flow tank with step of feed flow rate in per tank area at 0.039 ft/s.

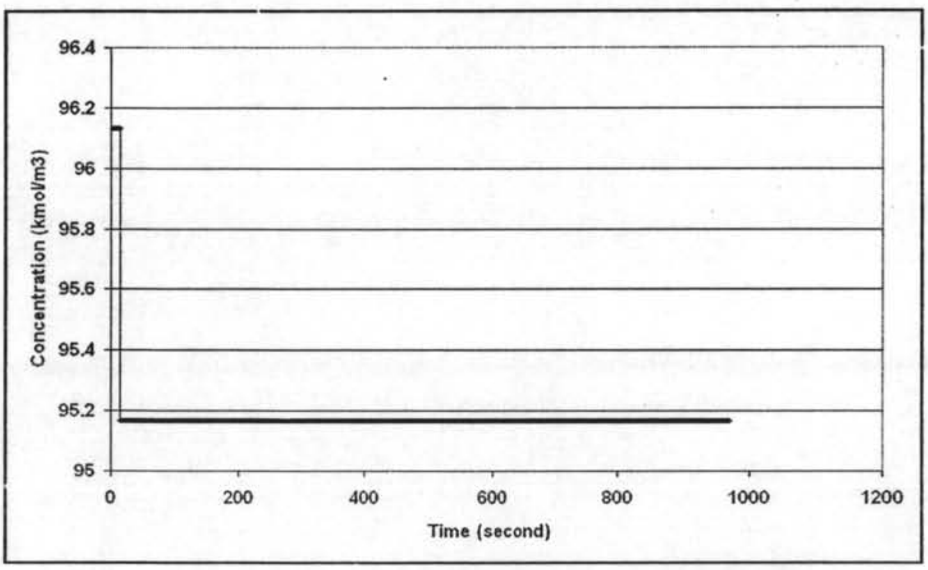

Figure G.2 Response curve of concentration in plug-flow plus CSTR with step of feed flow rate 1 kmol/s.

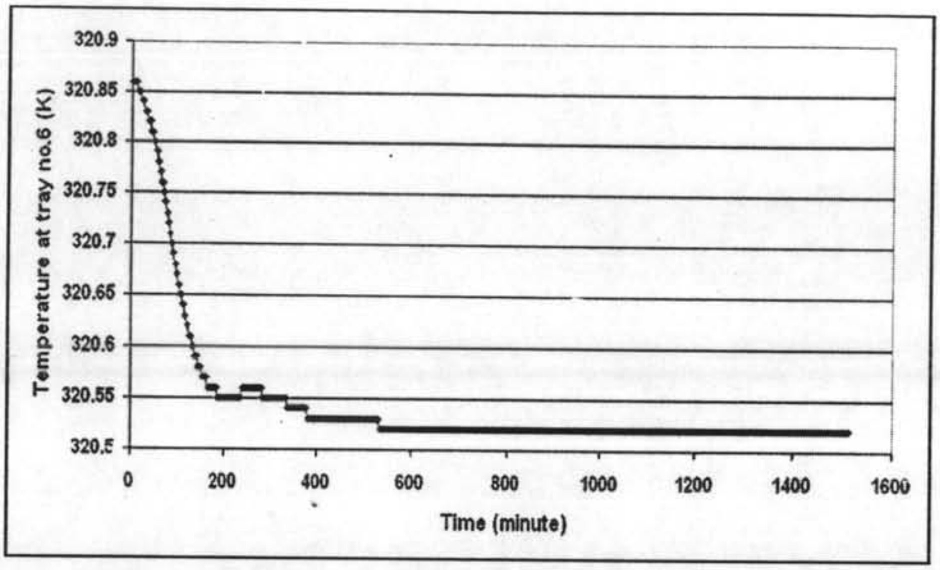

Figure G.3 Response curve of tray no.6 with step of reflux flowrate at 0.001 kmol/minute.

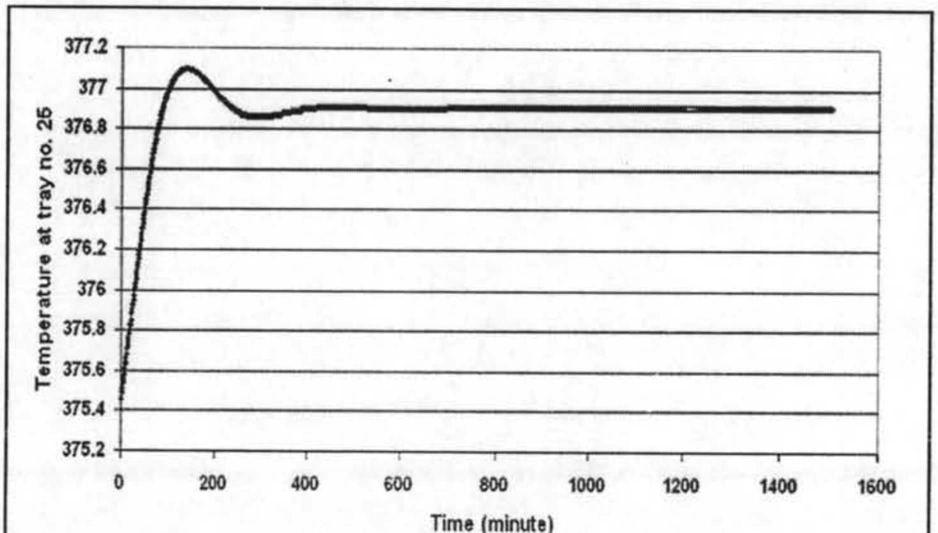

Figure G.4 Response curve of tray no.25 with step of steam flowrate at 0.01 kmol/30 second.

Appendix H Source Code of Gravitational Flow Tank

H.1 Gravitational Flow Tank with Feed Forward Control

```
program gravitytank
        real(8) v               !velocity
        real(8) h               !height
        real(8) f               !feed
        real(8) sp              !set point
        real(8) time                    !time
        real(8) delta                   !time step
        real(8) vdot                    !derivative of velocity
        real(8) hdot                    !derivative of height
        real(8) fdot                    !derivative of feedin
        real(8) fold
        real(8) k               !proportional gain
        real(8) ti              !reset time
        real(8) td              !derivative time
        open (1, file = 'output.xls')
        !initial
        h=4.6546
        v=4.98397
        f=0.311
        fold=0.311
        k=0.6*2
        ti=2/2.
        td=2/8.
        sp=0.311
        fdot=0
        time=0
        delta=1
100     vdot=0.0107*h-0.002005*v**2
        if(time.eq.2)then
                f=0.35
        end if
        fdot=k*((sp-f)+1/ti*(sp-fold-fdot*delta/2)*delta-td*fdot)
        fold=f
        f=f+fdot*delta
        if (f.le.0)then
                f=0
        end if
        hdot=f-0.0624*v
        write (1,3)time,v,h,f
3       format(4f10.5)
        v=v+vdot*delta
        if (v.le.0)then
                v=0
        end if
        h=h+hdot*delta
        if (h.le.0)then
                h=0
        end if
        time=time+delta
        if(time.le.8000) goto 100
end program
```

H.2 Gravitational Flow Tank with Feedback Control

```
program gravitytank
        real(8) v               !velocity
        real(8) h               !height
        real(8) hold
        real(8) f               !feed
        real(8) sp              !set point
        real(8) time                    !time
        real(8) delta                   !time step
```

```
        real(8) vdot                    !derivative of velocity
        real(8) hdot                    !derivative of height
        real(8) fdot                    !derivative of feedin
        real(8) k           !proportional gain
        real(8) ti          !reset time
        real(8) td          !derivative time
        open (1, file = 'output.xls')
        !initial
        h=4.6546
        hold=h
        v=4.98397
        f=0.311
        k=0.6*0.0193
        ti=44./2.
        td=44./8.
        sp=4.6546
        fdot=0
        time=0
        delta=1
100     vdot=0.0107*h-0.00205*v**2
        if(time.eq.2)then
!               f=0.35
                sp=4.7
        end if
        hdot=f-0.0624*v
        write (1,3)time,v,h,f
3       format(4f10.5)
        v=v+vdot*delta
        hold=h
        h=h+hdot*delta
        fdot=k*((sp-h)+1/ti*(sp-hold-hdot*delta/2)*delta-td*hdot)
        f=f+fdot*delta
        time=time+delta
        if(time.le.8000) goto 100
end program
```

H.3 Gravitational Flow Tank with Cascade Control

```
program gravitytank
        real(8) v           !velocity
        real(8) h           !height
        real(8) f           !feed
        real(8) sp          !set point of height of level in tank
        real(8) time        !time
        real(8) delta       !time step
        real(8) vdot        !derivative of velocity
        real(8) hdot        !derivative of height
        real(8) hold
        real(8) fdot        !derivative of feed in
        real(8) fold
        real(8) spdot       !derivative of set point of feed in
        real(8) k1          !proportional gain of master controller
        real(8) k2          !proportional gain of slave controller
        real(8) ti          !integral term of master controller
        real(8) ti1         !integral term of slave controller
        real(8) td          !derivative term of master controller
        real(8) td1         !derivative term of slave controller
        real(8) sph         !set point of velocity of feed in
        open (1, file = 'output.xls')
        !initial
        h=4.6546
        hold=4.6546
        v=4.98397
        f=0.311
        fold=0.311
        k1=0.6*2
        ti1=2/2.
        td1=2/8.
        k2=0.6*0.33339
```

```
          ti=2/2.
          td=2/8.
          sp=4.6546
          sph=0.311
          fdot=0
          time=0
          delta=1
100       vdot=0.0107*h-0.002005*v**2
          if(time.eq.1)then
!                 f=0.35
                  sp=4.7
          end if
          fdot=k1*((sph-f)+1/ti1*(sph-fold-fdot*delta/2)*delta-td1*fdot)
          fold=f
          f=f+fdot*delta
          if (f.le.0)then
                  f=0
          end if
          hdot=f-0.0624*v
          write (1,3)time,v,h,f
3         format(4f10.5)
          v=v+vdot*delta
          if (v.le.0)then
                  v=0
          end if
          hold=h
          h=h+hdot*delta
          if (h.le.0)then
                  h=0
          end if
          spdot=k2*((sp-h)+1/ti*(sp-hold-hdot*delta/2)*delta-td*hdot)
          sph=sph+spdot*delta
          time=time+delta
          if(time.le.8000) goto 100
end program
```

H.4 Gravitational Flow Tank with DMC

```
program gravitytank
          implicit none
          integer i,j,k,l,m
          real(8) v                      !velocity
          real(8) h                      !height
          real(8) f                      !feed
          real(8) time                   !time
          real(8) delta                  !time step
          real(8) vdot                   !derivative of velocity
          real(8) hdot                   !derivative of height
          real(8) vsim                   !velocity in simulation
          real(8) vdotsim                !derivative of velocity in simulation
          real(8) hdotsim                !derivative of height in simualtion
          real(8) sp                     !set point
          real(8) a1(80,40)
          real(8) b1(160)
          real(8) x(80)
          real(8) dmo(80)
          real(8) dm(40)
          real(8) xol(80)
          real(8) xcl(80)
          real(8) df
          real(8) jj(80)
          real(8) ff
          real(8) a1t(40,80)
          real(8) ata(40,40)
          real(8) ii(40,40)
          real(8) atai(40,40)
          real(8) aaa(40,80)
          real(8) rr(80)
          real(8) aa
```

```
real(8) bb
real(8) cc
open (1, file = 'output.xls')
bl(   1 )=      5.01090941
bl(   2 )=      9.998794226
bl(   3 )=      14.88592424
bl(   4 )=      19.60360219
bl(   5 )=      24.09246882
bl(   6 )=      28.30264488
bl(   7 )=      32.19371004
bl(   8 )=      35.73452293
bl(   9 )=      38.90289183
bl(   10        )=41.68510982
bl(   11        )=44.07537208
bl(   12        )=46.07509619
bl(   13        )=47.69216763
bl(   14        )=48.9401339
bl(   15        )=49.83737013
bl(   16        )=50.40623778
bl(   17        )=50.67225629
bl(   18        )=50.66330495
bl(   19        )=50.40886921
bl(   20        )=49.93934295
bl(   21        )=49.28539502
bl(   22        )=48.47740545
bl(   23        )=47.5449745
bl(   24        )=46.51650493
bl(   25        )=45.41885641
bl(   26        )=44.27706926
bl(   27        )=43.11415359
bl(   28        )=41.95093903
bl(   29        )=40.80597964
bl(   30        )=39.69550859
bl(   31        )=38.63343649
bl(   32        )=37.63138804
bl(   33        )=36.69877116
bl(   34        )=35.84287354
bl(   35        )=35.06898157
bl(   36        )=34.38051693
bl(   37        )=33.77918686
bl(   38        )=33.26514392
bl(   39        )=32.83715204
bl(   40        )=32.49275544
bl(   41        )=32.22844782
bl(   42        )=32.03983924
bl(   43        )=31.92181852
bl(   44        )=31.86870937
bl(   45        )=31.87441855
bl(   46        )=31.93257484
bl(   47        )=32.03655764
bl(   48        )=32.18011453
bl(   49        )=32.35646705
bl(   50        )=32.55940432
bl(   51        )=32.78286451
bl(   52        )=33.02110385
bl(   53        )=33.26875373
bl(   54        )=33.52086589
bl(   55        )=33.77294644
bl(   56        )=34.02097917
bl(   57        )=34.2614389
bl(   58        )=34.49129571
bl(   59        )=34.70801083
bl(   60        )=34.90952518
bl(   61        )=35.09424145
bl(   62        )=35.26100062
bl(   63        )=35.40905405
bl(   64        )=35.53803185
bl(   65        )=35.64790851
bl(   66        )=35.73896665
bl(   67        )=35.81175969
bl(   68        )=35.86707409
```

bl(	69	)=35.90589184
bl(	70	)=35.92935388
bl(	71	)=35.93872481
bl(	72	)=35.93535937
bl(	73	)=35.92067113
bl(	74	)=35.89610352
bl(	75	)=35.86310353
bl(	76	)=35.82309816
bl(	77	)=35.77747374
bl(	78	)=35.72755809
bl(	79	)=35.67460556
bl(	80	)=35.61978487
bl(	81	)=35.5641696
bl(	82	)=35.50873122
bl(	83	)=35.45433454
bl(	84	)=35.40173533
bl(	85	)=35.35157991
bl(	86	)=35.30440659
bl(	87	)=35.26064861
bl(	88	)=35.22063849
bl(	89	)=35.18461353
bl(	90	)=35.15272216
bl(	91	)=35.1250311
bl(	92	)=35.10153304
bl(	93	)=35.08215463
bl(	94	)=35.06676475
bl(	95	)=35.05518274
bl(	96	)=35.04718654
bl(	97	)=35.04252071
bl(	98	)=35.04090399
bl(	99	)=35.04203661
bl(	100	)=35.04560695
bl(	101	)=35.05129785
bl(	102	)=35.0587922
bl(	103	)=35.06777801
bl(	104	)=35.07795281
bl(	105	)=35.08902748
bl(	106	)=35.10072942
bl(	107	)=35.11280512
bl(	108	)=35.12502218
bl(	109	)=35.13717074
bl(	110	)=35.14906446
bl(	111	)=35.16054093
bl(	112	)=35.17146173
bl(	113	)=35.18171208
bl(	114	)=35.19120015
bl(	115	)=35.19985605
bl(	116	)=35.20763061
bl(	117	)=35.214494
bl(	118	)=35.22043406
bl(	119	)=35.22545467
bl(	120	)=35.22957396
bl(	121	)=35.23282248
bl(	122	)=35.23524141
bl(	123	)=35.23688075
bl(	124	)=35.23779762
bl(	125	)=35.23805452
bl(	126	)=35.23771783
bl(	127	)=35.2368563
bl(	128	)=35.23553969
bl(	129	)=35.23383758
bl(	130	)=35.23181827
bl(	131	)=35.22954782
bl(	132	)=35.22708924
bl(	133	)=35.22450181
bl(	134	)=35.22184053
bl(	135	)=35.21915572
bl(	136	)=35.21649268
bl(	137	)=35.21389155
bl(	138	)=35.21138718
bl(	139	)=35.20900916

```
b1(   140        )=35.20678152
b1(   141        )=35.20472484
b1(   142        )=35.20285257
b1(   143        )=35.20117521
b1(   144        )=35.19969869
b1(   145        )=35.19842511
b1(   146        )=35.1973531
b1(   147        )=35.19647823
b1(   148        )=35.19579339
b1(   149        )=35.19528921
b1(   150        )=35.19495444
b1(   151        )=35.19477634
b1(   152        )=35.194741
b1(   153        )=35.19483376
b1(   154        )=35.19503945
b1(   155        )=35.19534274
b1(   156        )=35.19572837
b1(   157        )=35.19618141
b1(   158        )=35.19668743
b1(   159        )=35.19723272
b1(   160        )=35.19780438
ii=0.
dm=1
do j=1,40
     ii(j,j)=1.0
end do
atai=ii
do j=1,80
     do k=1,40
       if (j+1-k.le.0)then
                a1(j,k)=0
       else
                a1(j,k)=b1(j+1-k)
       end if
     end do
end do
a1t=transpose(a1)
ata=matmul(a1t, a1)
ata=ata+20*ii
do i=1,40
     aa=ata(i,i)
     do j=1,40
       ata(i,j)=ata(i,j)/aa
       atai(i,j)=atai(i,j)/aa
     end do
     if (i.ne.40)then
       do j=1,40-i
                bb=ata(41-j,i)
                do l=1,40
                  ata(41-j,l)=ata(41-j,l)-bb*ata(i,l)
                  atai(41-j,l)=atai(41-j,l)-bb*atai(i,l)
                end do
       end do
     end if
end do
do i=1,39
     if (i.ne.40)then
       do j=1,40-i
                bb=ata(j,41-i)
                do l=1,40
                  ata(j,l)=ata(j,l)-bb*ata(41-i,l)
                  atai(j,l)=atai(j,l)-bb*atai(41-i,l)
                end do
       end do
     end if
end do
!initial
h=4.654597719
v=4.9839743261
f=0.311
sp=4.654597719
```

```
          time=0
          delta=1
100       vdot=0.0107*h-0.002005*v**2
          if (cc.eq.0)then
                f=f+df
          end if
          if (f.lt.0)then
                f=0
          end if
          if (time.eq.0)then
!               sp=4.7
                f=0.35
          end if
          hdot=f-0.0624*v
!if (cc.eq.0)then
          write (1,3)time,v,h,f,df
3         format(15f15.10)
!end if
          i=i+1
          if (i.eq.60)then
                i=0
          end if
          v=v+vdot*delta
          h=h+hdot*delta
          if (cc.eq.0)then
          do j=1,79
                dmo(81-j)=dmo(80-j)
          end do
          dmo(1)=dm(1)
          if (time.eq.0)then
                dmo(1)=0
          end if
          do j=1,80
                xol(j)=0
                do k=1,80
                   xol(j)=xol(j)+(b1(j+k)-b1(k))*dmo(k)
                end do
                xol(j)=h+xol(j)
          end do
          aaa=matmul(atai,a1t)
          do i=1,80
                x(i)=sp-xol(i)
          end do
          dm=matmul(aaa,x)
          df=dm(1)
          end if
          cc=cc+1
          if (cc.eq.5)then
                cc=0
          end if
          time=time+delta
          if(time.le.1000) goto 100
end program
```

Appendix I Source Code of Plug-flow and CSTR

I.1 Plug-flow and CSTR with Feedback Control

```
program gravitytank  !this is plug-flow plus CSTR
        implicit none
        integer i                                   !index
        real(8) h                                   !height
        real(8) f                                   !feed
        real(8) time                                !time
        real(8) delta                               !time step
        real(8) sp                                  !set point
        real(8) b1(32)
        real(8) ff(16)
        real(8) hold
        real(8) df
        real(8) dv
        real(8) dc(20)
        real(8) con(16)                             !concentration of substance
        real(8) incon                               !initial concentration
        real(8) aa
        real(8) bb
        real(8) cc
        real(8) dh
        real(8) k,tari,tard                         !controller parameter
        OPEN (1, file = 'output.xls')
        !initial
        f=4.0d0
        dv=1.0d0
        incon=100.0d0
        con=0.0d0
        sp=103.8522256042d0
        time=0
        delta=1.0d0
100     f=f+df
        if (time.eq.30) then
                f=6.0d0
!               sp=18.00D0
        end if
        !CSTR
        !conversion of CSTR =0.5 per volumn of CSTR
        ff(16)=0.5*ff(15)
        con(16)=con(15)-(ff(15)-ff(16))/10.0  !Volumn of CSTR =10 m3
        hold=h
        h=con(16)
        !plug flow
        !conversion of plug flow =0.2 per dv
        do i=1,15
                if (16-i.eq.1)then
                        ff(16-i)=0.8*f
                        con(16-i)=incon-(ff(16-i)-f)/dv
                else
                        ff(16-i)=0.8*ff(15-i)
                        con(16-i)=con(15-i)-(ff(16-i)-ff(15-i))/dv
                end if
        end do
        !if (cc.eq.0) then
        write(1,400) time,h,f,df,sp
        400 format(15f20.10)
        !end if
        if (time.ge.30) then
                k=0.6*0.1052
                tari=62/2.
                tard=62/8.
                dh=df
                df=k*((sp-h)+1/tari*(sp-incon+(ff(15)-f)/1d0+(ff(15)-ff(16))/10.0d0)*delta-tard*dh)
        end if
```

```
        time=time+delta
        if(time.le.10000) goto 100
end program
```

I.2 Plug-flow and CSTR with DMC

```
program gravitytank  !this is plug-flow plus CSTR
        implicit none
        integer i,j,k,l,m
        real(8) h                          !height
        real(8) f                          !feed (kmol/s)
        real(8) time                       !time
        real(8) delta                      !time step
        real(8) sp                         !set point
        real(8) a1(11,4)
        real(8) b1(32)
        real(8) x(11)
        real(8) ff(16)
        real(8) dmo(11)
        real(8) dm(4)
        real(8) xol(11)
        real(8) xcl(11)
        real(8) df
        real(8) dv                         !differential of plug-flow volumn (m3)
        real(8) a1t(4,11)
        real(8) ata(4,4)
        real(8) ii(4,4)
        real(8) atai(4,4)
        real(8) aaa(4,11)
        real(8) con(16)                    !concentration of substance (kmol/m3)
        real(8) incon                      !initial concentration of substance (kmol/m3)
        real(8) aa
        real(8) bb
        real(8) cc
        OPEN (1, file = 'output.xls')
        b1(     1       )=      0
        b1(     2       )=      0
        b1(     3       )=      0
        b1(     4       )=      -0.966574839
        b1(     5       )=      -0.966574839
        b1(     6       )=      -0.966574839
        b1(     7       )=      -0.966574839
        b1(     8       )=      -0.966574839
        b1(     9       )=      -0.966574839
        b1(     10      )=      -0.966574839
        b1(     11      )=      -0.966574839
        b1(     12      )=      -0.966574839
        b1(     13      )=      -0.966574839
        b1(     14      )=      -0.966574839
        b1(     15      )=      -0.966574839
        b1(     16      )=      -0.966574839
        b1(     17      )=      -0.966574839
        b1(     18      )=      -0.966574839
        b1(     19      )=      -0.966574839
        b1(     20      )=      -0.966574839
        b1(     21      )=      -0.966574839
        b1(     22      )=      -0.966574839
        b1(     23      )=      -0.966574839
        b1(     24      )=      -0.966574839
        b1(     25      )=      -0.966574839
        b1(     26      )=      -0.966574839
        b1(     27      )=      -0.966574839
        b1(     28      )=      -0.966574839
        b1(     29      )=      -0.966574839
        b1(     30      )=      -0.966574839
        b1(     31      )=      -0.966574839
        b1(     32      )=      -0.966574839
        ii=0.
```

```
        dm=1
        dmo=0
        do j=1,4
                ii(j,j)=1.0
        end do
        atai=ii
        do j=1,11
                do k=1,4
                        if (j+1-k.le.0)then
                                a1(j,k)=0
                        else
                                a1(j,k)=b1(j+1-k)
                        end if
                end do
        end do
        a1t=transpose(a1)
        ata=matmul(a1t, a1)
        ata=ata+40*ii
        do i=1,4
                aa=ata(i,i)
                do j=1,4
                        ata(i,j)=ata(i,j)/aa
                        atai(i,j)=atai(i,j)/aa
                end do
                if (i.ne.4)then
                        do j=1,4-i
                                bb=ata(5-j,i)
                                do l=1,4
                                        ata(5-j,l)=ata(5-j,l)-bb*ata(i,l)
                                        atai(5-j,l)=atai(5-j,l)-bb*atai(i,l)
                                end do
                        end do
                end if
        end do
        do i=1,3
                if (i.ne.4)then
                        do j=1,4-i
                                bb=ata(j,5-i)
                                do l=1,4
                                        ata(j,l)=ata(j,l)-bb*ata(5-i,l)
                                        atai(j,l)=atai(j,l)-bb*atai(5-i,l)
                                end do
                        end do
                end if
        end do
        !initial
        f=4.0d0
        dv=1.0d0
        incon=100.0d0
        con=0
        sp=96.1337006438
        time=0
        delta=1
        cc=0.
100     if (cc.eq.0)then
                f=f+df
        end if
        if (time.eq.30) then
!               f=6.0d0
                sp=18.00D0
        end if
        !CSTR
        !conversion of CSTR =0.5 per volumn of CSTR
        ff(16)=0.5*ff(15)
        con(16)=con(15)-(ff(15)-ff(16))/10  !Volumn of CSTR =10 m3
        h=con(16)
        !plug flow
        !conversion of plug flow =0.2 per dv
        do i=1,15
                if (16-i.eq.1)then
                        ff(16-i)=0.8*f
```

```
                        con(16-i)=incon+(ff(16-i)-f)/dv
                else
                        ff(16-i)=0.8*ff(15-i)
                        con(16-i)=con(15-i)+(ff(16-i)-ff(15-i))/dv
                end if
        end do
        !if (cc.eq.0) then
        write(1,400) time,h,f,df
        400 format(15f20.10)
        !end if
        if (cc.eq.0.and.time.ge.30)then
        do j=1,10
                dmo(12-j)=dmo(11-j)
        end do
        dmo(1)=dm(1)/10
        if (time.eq.0)then
                dmo(1)=0
        end if
        do j=1,11
                xol(j)=0
                do k=1,11
                        xol(j)=xol(j)+(b1(j+k)-b1(k))*dmo(k)
                end do
                xol(j)=h+xol(j)
        end do
        aaa=matmul(atai,a1t)
        do i=1,11
                x(i)=sp-xol(i)
        end do
        dm=matmul(aaa,x)
        df=dm(1)
        end if
        cc=cc+delta
        if (cc.eq.5)then
                cc=0
        end if
        time=time+delta
        if(time.le.1000) goto 100
end program
```

Appendix J Source Code of Depropanizer Column

J.1 Depropanizer Column with Cascade Control

```
program distillation
        implicit none
        integer i,ite,j,k               !index
        integer ib,it                   !index of sensitive tray
        integer h,m,s                   !time index
        integer tf                      !tray of feed
        integer n                       !number if tray and n th tray
        real(8) a                       !factor
        real(8) aa                      !parameter
        real(8) am(200,2)               !accumulate of liquid in tray (kg-mol/minute)
        real(8) amo                     !accumulate of liquid in tray at old iteration (kg-mol/minute)
        real(8) b(2)                    !bottom product flowrate (kg-mol/minute)
        real(8) cpn                     !heat capacity of cool water (kJ/(C*kg-mol))
        real(8) cpw                     !heat capacity of hot water      (kJ/(C*kg-mol))
        real(8) d(2)                    !distillate (kg-mol/minute)
        real(8) db                      !bottom product flow rate change (kg-mol/s)
        real(8) dcb                     !set point of reboiler change (kg-mol/s)
        real(8) dct                     !set point of reflux change (kg-mol/s)
        real(8) dd                      !distillate flow rate change (kg-mol/s)
        real(8) denliq(200)             !density of liquid (kg-mol/m3)
        real(8) dl1                     !reflux flow rate change (kg-mol/s)
        real(8) ds                      !steam flow rate change (kg-mol/s)
        real(8) dt                      !constant step time     (1 second)
        real(8) f                       !feed (kg-mol/minute)
        real(8) finequa                 !feed in equation
        real(8) ft                      !feed temperature
        real(8) ha                      !total feed enthalpy
        real(8) haineq                  !enthalpy of feed in equation
        real(8) high(200)               !high of liquid in tray,bottom column and reflux reboiler (m)
        real(8) highold(2)              !high of liquid in bottom column and reflux reboiler at old step time (m)
        real(8) hl(200)                 !total liquid enthalpy (kj/kg-mol)
        real(8) hlb                     !liquid enthalpy of bottom column (kj/kg-mol)
        real(8) hv(200)                 !total vapor enthalpy (kj/kg-mol)
        real(8) hvb                     !vapor enthalpy of bottom column (kj/kg-mol)
        real(8) keep(1000)              !keep value
        real(8) l(200,2)                !liquid flow (kg-mol/minute)
        real(8) lo                      !liquid flow of tray No. 1 at old step time (kg-mol/minute)
        real(8) p(200)                  !pressure on tray (bar)
        real(8) pb                      !pressure of bottom column (bar)
        real(8) pf                      !pressure of feed (bar)
        real(8) qc                      !heat duty of condenser (kj)
        real(8) qcc                     !heat duty of condenser for minute (kj)
        real(8) qr                      !heat duty of reboiler (kj)
        real(8) qrc                     !heat duty of reboiler for minute (kj)
        real(8) qn                      !flowrate of cool water (kg-mol/half-minute)
        real(8) qw                      !flowrate of hot water (kg-mol/half-minute)
        real(8) qwo                     !flowrate of hot water at old step time (kg-mol/minute)
        real(8) scond                   !surface area of condenser (m2)
        real(8) sph                     !set point of liquid level in drum (m)
        real(8) sphb                    !set point of liquid level in bottom column (m)
        real(8) spl1                    !set point of reflux (kg-mol/min)
        real(8) spcb                    !set point of cascade at bottom column (K)
        real(8) spct                    !set point of cascade at top column (K)
        real(8) sps                     !setpoint of steam flow rate (kg-mol/s)
        real(8) sreb                    !surface area of reboiler (m2)
        real(8) t(200)                  !temperature of tray (K)
        real(8) tb                      !bottom temperature (K)
        real(8) tib                     !temperature at tray no.ib th
        real(8) tit                     !temperature at tray no.it th
        real(8) tnout                   !temperature of nitrogen out of condenser (K)
        real(8) tnin                    !temperature of nitrogen enter condenser (K)
        real(8) told(2)                 !temperature of sensitive tray at30 second ago (K)
        real(8) twout                   !temperature of hot water out of reboler (K)
        real(8) twin                    !temperature of hot water enter reboiler (K)
```

```
real(8) ureb                !over all heat transfer coefficient of reboiler (Kw/m2 C)
real(8) ucond               !over all heat transfer coefficient of condenser (Kw/m2 C)
real(8) unwant              !unwant parameter
real(8) v(200,2)            !vapor flow (kg-mol/minute)
real(8) x(2,200,2)          !liquid composition (component,tray,time)
real(8) xb(2)               !liquid composition at bottom column
real(8) xx(2)               !keep liquid component value
real(8) y(2,200,2)          !vapor composition (component,tray,time)
real(8) yb(2)               !vapor composition at bottom column
real(8) z(2)                !feed composition
open (1,file='output.xls')
open (2,file='save.dat')
!initial value
n=30
am=0.50312
cpn=6024.96
cpw=6024.96
dt=1./60
f=0.09
unwant=0
ft=323
hl=0
l=0
it=6
ib=25
p=1.01325
pf=2.0265
pb=1.01325
qn=0.5
qw=0.001
scond=1000
sreb=1000
spcb=375.8
spct=321.1
sph=0.4
sphb=0.4
spl1=0.315
sps=0.20
t=320
tb=320
tf=n
tnin=288
twin=393
ureb=0.438139514
ucond=0.438139514
v=0
xb=0
yb(1)=0.5
yb(2)=0.5
z(1)=0.5
z(2)=0.5
call enth(pf,ft,unwant,unwant,z(1),z(2),unwant,ha) !calculate enthalpy
do j=1,n
        do i=1,2
                x(i,j,1)=0
                x(i,j,2)=0
        end do
        if (j.lt.n)then
                y(1,j,2)=0.5
                y(2,j,2)=0.5
        end if
        call enth(p(j),t(j),x(1,j,1),x(2,j,1),y(1,j,2),y(2,j,2),hl(j),hv(j)) !calculate enthalpy
        hl(j)=hv(j)
end do
call enth(pb,tb,xb(1),xb(2),yb(1),yb(2),hlb,hvb)
do i=1,1000
        read (2,*) keep(i)
end do
do i=1,n-1
        x(1,i,2)=keep(i)
end do
```

```
xb(1)=keep(30)
do i=1,n-1
        x(2,i,2)=keep(30+i)
end do
xb(2)=keep(60)
do i=1,n
        y(1,i,2)=keep(60+i)
end do
yb(1)=keep(91)
do i=1,n
        y(2,i,2)=keep(91+i)
end do
yb(2)=keep(122)
do i=1,n
        am(i,2)=keep(122+i)
end do
do i=1,n
        am(i,1)=keep(152+i)
end do
do i=1,n
        high(i)=keep(182+i)
end do
do i=1,n-1
        t(i)=keep(212+i)
end do
tb=keep(242)
told(1)=keep(243)
told(2)=keep(244)
do i=1,n-1
        p(i)=keep(244+i)
end do
pb=keep(274)
do i=1,n
        hl(i)=keep(274+i)
end do
hlb=keep(305)
do i=1,n
        hv(i)=keep(305+i)
end do
hvb=keep(336)
ha=keep(337)
ft=keep(338)
f=keep(339)
z(1)=keep(340)
z(2)=keep(341)
do i=1,n
        v(i,2)=keep(341+i)
end do
do i=1,n
        l(i,2)=keep(371+i)
end do
d(2)=keep(402)
b(2)=keep(403)
qw=keep(404)
qwo=keep(405)
qr=keep(406)
qc=keep(407)
qcc=keep(408)
qrc=keep(409)
lo=keep(410)
do i=1,n
        x(1,i,1)=keep(410+i)
end do
do i=1,n
        x(2,i,1)=keep(440+i)
end do
do i=1,n
        y(1,i,1)=keep(470+i)
end do
do i=1,n
        y(2,i,1)=keep(500+i)
```

```
end do
do i=1,n
        v(i,1)=keep(530+i)
end do
do i=1,n
        l(i,1)=keep(560+i)
end do
sreb=keep(591)
spcb=keep(592)
spct=keep(593)
sph=keep(594)
sphb=keep(595)
spl1=keep(596)
sps=keep(597)
tf=keep(598)
it=keep(599)
ib=keep(600)
pf=keep(601)
scond=keep(602)
amo=keep(603)
ucond=keep(604)
ureb=keep(605)
dd=keep(606)
dl1=keep(607)
ds=keep(608)
dcb=keep(609)
dct=keep(610)
db=keep(611)
qn=keep(612)
tnin=keep(613)
tnout=keep(614)
twin=keep(615)
twout=keep(616)
do i=1,n
        denliq(i)=keep(616+i)
end do

do h=1,8000
        do m=1,60
                do s=1,60
                        write (6,111) h,high(1),high(n),t(6),t(25),l(1,2),qw,b(2),d(2)
                        111 format (1i,15f13.7)
                        if (high(n/2).ge.0.03175)then
                                tf=n/2
                                pf=17.0
                                ft=369.0
                                f=0.09
                                z(1)=0.5
                                z(2)=0.5
                                if (h.ge.1)then  !disturbance occur
                                        !z(1)=0.3
                                        !z(2)=0.7
                                        !f=0.1
                                        !spct=323.1
                                        !qw=0.02
                                end if
                                unwant=0
                                call enth(pf,ft,z(1),z(2),unwant,unwant,ha,unwant) !calculate enthalpy
                        end if
                        if (s.eq.1)then
                                told(2)=t(it)
                                spl1=spl1+dct
                        end if
                        !condenser & reflux drum
                        call l1control(spl1,l(1,2),dl1,lo) !  call control of reflux flow rate
                        lo=l(1,2)
                        l(1,2)=l(1,2)+dl1
                        if (s.eq.1)then
                                d(2)=d(2)+dd
                        end if
                        if (d(2).lt.0.or.high(1).le.0)then
```

```
        d(2)=0
        dd=0
    end if
    if (l(1,2).lt.0.or.high(1).le.0)then
        l(1,2)=0
    end if
    am(1,2)=am(1,1)+(v(2,2)-l(1,2)-d(2))*dt !calculate accumulate in drum
    if (am(1,2).lt.0)then
        am(1,2)=0
    end if
    call dliq(t(1),x(1,1,2),x(2,1,2),denliq(1))
    if (s.eq.1)then
        highold(1)=high(1)
    end if
    high(1)=am(1,2)/(denliq(1)*1.23)
    if (denliq(1).eq.0.or.high(1).le.0)then
        high(1)=0
    end if
    if (x(1,1,1).eq.0.and.x(2,1,1).eq.0) then
        do i=1,2
            x(i,1,1)=y(i,1,2)
        end do
    end if
x(1,1,2)=(x(1,1,1)*am(1,1)+(v(2,2)*y(1,2,2))*dt)/(am(1,2)+(l(1,2)+d(2))*dt) !calculate composition in drum
    if (x(1,1,2).lt.0.0000000001)then
        x(1,1,2)=0
    end if
    x(2,1,2)=1.-x(1,1,2)
    a=exp(-(ucond*scond)/(qn*cpn))
    tnout=tnin+(1-a)*(t(2)-tnin)
    qc=qn*cpn*(tnout-tnin) !calculate heat duty of reboiler
    if (t(1).lt.308)then
        qc=0
    end if
    p(1)=16.00
    call bubpt(p(1),x(1,1,2),x(2,1,2),y(1,1,2),y(2,1,2),t(1))
    call enth(p(1),t(1),x(1,1,2),x(2,1,2),y(1,1,2),y(2,1,2),hl(1),hv(1))
    x(1,1,1)=x(1,1,2)
    x(2,1,1)=x(2,1,2)
    y(1,1,1)=y(1,1,2)
    y(2,1,1)=y(2,1,2)
    am(1,1)=am(1,2)
    v(1,1)=v(1,2)
    l(1,1)=l(1,2)

    !tray
    do j=2,n-1
        if(j.eq.tf)then
            finequa=f
            haineq=ha
        else
            finequa=0
            haineq=0
        end if
        am(j,2)=am(j,1)
1       amo=am(j,2)
        call dliq(t(j),x(1,j,2),x(2,j,2),denliq(j))
        high(j)=am(j,2)/(denliq(j)*0.982)
        if (denliq(j).eq.0.or.high(j).le.0)then
            high(j)=0
        end if
        if (high(j).lt.0.03175) then
            l(j,2)=0
        else
            l(j,2)=denliq(j)*1.17*(am(j,2)/(denliq(j)*0.982)-
0.03175)**1.5
            if ((am(j,2))/(denliq(j)*0.982).lt.0.03175)then
                l(j,2)=0
            end if
```

```
                    if (l(j,2).lt.0)then
                            l(j,2)=0
                    end if
            end if
            am(j,2)=am(j,1)+(finequa+v(j+1,2)+l(j-1,2)-l(j,2)-v(j,2))*dt !calculate accumulate in tray
            if (am(j,2).lt.0)then
                    am(j,2)=0
            end if
            if (abs((amo-am(j,2))/amo).gt.0.000001) goto 1
            if (denliq(j).eq.0)then
                    am(j,2)=am(j,1)+(finequa+v(j+1,2)+l(j-1,2)-v(j,2))*dt
                    if (am(j,2).lt.0)then
                            am(j,2)=0
                    end if
            end if
            if (x(1,j,1).eq.0.and.x(2,j,1).eq.0) then
                    do i=1,2
                            x(i,j,1)=y(i,j,2)
                    end do
            end if
            x(1,j,2)=(x(1,j,1)*am(j,1)+(finequa*z(1)+v(j+1,2)*y(1,j+1,2)+l(j-1,2)*x(1,j-1,2)-v(j,2)*y(1,j,2))*dt)/(am(j,2)+l(j,2)*dt)
            if (x(1,j,2).lt.0)then
                    x(1,j,2)=0
            end if
            x(2,j,2)=1.-x(1,j,2)
            p(j)=p(j-1)+0.065
            call bubpt(p(j),x(1,j,2),x(2,j,2),y(1,j,2),y(2,j,2),t(j))
            call enth(p(j),t(j),x(1,j,2),x(2,j,2),y(1,j,2),y(2,j,2),hl(j),hv(j))
            v(j,2)=(hv(j+1)*v(j+1,2)+hl(j-1)*l(j-1,2)+finequa*haineq-l(j,2)*hl(j))/hv(j)
            if (v(j,2).lt.0)then
                    v(j,2)=0
            end if
    end do
    do j=2,n-1
            x(1,j,1)=x(1,j,2)
            x(2,j,1)=x(2,j,2)
            y(1,j,1)=y(1,j,2)
            y(2,j,1)=y(2,j,2)
            am(j,1)=am(j,2)
            v(j,1)=v(j,2)
            l(j,1)=l(j,2)
    end do
    !reboiler & column bottom
    if (s.eq.1)then
            told(1)=t(ib)
            sps=sps+dcb
    end if
    if (sps.lt.0)then
            sps=0
    end if
    if(n.eq.tf)then
            finequa=f
            haineq=ha
    else
            finequa=0
            haineq=0
    end if
    if (high(n).ge.0.3)then
            call scontrol(sps,qw,ds,qwo) !  call control of steam flow rate
    else
            ds=0
    end if
    qwo=qw
    qw=qw+ds
    if (qw.lt.0)then
            qw=0
    end if
    if (qw.le.0.000001) goto 2
```

```
if (high(n).ge.0.3)then
        a=exp((ureb*sreb)/(qw*cpw))
        twout=(twin+(a-1)*tb)/a
        qr=qw*cpw*(twin-twout) !calculate heat duty of reboiler
end if
2       if (high(n).lt.0.1.or.qw.le.0.0001)then
        qr=0
end if
am(n,2)=am(n,1)+(finequa+l(n-1,2)-v(n,2)-b(2))*dt !calculate accumulate in
bottom column
if (am(n,2).lt.0)then
        am(n,2)=0
end if
if (high(n).lt.0.3.and.v(n,2).ne.0)then
        unwant=0
        call enth(pb,tb,unwant,unwant,yb(1),yb(2),unwant,hvb) !calculate
enthalpy
        hv(n)=hvb
        do i=1,2
                y(i,n,2)=yb(i)
        end do
end if
if (xb(1).eq.0.and.xb(2).eq.0)then
        xb(1)=yb(1)
        xb(2)=yb(2)
end if
xb(1)=(xb(1)*am(n,1)+(finequa*z(1)+l(n-1,2)*x(1,n-1,2)-
v(n,2)*yb(1))*dt)/(am(n,2)+b(2)*dt) !calculate liquid composition in bottom column
if (xb(1).lt.0.0000000001)then
        xb(1)=0
end if
xb(2)=1.-xb(1)
pb=p(n-1)+0.065
call bubpt(pb,xb(1),xb(2),yb(1),yb(2),tb)
do i=1,2
        y(i,n,2)=yb(i)
end do
call dliq(t(n),xb(1),xb(2),denliq(n))
if (s.eq.1)then
        highold(2)=high(n)
end if
high(n)=am(n,2)/(denliq(n)*1.23)
if (denliq(n).eq.0.or.high(n).le.0)then
        high(n)=0
end if
call enth(pb,tb,xb(1),xb(2),yb(1),yb(2),hlb,hvb)
v(n,2)=(qr+finequa*haineq+hl(n-1)*l(n-1,2)-hlb*b(2))/hvb
if (v(n,2).lt.0)then
        v(n,2)=0
end if
if (s.eq.1)then
        b(2)=b(2)+db
end if
if (high(n).le.0)then
        high(n)=0
        b(2)=0
        db=0
end if
if (b(2).lt.0)then
        b(2)=0
        db=0
end if
do i=1,2
        x(i,n,2)=xb(i)
        y(i,n,2)=yb(i)
end do
x(1,n,1)=x(1,n,2)
x(2,n,1)=x(2,n,2)
y(1,n,1)=y(1,n,2)
y(2,n,1)=y(2,n,2)
am(n,1)=am(n,2)
```

```
v(n,1)=v(n,2)
l(n,1)=l(n,2)
call dcontrol(sph,high(1),dd,v(2,2),d(2),l(1,2),denliq(1),highold(1))
call bcontrol(sphb,high(n),db,v(n,2),b(2),l(n-1,2),denliq(n),highold(2)) ! call
```

control of bottom flow rate

```
if (h.ge.1000.and.m.eq.60.and.s.eq.60)then
        open (2,file='save.dat')
        do i=1,n-1
                keep(i)=x(1,i,2)
        end do
                keep(30)=xb(1)
        do i=1,n-1
                keep(30+i)=x(2,i,2)
        end do
                keep(60)=xb(2)
        do i=1,n
                keep(60+i)=y(1,i,2)
        end do
        keep(91)=yb(1)
        do i=1,n
                keep(91+i)=y(2,i,2)
        end do
                keep(122)=yb(2)
        do i=1,n
                keep(122+i)=am(i,2)
        end do
        do i=1,n
                keep(152+i)=am(i,1)
        end do
        do i=1,n
                keep(182+i)=high(i)
        end do
        do i=1,n-1
                keep(212+i)=t(i)
        end do
        keep(242)=tb
        keep(243)=told(1)
        keep(244)=told(2)
        do i=1,n-1
                keep(244+i)=p(i)
        end do
                keep(274)=pb
        do i=1,n
                keep(274+i)=hl(i)
        end do
                keep(305)=hlb
        do i=1,n
                keep(305+i)=hv(i)
        end do
        keep(336)=hvb
        keep(337)=ha
        keep(338)=ft
        keep(339)=f
        keep(340)=z(1)
        keep(341)=z(2)
        do i=1,n
                keep(341+i)=v(i,2)
        end do
        do i=1,n
                keep(371+i)=l(i,2)
        end do
        keep(402)=d(2)
        keep(403)=b(2)
        keep(404)=qw
        keep(405)=qwo
        keep(406)=qr
        keep(407)=qc
        keep(408)=qcc
        keep(409)=qrc
        keep(410)=lo
        do i=1,n
```

```
                        keep(410+i)=x(1,i,1)
                end do
                do i=1,n
                        keep(440+i)=x(2,i,1)
                end do
                do i=1,n
                        keep(470+i)=y(1,i,1)
                end do
                do i=1,n
                        keep(500+i)=y(2,i,1)
                end do
                do i=1,n
                        keep(530+i)=v(i,1)
                end do
                do i=1,n
                        keep(560+i)=l(i,1)
                end do
                keep(591)=sreb
                keep(592)=spcb
                keep(593)=spct
                keep(594)=sph
                keep(595)=sphb
                keep(596)=spl1
                keep(597)=sps
                keep(598)=tf
                keep(599)=it
                keep(600)=ib
                keep(601)=pf
                keep(602)=scond
                keep(603)=amo
                keep(604)=ucond
                keep(605)=ureb
                keep(606)=dd
                keep(607)=dl1
                keep(608)=ds
                keep(609)=dcb
                keep(610)=dct
                keep(611)=db
                keep(612)=qn
                keep(613)=tnin
                keep(614)=tnout
                keep(615)=twin
                keep(616)=twout
                do i=1,n
                        keep(616+i)=denliq(i)
                end do
                do i=1,1000
                        write(2,*) keep(i)
                end do
                close(2)
        end if
    end do !s
    !DO J=1,N
        !IF (M.GE.53.AND.H.GE.1) THEN !S.EQ.60.AND.
        IF (H.ge.1.AND.M.GE.1)
THEN !S.EQ.60.AND.M.GE.53.AND.H.GE.1   !.AND.M.GE.60.AND.s.eq.2
!       if (j.eq.n)then
        write(1,402)
h,m,t(6),t(25),x(1,1,2),xb(2),l(1,2),qw,d(2),b(2),high(1),high(n),spcb,spct
!       write(1,402)
H,M,J,TF,xb(1),xb(2),yb(1),yb(2),v(n,2),l(n,2),Tb,Pb,high(n),am(n,2),qr,b(2)
!       else
!       WRITE(1,402)
H,M,J,TF,x(1,j,2),x(2,j,2),y(1,j,2),y(2,j,2),v(j,2),l(j,2),T(J),P(J),high(J),am(J,2),denliq(j),d(2)
!       end if
        402 FORMAT(2i,2f10.1,20f10.4)
!       402 FORMAT(1I,1X,1I,1X,1I,1X,1I,1X,15F12.4)
        end if
!   END DO

    if (high(n).gt.0)then
```

```
                        tib =t(ib)
                        call cutdec1(tib)
                        call cbcontrol(spcb,tib,dcb,finequa,z(1),v(ib+1,2),y(1,ib+1,2),l(ib-1,2),x(1,ib-
1,2),v(ib,2),y(1,ib,2),l(ib,2),x(1,ib,2),told(1),am(ib,2))
                    else
                        dcb=0
                    end if
                    if (high(1).gt.0)then
                        tit=t(it)
                        call cutdec1(tit)
                        call ctcontrol(spct,tit,dct,finequa,z(1),v(it+1,2),y(1,it+1,2),l(it-1,2),x(1,it-
1,2),v(it,2),y(1,it,2),l(it,2),x(1,it,2),told(2),am(it,2))
                    else
                        dct=0
                    end if
                end do !m
            end do !h
end program


subroutine bubpt(pp,x1,x2,y1,y2,tt) !calculate temperature from bubble point equation
            integer i                                   !index
            real(8)  df                                 !differential of function
            real(8)  f                                  !function
            real(8)  pp                                 !pressure (bar)
            real(8)  ps1,ps2                            !vapor pressure (bar)
            real(8)  tt                                 !temperature (K)
            real(8)  x1,x2                              !liquid composition
            real(8) y1,y2                               !vapor composition
            real(8) yy1,yy2
1           ps1=exp(-369.348/(tt-168.126)+5.23749)              !calculate vapor pressure of propane
            ps2=exp(-1275.718/(tt-59.782)+6.85137)              !calculate vapor pressure of butane
            y1=x1*ps1/pp      !calculate vapor composition
            y2=x2*ps2/pp
            if (abs(1-y1-y2).lt.0.00000001) goto 10     !find correct temperature
            f=1-y1-y2
            df=x1/pp*ps1*369.348/(tt-168.126)**2
            df=df+x2/pp*ps2*1275.718/(tt-59.782)**2
            tt=tt+f/df
            goto 1
10          return
end


subroutine enth(p,t,x3,x4,y3,y4,hl,ha) ! calculate liquid and vapor entralpy from pressure,temperature, and composition
            use numerical_libraries
            implicit real*8 (a-h,o-z)
            real(8) t              !temperature
            real(8) p              !pressure
            real(8) y3,y4          !vapor composition of propane and butane
            real(8) x3,x4          !liquid composition
            real(8) ha             !total vapor enthalpy
            real(8) ha3            !vapor enthalpy of propane
            real(8) ha4            !vapor enthalpy of butane
            real(8) hll(2)         !liqid enthalpy of propane and butane
            real(8) hl             !total liquid enthalpy
            common/blkd1/popv(5),hvc3(5),hvc4(5)
            data popv/1.,5.,10.,15.,20./
            parameter (korder=3,ndata=5,nknot=ndata+korder)
            dimension x1data(ndata),f1data(ndata)
            dimension x1knot(nknot),bscoef1(ndata)
            integer i

            !calculate vapor enthalpy
            t=t-273.15
            if (p.eq.1.or.p.eq.5.or.p.eq.10.or.p.eq.15.or.p.eq.20)then
                    if (p.eq.1)then

            ha3=0.0000243589743879133*t**3+0.0216068764561292*t**2+16.7600885781487*t+3948.29071794724
                                  ha4=5171.95353379809+22.7750602176193*t+0.0285385198127802*t**2-
0.0000006546231517426*t**3
```

```
                end if
                if (p.eq.5)then

        ha3=3785.7155058276l+18.240793123538*t+0.0139970279720996*t**2+0.0000212237762234762*t**3
                            ha4=13362.9290022956-614.055453861994*t+19.4411005643476*t**2-
0.305859930252696*t**3+0.00264210823154405*t**4-0.0000118981890756778*t**5+0.0000000218680429435476*t**6
                end if
                if (p.eq.10)then
                            ha3=9299.88843643293-489.679087204064*t+18.2134871645406*t**2-
0.335630483024728*t**3+0.00337653409332662*t**4-0.0000176090629930964*t**5+0.0000000372728987837522*t**6
                            ha4=52119.620884926-4542.38831847744*t+183.561795154405*t**2-
3.96420633705897*t**3+0.0496691999500929*t**4-0.000361742582892285*t**5+0.00000142214836684578*t**6-
0.00000000233518724898894*t**7
                end if
                if (p.eq.15)then
                            ha3=3499.26966208774+10.0480539969921*t+0.235411990181417*t**2-
0.00185526320973007*t**3+0.00000546197552656038*t**4
                            ha4=-41073.9677943845+4570.52957391954*t-
185.978489301388*t**2+4.09239659695254*t**3-0.0523767526218596*t**4+0.000390079118628205*t**5-
0.00000156690531090442*t**6+0.00000000262353582012308*t**7
                end if
                if (p.eq.20)then
                            ha3=4127.1570396016+73.4391303904704*t-
4.99493677579601*t**2+0.125573969112786*t**3-0.00143072973061548*t**4+0.0000077793456208826*t**5-
0.0000000164069371112414*t**6
                            ha4=54716.6018791736-4931.18850411005*t+206.110049953317*t**2-
4.63591405624864*t**3+0.0608851762849367*t**4-0.000467220003840682*t**5+0.00000194083612282833*t**6-
0.00000000336865665585238*t**7
                end if
        else
                do i=1,5
                            x1data(i)=popv(i)
                end do
                do i=1,5
                            if (i.eq.1)then
                                        hvc3(i)=2.43589743879133*10**(-
6)*t**3+0.0216068764561292*t**2+16.7600885781487*t+3948.29071794724
                                        hvc4(i)=5171.95353379809+22.7750602176193*t+0.0285385198127802*t**2-
0.0000006546231517426*t**3
                            end if
                            if (i.eq.2)then

        hvc3(i)=3785.7155058276l+18.240793123538*t+0.0139970279720996*t**2+0.0000212237762234762*t**3
                                        hvc4(i)=13362.9290022956-614.055453861994*t+19.4411005643476*t**2-
0.305859930252696*t**3+0.00264210823154405*t**4-0.0000118981890756778*t**5+0.0000000218680429435476*t**6
                            end if
                            if (i.eq.3)then
                                        hvc3(i)=9299.88843643293-489.679087204064*t+18.2134871645406*t**2-
0.335630483024728*t**3+0.00337653409332662*t**4-0.0000176090629930964*t**5+0.0000000372728987837522*t**6
                                        hvc4(i)=52119.620884926-4542.38831847744*t+183.561795154405*t**2-
3.96420633705897*t**3+0.0496691999500929*t**4-0.000361742582892285*t**5+0.00000142214836684578*t**6-
0.00000000233518724898894*t**7
                            end if
                            if (i.eq.4)then
                                        hvc3(i)=3499.26966208774+10.0480539969921*t+0.235411990181417*t**2-
0.00185526320973007*t**3+0.00000546197552656038*t**4
                                        hvc4(i)=-41073.9677943845+4570.52957391954*t-
185.978489301388*t**2+4.09239659695254*t**3-0.0523767526218596*t**4+0.000390079118628205*t**5-
0.00000156690531090442*t**6+0.00000000262353582012308*t**7
                            end if
                            if (i.eq.5)then
                                        hvc3(i)=4127.1570396016+73.4391303904704*t-
4.99493677579601*t**2+0.125573969112786*t**3-0.00143072973061548*t**4+0.0000077793456208826*t**5-
0.0000000164069371112414*t**6
                                        hvc4(i)=54716.6018791736-4931.18850411005*t+206.110049953317*t**2-
4.63591405624864*t**3+0.0608851762849367*t**4-0.000467220003840682*t**5+0.00000194083612282833*t**6-
0.00000000336865665585238*t**7
                            end if
                            f1data(i)=hvc3(i)
                end do
                call dbsnak(ndata,x1data,korder,x1knot)
```

```
                call dbsint(ndata,x1data,f1data,korder,x1knot,bscoef1)
                ncoef=ndata
                ha3=dbsval(p,korder,x1knot,ncoef,bscoef1)
                do i=1,5
                        f1data(i)=hvc4(i)
                enddo
                call dbsint(ndata,x1data,f1data,korder,x1knot,bscoef1)
                ha4=dbsval(p,korder,x1knot,ncoef,bscoef1)
        end if
        ha=4.186*(ha3*y3+ha4*y4)
        t=t+273.15
        ! calculate liquid enthalpy
        do i=1,2
                check_component: select case (i) ! select composition
                case (1)
                        if(t.le.373)then
                                hll(1)=0.000198088*t**4-0.263253174*t**3+131.264949*t**2-
29069.26192*t+2410921.733
                        else
                                hll(1)=0.0227*t**2+9.0203*t-2851.2
                        end if
                case (2)
                        hll(2)=0.00000626941753153494*t**4-0.008361954*t**3+4.249105865*t**2-
936.7516086*t+74283.83672
                end select check_component
        end do
        hl=4.186*(x3*hll(1)+x4*hll(2))
end

subroutine dliq(tt,x11,x22,denliq) !calculate density of liquid
        real(8) a(2)                    !parameter
        real(8) avmw                    !average molecular weight
        real(8) b(2)                    !parameter
        real(8) den(2)                  !liquid density of i component
        real(8) denliq                  !mixture liquid density
        real(8) n(2)                    !parameter
        real(8) m(2)                    !molecular weight
        real(8) tt                      !temperature
        real(8) tc(2)                   !critical temperature
        real(8) x1,x11                  !liquid propane composition
        real(8) x2,x22                  !liquid butane composition
        data tc(1),tc(2)/369.82,452.15/ ! critical temperature
        data m(1),m(2)/44.097,58.124/  ! molecular weight
        data a(1),a(2)/0.22151,0.22827/ ! parameter for calculate liquid density
        data b(1),b(2)/0.27744,0.27240/ ! parameter for calculate liquid density
        data n(1),n(2)/0.28700,0.28630/ ! parameter for calculate liquid density
        if (x11.eq.0.and.x22.eq.0)then
                denliq=0
                return
        end if
        x1=x11/(x11+x22)
        x2=x22/(x11+x22)
        if (tt.gt.369.8)then
                den(1)=a(1)*b(1)**(-1*(1-369.8/tc(1))**n(1))
                den(2)=a(2)*b(2)**(-1*(1-tt/tc(2))**n(2))
                goto 1
        end if
        do i=1,2  ! calculate density of component
                den(i)=a(i)*b(i)**(-1*(1-tt/tc(i))**n(i))
        end do
1       avmw=x1*m(1)+x2*m(2) ! calculate average molecular weight
        denliq=1000*(x1*den(1)/m(1)+x2*den(2)/m(2)) ! calculate density of liquid mixture
end

subroutine cutdecl(dd) ! cut decimal
        real(8) dd,aa,bb,cc
        aa=(int(dd*100))
        bb=(int(dd*10))
        cc=aa/100-bb/10
```

```
            if (cc*100.ge.5)then
                    dd=bb/10+0.1d0
            else
                    dd=bb/10
            end if
end

subroutine dcontrol(sph,h,dd,v2,d,l1,den,hold) ! control level in reflux drum (feed back)
            real(8) sph,h,k,tari,tard,dt,dd,dh,v2,d,l1,den,hold
            integer i
            k=0.6*15
            tari=18/2.
            tard=18/8.
            dt=1.
            if (den.eq.0)then
                    dd=0
                    return
            end if
            dh=(v2-d-l1)/(12.33*den)
            dd=k*((h-sph)+1/tari*(hold+dh*dt/2-sph)*dt+tard*dh)
end

subroutine l1control(sp,l1,dl1,l1o) ! control reflux flow rate
            real(8) sp,l1,k,tari,tard,dt,dl1,l1o
            integer i
            k=0.6*2
            tari=2/2.
            tard=2/8.
            dt=1.
            dl1=k*((sp-l1)+1/tari*(sp-l1o-dl1*dt/2)*dt-tard*dl1)
end

subroutine scontrol(sp,s,ds,so) ! control steam flow rate (feed forward)
            real(8) sp,s,k,tari,tard,dt,ds,so
            integer i
            k=0.6*2
            tari=2/2.
            tard=2/8.
            dt=1.
            ds=k*((sp-s)+1/tari*(sp-so-ds*dt/2)*dt-tard*ds)
end


subroutine bcontrol(sph,h,db,vn,b,lnm1,den,hold) ! control level in bottom column (feed back)
            real(8) sph,h,k,tari,tard,dt,db,dh,vn,b,lnm1,den,d2h,hold
            integer i
            k=0.6*15
            tari=17/2.
            tard=17/8.
            dt=1.
            if (den.eq.0)then
                    db=0
                    return
            end if
            dh=(lnm1-vn-b)/(12.33*den)
            db=k*((h-sph)+1/tari*(hold+dh*dt/2-sph)*dt+tard*dh)
end


subroutine ctcontrol(spt,t,db,f,z1,vp1,y1p1,lm1,x1m1,v,y1,l,x1,told,am) ! control level in bottom column (feed back)
            real(8) spt,t                   !set point of temperature and temperature
            real(8) k,tari,tard             !tuning parameter
            real(8) dt                      !time step
            real(8) db                      !set point of reflux change
            real(8) dtt                     !differentiate of temperature
            real(8) f,z1,z2                 !feed flow rate and composition of feed
            real(8) vp1,y2p1,y1p1           !vapor flow rate and composition from tray below sensitive tray
            real(8) lm1,x2m1,x1m1           !liquid flow rate and composition from  tray above sensitive tray
            real(8) v,l                     !vapor and liquid flow rate of sensitive tray
            real(8) y1,x1,y2,x2             !composition of sensitive tray
            real(8) dx1,dx2                 !differentiate of liquid composition
```

```
            real(8) k1,k2                 !equilibrium cofficient
            real(8) am                    !accumulate on sensitive tray
            real(8) told                  !temperature of sensitive tray at 30 second ago
            k=0.6*0.00002
            tari=512/2.
            tard=512/8.
            dt=1.
            x2=1-x1
            y2=1-y1
            y2p1=1-y1p1
            x2m1=1-x1m1
            k1=y1/x1
            k2=y2/x2
            dx2=(f*(z2-x2)+vp1*(y2p1-x2)+lm1*(x2m1-x2)-v*(y2-x2))/am
            dx1=(f*(z1-x1)+vp1*(y1p1-x1)+lm1*(x1m1-x1)-v*(y1-x1))/am
            dtt=(-k2*dx2-k1*dx1)/(x1*(k1*369.348/(t-168.126)**2)+x2*(k2*1275.718/(t-59.782)**2))
            db=k*((t-spt)+1/tari*(told+dtt*dt/2-spt)*dt+tard*dtt)
end

subroutine cbcontrol(spt,t,db,f,z1,vp1,y1p1,lm1,x1m1,v,y1,l,x1,told,am) ! control level in bottom column (feed back)
            real(8) spt,t                 !set point of temperature and temperature
            real(8) k,tari,tard           !tuning parameter
            real(8) dt                    !time step
            real(8) db                    !set point of reflux change
            real(8) dtt                   !differentiate of temperature
            real(8) f,z1,z2               !feed flow rate and composition of feed
            real(8) vp1,y2p1,y1p1         !vapor flow rate and composition from tray below sensitive tray
            real(8) lm1,x2m1,x1m1         !liquid flow rate and composition from  tray above sensitive tray
            real(8) v,l                   !vapor and liquid flow rate of sensitive tray
            real(8) y1,x1,y2,x2           !composition of sensitive tray
            real(8) dx1,dx2               !differentiate of liquid composition
            real(8) k1,k2                 !equilibrium cofficient
            real(8) am                    !accumulate on sensitive tray
            real(8) told                  !temperature of sensitive tray at30 second ago
            k=0.6*0.00001
            tari=604/2.
            tard=604/8.
            dt=1.
            x2=1-x1
            y2=1-y1
            y2p1=1-y1p1
            x2m1=1-x1m1
            k1=y1/x1
            k2=y2/x2
            dx2=(f*(z2-x2)+vp1*(y2p1-x2)+lm1*(x2m1-x2)-v*(y2-x2))/am
            dx1=(f*(z1-x1)+vp1*(y1p1-x1)+lm1*(x1m1-x1)-v*(y1-x1))/am
            dtt=(-k2*dx2-k1*dx1)/(x1*(k1*369.348/(t-168.126)**2)+x2*(k2*1275.718/(t-59.782)**2))
            db=k*((spt-t)+1/tari*(spt-told-dtt*dt/2)*dt-tard*dtt)
end
```

J.2 Depropanizer Column with DMC

```
program distillation
            implicit none
            integer iii,ll
            integer i,ite,j,k             !index
            integer ib,it                 !index of sensitive tray
            integer h,m,s                 !time index
            integer tf                    !tray of feed
            integer n                     !number if tray and n th tray
            real(8) a                     !factor
            real(8) aa                    !parameter
            real(8) aaa1(150,521)
            real(8) aaa2(150,692)
            real(8) am(200,2)             !accumulate of liquid in tray (kg-mol/minute)
            real(8) amo                   !accumulate of liquid in tray at old iteration (kg-mol/minute)
            real(8) amv(200)              !accumulate of vapor (kg-mol/minute)
```

```
real(8) ata1(150,150)
real(8) ata2(150,150)
real(8) atai1(150,150)
real(8) atai2(150,150)        !inverse matrix of
real(8) a1(521,150)
real(8) a2(692,150)
real(8) a1t(150,521)
real(8) a2t(150,692)
real(8) bb                    !parameter
real(8) b(2)                  !bottom product flowrate (kg-mol/minute)
real(8) b1(1042)
real(8) b2(1384)
real(8) cpn                   !heat capacity of cool water (kJ/(C*kg-mol))
real(8) cpw                   !heat capacity of hot water(kJ/(C*kg-mol))
real(8) d(2)                  !distillate (kg-mol/minute)
real(8) db                    !bottom product flow rate change (kg-mol/s)
real(8) dcb                   !set point of reboiler change (kg-mol/s)
real(8) dct                   !set point of reflux change (kg-mol/s)
real(8) dd                    !distillate flow rate change (kg-mol/s)
real(8) denliq(200)           !density of liquid (kg-mol/m3)
real(8) dl1                   !reflux flow rate change (kg-mol/s)
real(8) dm1(150)              !manipulated variable move
real(8) dm2(150)              !manipulated variable move
real(8) dma1(521)
real(8) dma2(692)
real(8) dmo1(521)
real(8) dmo2(692)
real(8) ds                    !steam flow rate change (kg-mol/s)
real(8)   dt                  !constant step time     (1 second)
real(8) f                     !feed (kg-mol/half-minute)
real(8) finequa               !feed in equation
real(8) ft                    !feed temperature
real(8) ha                    !total feed enthalpy
real(8) haineq                !enthalpy of feed in equation
real(8) high(200)             !high of liquid in tray,bottom column and reflux reboiler (m)
real(8) highold(2)            !high of liquid in bottom column and reflux reboiler at old steptime (m)
real(8) hl(200)               !total liquid enthalpy (kj/kg-mol)
real(8) hlb                   !liquid enthalpy of bottom column (kj/kg-mol)
real(8) hv(200)               !total vapor enthalpy (kj/kg-mol)
real(8) hvb                   !vapor enthalpy of bottom column (kj/kg-mol)
real(8) ii(150,150)           !identity matrix
real(8) keep(1000)            !keep value
real(8) l(200,2)              !liquid flow (kg-mol/half-minute)
real(8) lo                    !liquid flow of tray No. 1 at old step time (kg-mol/half-minute)
real(8) p(200)                !pressure on tray (bar)
real(8) pb                    !pressure of bottom column (bar)
real(8) pf                    !pressure of feed (bar)
real(8) qc                    !heat duty of condenser (kj)
real(8) qcc                   !heat duty of condenser for minute (kj)
real(8) qr                    !heat duty of reboiler (kj)
real(8) qrc                   !heat duty of reboiler for minute (kj)
real(8) qn                    !flowrate of cool water (kg-mol/minute)
real(8) qw                    !flowrate of hot water (kg-mol/minute)
real(8) qwo                   !flowrate of hot water at old step time (kg-mol/minute)
real(8) scond                 !surface area of condenser (m2)
real(8) sph                   !set point of liquid level in drum (m)
real(8) sphb                  !set point of liquid level in bottom column  (m)
real(8) spl1                  !set point of reflux (kg-mol/minute)
real(8) spcb                  !set point of cascade at bottom column (K)
real(8) spct                  !set point of cascade at top column (K)
real(8) sps                   !setpoint of steam flow rate (kg-mol/s)
real(8) sreb                  !surface area of reboiler (m2)
real(8) t(200)                !temperature of tray (K)
real(8) tb                    !bottom temperature (K)
real(8) tib                   !temperature at tray no. ib th (K)
real(8) tit                   !temperature at tray no. it th (K)
real(8) tnout                 !temperature of nitrogen out of Kcondenser (K)
real(8) tnin                  !temperature of nitrogen enter condenser (K)
real(8) told(2)               !temperature of sensitive tray at 30 second ago (K)
real(8) twout                 !temperature of hot water out of reboiler (K)
real(8) twin                  !temperature of hot water enter reboiler (K)
```

```
real(8) ureb                  !over all heat transfer coefficient of reboiler (Kw/m2 C)
real(8) ucond                 !over all heat transfer coefficient of condenser (Kw/m2 C)
real(8) unwant                !unwant parameter
real(8) v(200,2)              !vapor flow (kg-mol/minute)
real(8) x(2,200,2)            !liquid composition (component,tray,time)
real(8) xb(2)                 !liquid composition at bottom column
real(8) xol1(521)
real(8) xol2(692)
real(8) xx(2)                 !keep liquid component value
real(8) y(2,200,2)            !vapor composition (component,tray,time)
real(8) yb(2)                 !vapor composition at bottom column
real(8) z(2)                  !feed composition
real(8) cc
open (1,file='output.xls')
open (2,file='save.dat')
!initial value
cc=0
iii=0
n=30
am=0.50312
cpn=6024.96
cpw=6024.96
dt=1./60
f=0.09
unwant=0
ft=323
hl=0
l=0
it=6
ib=25
p=1.01325
pf=2.0265
pb=1.01325
qn=0.5
qw=0.001
scond=1000
sreb=1000
spcb=375.8
spct=321.1
sph=0.4
sphb=0.4
spl1=0.315
sps=0.20
t=320
tb=320
tf=n
tnin=288
twin=393
ureb=0.438139514
ucond=0.438139514
v=0
xb=0
yb(1)=0.5
yb(2)=0.5
z(1)=0.5
z(2)=0.5
call enth(pf,ft,unwant,unwant,z(1),z(2),unwant,ha) !calculate enthalpy
do j=1,n
        do i=1,2
                x(i,j,1)=0
                x(i,j,2)=0
        end do
        if (j.lt.n)then
                y(1,j,2)=0.5
                y(2,j,2)=0.5
        end if
        call enth(p(j),t(j),x(1,j,1),x(2,j,1),y(1,j,2),y(2,j,2),hl(j),hv(j)) !calculate enthalpy
        hl(j)=hv(j)
end do
call enth(pb,tb,xb(1),xb(2),yb(1),yb(2),hlb,hvb)
do i=1,1000
```

```
        read (2,*) keep(i)
end do
do i=1,n-1
        x(1,i,2)=keep(i)
end do
        xb(1)=keep(30)
do i=1,n-1
        x(2,i,2)=keep(30+i)
end do
        xb(2)=keep(60)
do i=1,n
        y(1,i,2)=keep(60+i)
end do
yb(1)=keep(91)
do i=1,n
        y(2,i,2)=keep(91+i)
end do
        yb(2)=keep(122)
do i=1,n
        am(i,2)=keep(122+i)
end do
do i=1,n
        am(i,1)=keep(152+i)
end do
do i=1,n
        high(i)=keep(182+i)
end do
do i=1,n-1
        t(i)=keep(212+i)
end do
tb=keep(242)
told(1)=keep(243)
told(2)=keep(244)
do i=1,n-1
        p(i)=keep(244+i)
end do
        pb=keep(274)
do i=1,n
        hl(i)=keep(274+i)
end do
        hlb=keep(305)
do i=1,n
        hv(i)=keep(305+i)
end do
hvb=keep(336)
ha=keep(337)
ft=keep(338)
f=keep(339)
z(1)=keep(340)
z(2)=keep(341)
do i=1,n
        v(i,2)=keep(341+i)
end do
do i=1,n
        l(i,2)=keep(371+i)
end do
d(2)=keep(402)
b(2)=keep(403)
qw=keep(404)
qwo=keep(405)
qr=keep(406)
qc=keep(407)
qcc=keep(408)
qrc=keep(409)
lo=keep(410)
do i=1,n
        x(1,i,1)=keep(410+i)
end do
do i=1,n
        x(2,i,1)=keep(440+i)
end do
```

```
do i=1,n
        y(1,i,1)=keep(470+i)
end do
do i=1,n
        y(2,i,1)=keep(500+i)
end do
do i=1,n
        v(i,1)=keep(530+i)
end do
do i=1,n
        l(i,1)=keep(560+i)
end do
sreb=keep(591)
spcb=keep(592)
spct=keep(593)
sph=keep(594)
sphb=keep(595)
spl1=keep(596)
sps=keep(597)
tf=keep(598)
it=keep(599)
ib=keep(600)
pf=keep(601)
scond=keep(602)
amo=keep(603)
ucond=keep(604)
ureb=keep(605)
dd=keep(606)
dl1=keep(607)
ds=keep(608)
dcb=keep(609)
dct=keep(610)
db=keep(611)
qn=keep(612)
tnin=keep(613)
tnout=keep(614)
twin=keep(615)
twout=keep(616)
do i=1,n
        denliq(i)=keep(616+i)
end do

b1(    1    )=    0.0
b1(    2    )=    0.0
b1(    3    )=    0.0
b1(    4    )=    0.0
b1(    5    )=    0.0
b1(    6    )=    0.0
b1(    7    )=    0.0
b1(    8    )=    0.0
b1(    9    )=    0.0
b1(    10   )=    0.0
b1(    11   )=    0.0
b1(    12   )=    0.0
b1(    13   )=    -10.0
b1(    14   )=    -10.0
b1(    15   )=    -10.0
b1(    16   )=    -10.0
b1(    17   )=    -10.0
b1(    18   )=    -10.0
b1(    19   )=    -10.0
b1(    20   )=    -10.0
b1(    21   )=    -10.0
b1(    22   )=    -20.0
b1(    23   )=    -20.0
b1(    24   )=    -20.0
b1(    25   )=    -20.0
b1(    26   )=    -20.0
b1(    27   )=    -20.0
b1(    28   )=    -20.0
b1(    29   )=    -30.0
```

bl(	30	)=	-30.0
bl(	31	)=	-30.0
bl(	32	)=	-30.0
bl(	33	)=	-30.0
bl(	34	)=	-30.0
bl(	35	)=	-30.0
bl(	36	)=	-30.0
bl(	37	)=	-40.0
bl(	38	)=	-40.0
bl(	39	)=	-40.0
bl(	40	)=	-40.0
bl(	41	)=	-40.0
bl(	42	)=	-40.0
bl(	43	)=	-50.0
bl(	44	)=	-50.0
bl(	45	)=	-50.0
bl(	46	)=	-50.0
bl(	47	)=	-50.0
bl(	48	)=	-50.0
bl(	49	)=	-60.0
bl(	50	)=	-60.0
bl(	51	)=	-60.0
bl(	52	)=	-60.0
bl(	53	)=	-60.0
bl(	54	)=	-70.0
bl(	55	)=	-70.0
bl(	56	)=	-70.0
bl(	57	)=	-70.0
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b2(	1330	)=	1450.0
b2(	1331	)=	1450.0
b2(	1332	)=	1450.0
b2(	1333	)=	1450.0
b2(	1334	)=	1450.0
b2(	1335	)=	1450.0
b2(	1336	)=	1450.0
b2(	1337	)=	1450.0
b2(	1338	)=	1450.0
b2(	1339	)=	1450.0
b2(	1340	)=	1450.0
b2(	1341	)=	1450.0
b2(	1342	)=	1450.0
b2(	1343	)=	1450.0
b2(	1344	)=	1450.0
b2(	1345	)=	1450.0
b2(	1346	)=	1450.0
b2(	1347	)=	1450.0
b2(	1348	)=	1450.0
b2(	1349	)=	1450.0
b2(	1350	)=	1450.0
b2(	1351	)=	1450.0
b2(	1352	)=	1450.0
b2(	1353	)=	1450.0
b2(	1354	)=	1450.0
b2(	1355	)=	1450.0
b2(	1356	)=	1450.0
b2(	1357	)=	1450.0
b2(	1358	)=	1450.0
b2(	1359	)=	1450.0
b2(	1360	)=	1450.0
b2(	1361	)=	1450.0
b2(	1362	)=	1450.0
b2(	1363	)=	1450.0
b2(	1364	)=	1450.0
b2(	1365	)=	1450.0
b2(	1366	)=	1450.0
b2(	1367	)=	1450.0
b2(	1368	)=	1450.0
b2(	1369	)=	1450.0
b2(	1370	)=	1450.0
b2(	1371	)=	1450.0
b2(	1372	)=	1450.0
b2(	1373	)=	1450.0
b2(	1374	)=	1450.0
b2(	1375	)=	1450.0
b2(	1376	)=	1450.0
b2(	1377	)=	1450.0
b2(	1378	)=	1450.0
b2(	1379	)=	1450.0
b2(	1380	)=	1450.0
b2(	1381	)=	1450.0
b2(	1382	)=	1450.0
b2(	1383	)=	1450.0
b2(	1384	)=	1450.0


ii=0.
do j=1,150
		ii(j,j)=1.0
end do
atai1=ii
do j=1,521
		do k=1,150
```

```
                        if (j+1-k.le.0)then
                                al(j,k)=0
                        else
                                al(j,k)=b1(j+1-k)
                        end if
                end do
end do
alt=transpose(al)
ata1=matmul(alt,al)
ata1=ata1+1e8*ii  !***************************** 1.5e10
do i=1,150
        aa=ata1(i,i)
        do j=1,150
                ata1(i,j)=ata1(i,j)/aa
                atai1(i,j)=atai1(i,j)/aa
        end do
        if (i.ne.150)then
                do j=1,150-i
                        bb=ata1(151-j,i)
                        do ll=1,150
                                ata1(151-j,ll)=ata1(151-j,ll)-bb*ata1(i,ll)
                                atai1(151-j,ll)=atai1(151-j,ll)-bb*atai1(i,ll)
                        end do
                end do
        end if
end do
do i=1,149
        if (i.ne.150)then
                do j=1,150-i
                        bb=ata1(j,151-i)
                        do ll=1,150
                                ata1(j,ll)=ata1(j,ll)-bb*ata1(151-i,ll)
                                atai1(j,ll)=atai1(j,ll)-bb*atai1(151-i,ll)
                        end do
                end do
        end if
end do
atai2=ii
do j=1,692
        do k=1,150
                if (j+1-k.le.0)then
                        a2(j,k)=0
                else
                        a2(j,k)=b2(j+1-k)
                end if
        end do
end do
a2t=transpose(a2)
ata2=matmul(a2t,a2)
ata2=ata2+1e7*ii !*************************** 0.2e10
do i=1,150
        aa=ata2(i,i)
        do j=1,150
                ata2(i,j)=ata2(i,j)/aa
                atai2(i,j)=atai2(i,j)/aa
        end do
        if (i.ne.150)then
                do j=1,150-i
                        bb=ata2(151-j,i)
                        do ll=1,150
                                ata2(151-j,ll)=ata2(151-j,ll)-bb*ata2(i,ll)
                                atai2(151-j,ll)=atai2(151-j,ll)-bb*atai2(i,ll)
                        end do
                end do
        end if
end do
do i=1,149
        if (i.ne.150)then
                do j=1,150-i
                        bb=ata2(j,151-i)
                        do ll=1,150
```

```
                              ata2(j,ll)=ata2(j,ll)-bb*ata2(151-i,ll)
                              atai2(j,ll)=atai2(j,ll)-bb*atai2(151-i,ll)
                        end do
                  end do
            end if
      end do


      do h=1,20000
            do m=1,60
                  do s=1,60
                        write (6,111) h,t(6),t(25),l(1,2),dm1(1) ,qw,dm2(1),sps,spct
                        111 format (1i,15f13.7)
                        if (high(n/2).ge.0.03175)then
                              tf=n/2
                              pf=17.0
                              ft=369.0
                              f=0.09
                              z(1)=0.5
                              z(2)=0.5
                              !if (h.ge.1)then !disturbance occur
                              if (h.eq.1.and.m.eq.1.and.s.eq.1)then
                                    !z(1)=0.3
                                    !z(2)=0.7
                                    !f=0.1
                                    qw=0.02
                                    !spct=323.1
                              end if
                              unwant=0
                              call enth(pf,ft,z(1),z(2),unwant,unwant,ha,unwant) !calculate enthalpy
                        end if


                        if (s.eq.1)then
                              told(2)=t(it)
                        end if
                        if (s.eq.1.and.cc.eq.0)then
                              spl1=spl1+dct
                        end if
                        !condenser & reflux drum
                        call l1control(spl1,l(1,2),dl1,lo) !  call control of reflux flow rate
                        lo=l(1,2)
                        l(1,2)=l(1,2)+dl1
                        if (s.eq.1)then
                              d(2)=d(2)+dd
                        end if
                        if (d(2).lt.0.or.high(1).le.0)then
                              d(2)=0
                              dd=0
                        end if
                        if (l(1,2).lt.0.or.high(1).le.0)then
                              l(1,2)=0
                        end if
                        am(1,2)=am(1,1)+(v(2,2)-l(1,2)-d(2))*dt !calculate accumulate in drum
                        if (am(1,2).lt.0)then
                              am(1,2)=0
                        end if
                        call dliq(t(1),x(1,1,2),x(2,1,2),denliq(1))
                        if (s.eq.1)then
                              highold(1)=high(1)
                        end if
                        high(1)=am(1,2)/(denliq(1)*1.23)
                        if (denliq(1).eq.0.or.high(1).le.0)then
                              high(1)=0
                        end if
                        if (x(1,1,1).eq.0.and.x(2,1,1).eq.0) then
                              do i=1,2
                                    x(i,1,1)=y(i,1,2)
                              end do
```

```
                  end if
x(1,1,2)=(x(1,1,1)*am(1,1)+(v(2,2)*y(1,2,2))*dt)/(am(1,2)+(l(1,2)+d(2))*dt) !calculate composition in drum
                  if (x(1,1,2).lt.0.0000000001)then
                          x(1,1,2)=0
                  end if
                  x(2,1,2)=1.-x(1,1,2)
                  a=exp(-(ucond*scond)/(qn*cpn))
                  tnout=tnin+(1-a)*(t(2)-tnin)
                  qc=qn*cpn*(tnout-tnin) !calculate heat duty of reboiler
                  if (t(1).lt.308)then
                          qc=0
                  end if
                  p(1)=16.00
                  call bubpt(p(1),x(1,1,2),x(2,1,2),y(1,1,2),y(2,1,2),t(1))
                  call enth(p(1),t(1),x(1,1,2),x(2,1,2),y(1,1,2),y(2,1,2),hl(1),hv(1))
                  x(1,1,1)=x(1,1,2)
                  x(2,1,1)=x(2,1,2)
                  y(1,1,1)=y(1,1,2)
                  y(2,1,1)=y(2,1,2)
                  am(1,1)=am(1,2)
                  v(1,1)=v(1,2)
                  l(1,1)=l(1,2)


                  !tray
                  do j=2,n-1
                          if(j.eq.tf)then
                                  finequa=f
                                  haineq=ha
                          else
                                  finequa=0
                                  haineq=0
                          end if
                          am(j,2)=am(j,1)
1                         amo=am(j,2)
                          call dliq(t(j),x(1,j,2),x(2,j,2),denliq(j))
                          high(j)=am(j,2)/(denliq(j)*0.982)
                          if (denliq(j).eq.0.or.high(j).le.0)then
                                  high(j)=0
                          end if
                          if (high(j).lt.0.03175) then
                                  l(j,2)=0
                          else
                                  l(j,2)=denliq(j)*1.17*(am(j,2)/(denliq(j)*0.982)-
0.03175)**1.5
                                  if ((am(j,2))/(denliq(j)*0.982).lt.0.03175)then
                                          l(j,2)=0
                                  end if
                                  if (l(j,2).lt.0)then
                                          l(j,2)=0
                                  end if
                          end if
                          am(j,2)=am(j,1)+(finequa+v(j+1,2)+l(j-1,2)-l(j,2)-v(j,2))*dt !calculate
accumulate in tray
                          if (am(j,2).lt.0)then
                                  am(j,2)=0
                          end if
                          if (abs((amo-am(j,2))/amo).gt.0.000001) goto 1
                          if (denliq(j).eq.0)then
                                  am(j,2)=am(j,1)+(finequa+v(j+1,2)+l(j-1,2)-v(j,2))*dt
                                  if (am(j,2).lt.0)then
                                          am(j,2)=0
                                  end if
                          end if
                          if (x(1,j,1).eq.0.and.x(2,j,1).eq.0) then
                                  do i=1,2
                                          x(i,j,1)=y(i,j,2)
                                  end do
                          end if
```

```
            x(1,j,2)=(x(1,j,1)*am(j,1)+(finequa*z(1)+v(j+1,2)*y(1,j+1,2)+l(j-
1,2)*x(1,j-1,2)-v(j,2)*y(1,j,2))*dt)/(am(j,2)+l(j,2)*dt)
            if (x(1,j,2).lt.0)then
                  x(1,j,2)=0
            end if
            x(2,j,2)=1.-x(1,j,2)
            p(j)=p(j-1)+0.065
            call bubpt(p(j),x(1,j,2),x(2,j,2),y(1,j,2),y(2,j,2),t(j))
            call enth(p(j),t(j),x(1,j,2),x(2,j,2),y(1,j,2),y(2,j,2),hl(j),hv(j))
            v(j,2)=(hv(j+1)*v(j+1,2)+hl(j-1)*l(j-1,2)+finequa*haineq-
l(j,2)*hl(j))/hv(j)
            if (v(j,2).lt.0)then
                  v(j,2)=0
            end if
      end do
      do j=2,n-1
            x(1,j,1)=x(1,j,2)
            x(2,j,1)=x(2,j,2)
            y(1,j,1)=y(1,j,2)
            y(2,j,1)=y(2,j,2)
            am(j,1)=am(j,2)
            v(j,1)=v(j,2)
            l(j,1)=l(j,2)
      end do
      !reboiler & column bottom
      if (s.eq.1)then
            told(1)=t(ib)
      end if
      if (s.eq.1.and.cc.eq.0)then
            sps=sps+dcb
      end if
      if (sps.lt.0)then
            sps=0
      end if
      if(n.eq.tf)then
            finequa=f
            haineq=ha
      else
            finequa=0
            haineq=0
      end if
      if  (high(n).ge.0.3)then
            call scontrol(sps,qw,ds,qwo) !  call control of steam flow rate
      else
            ds=0
      end if
      qwo=qw
      qw=qw+ds
      if (qw.lt.0)then
            qw=0
      end if
      if (qw.le.0) goto 2
      if (high(n).ge.0.3)then
            a=exp((ureb*sreb)/(qw*cpw))
            twout=(twin+(a-1)*tb)/a
            qr=qw*cpw*(twin-twout) !calculate heat duty of reboiler
      end if
2     if (high(n).lt.0.1.or.qw.le.0)then
            qr=0
      end if
      am(n,2)=am(n,1)+(finequa+l(n-1,2)-v(n,2)-b(2))*dt !calculate accumulate in
bottom column
      if (am(n,2).lt.0)then
            am(n,2)=0
      end if
      if (high(n).lt.0.3.and.v(n,2).ne.0)then
            unwant=0
            call enth(pb,tb,unwant,unwant,yb(1),yb(2),unwant,hvb) !calculate
enthalpy
            hv(n)=hvb
            do i=1,2
```

```
                    y(i,n,2)=yb(i)
            end do
        end if
        if (xb(1).eq.0.and.xb(2).eq.0)then
            xb(1)=yb(1)
            xb(2)=yb(2)
        end if
        xb(1)=(xb(1)*am(n,1)+(finequa*z(1)+l(n-1,2)*x(1,n-1,2)-
v(n,2)*yb(1))*dt)/(am(n,2)+b(2)*dt) !calculate liquid composition in bottom column
        if (xb(1).lt.0.0000000001)then
            xb(1)=0
        end if
        xb(2)=1-xb(1)
        pb=p(n-1)+0.065
        call bubpt(pb,xb(1),xb(2),yb(1),yb(2),tb)
        do i=1,2
            y(i,n,2)=yb(i)
        end do
        call dliq(t(n),xb(1),xb(2),denliq(n))
        if (s.eq.1)then
            highold(2)=high(n)
        end if
        high(n)=am(n,2)/(denliq(n)*1.23)
        if (denliq(n).eq.0.or.high(n).le.0)then
            high(n)=0
        end if
        call enth(pb,tb,xb(1),xb(2),yb(1),yb(2),hlb,hvb)
        v(n,2)=(qr+finequa*haineq+hl(n-1)*l(n-1,2)-hlb*b(2))/hvb
        if (v(n,2).lt.0)then
            v(n,2)=0
        end if
        if (s.eq.1)then
            b(2)=b(2)+db
        end if
        if (high(n).le.0)then
            high(n)=0
            b(2)=0
            db=0
        end if
        if (b(2).lt.0)then
            b(2)=0
            db=0
        end if
        do i=1,2
            x(i,n,2)=xb(i)
            y(i,n,2)=yb(i)
        end do
        x(1,n,1)=x(1,n,2)
        x(2,n,1)=x(2,n,2)
        y(1,n,1)=y(1,n,2)
        y(2,n,1)=y(2,n,2)
        am(n,1)=am(n,2)
        v(n,1)=v(n,2)
        l(n,1)=l(n,2)
        cc=cc+1
        if (cc.eq.120)then
            cc=0
        end if
        call dcontrol(sph,high(1),dd,v(2,2),d(2),l(1,2),denliq(1),highold(1))
        call bcontrol(sphb,high(n),db,v(n,2),b(2),l(n-1,2),denliq(n),highold(2)) ! call
control of bottom flow rate
        if (h.eq.8000.and.m.eq.60.and.s.eq.1)then
            open (2,file='save.dat')
            do i=1,n-1
                keep(i)=x(1,i,2)
            end do
            keep(30)=xb(1)
            do i=1,n-1
                keep(30+i)=x(2,i,2)
            end do
                keep(60)=xb(2)
```

```
do i=1,n
        keep(60+i)=y(1,i,2)
end do
keep(91)=yb(1)
do i=1,n
        keep(91+i)=y(2,i,2)
end do
        keep(122)=yb(2)
do i=1,n
        keep(122+i)=am(i,2)
end do
do i=1,n
        keep(152+i)=am(i,1)
end do
do i=1,n
        keep(182+i)=high(i)
end do
do i=1,n-1
        keep(212+i)=t(i)
end do
keep(242)=tb
keep(243)=told(1)
keep(244)=told(2)
do i=1,n-1
        keep(244+i)=p(i)
end do
        keep(274)=pb
do i=1,n
        keep(274+i)=hl(i)
end do
        keep(305)=hlb
do i=1,n
        keep(305+i)=hv(i)
end do
keep(336)=hvb
keep(337)=ha
keep(338)=ft
keep(339)=f
keep(340)=z(1)
keep(341)=z(2)
do i=1,n
        keep(341+i)=v(i,2)
end do
do i=1,n
        keep(371+i)=l(i,2)
end do
keep(402)=d(2)
keep(403)=b(2)
keep(404)=qw
keep(405)=qwo
keep(406)=qr
keep(407)=qc
keep(408)=qcc
keep(409)=qrc
keep(410)=lo
do i=1,n
        keep(410+i)=x(1,i,1)
end do
do i=1,n
        keep(440+i)=x(2,i,1)
end do
do i=1,n
        keep(470+i)=y(1,i,1)
end do
do i=1,n
        keep(500+i)=y(2,i,1)
end do
do i=1,n
        keep(530+i)=v(i,1)
end do
do i=1,n
```

```
                        keep(560+i)=l(i,1)
                end do
                keep(591)=sreb
                keep(592)=spcb
                keep(593)=spct
                keep(594)=sph
                keep(595)=sphb
                keep(596)=spl1
                keep(597)=sps
                keep(598)=tf
                keep(599)=it
                keep(600)=ib
                keep(601)=pf
                keep(602)=scond
                keep(603)=amo
                keep(604)=ucond
                keep(605)=ureb
                keep(606)=dd
                keep(607)=dl1
                keep(608)=ds
                keep(609)=dcb
                keep(610)=dct
                keep(611)=db
                keep(612)=qn
                keep(613)=tnin
                keep(614)=tnout
                keep(615)=twin
                keep(616)=twout
                do i=1,n
                        keep(616+i)=denliq(i)
                end do
                do i=1,1000
                        write(2,*) keep(i)
                end do
                close(2)
        end if

        if (cc.eq.0)then
                do j=1,520
                        dmo1(522-j)=dmo1(521-j)
                end do
                dmo1(1)=dm1(1)
                do j=1,521
                        xol1(j)=0
                        do k=1,521
                                xol1(j)=xol1(j)+(b1(j+k)-b1(k))*dmo1(k)
                        end do
                        tit=t(6)
                        call cutdec1(tit)
                        xol1(j)=tit+xol1(j)
                end do
                aaa1=matmul(atai1,a1t)
                do i=1,521
                        dma1(i)=spct-xol1(i)
                end do
                dm1=matmul(aaa1,dma1)
                dct=dm1(1)


                do j=1,691
                        dmo2(693-j)=dmo2(692-j)
                end do
                dmo2(1)=dm2(1)
                do j=1,692
                        xol2(j)=0
                        do k=1,692
                                xol2(j)=xol2(j)+(b2(j+k)-b2(k))*dmo2(k)
                        end do
                        tib=t(25)
                        call cutdec1(tib)
                        xol2(j)=tib+xol2(j)
```

```
                                        end do
                                        aaa2=matmul(atai2,a2t)
                                        do i=1,692
                                                dma2(i)=spcb-xol2(i)
                                        end do
                                        dm2=matmul(aaa2,dma2)
                                        dcb=dm2(1)
                                end if
                        end do !s
                !DO J=1,N
                !IF (S.EQ.1.AND.M.GE.53.AND.H.GE.1) THEN
                IF (H.ge.1.AND.M.GE.1) THEN
                !if (j.eq.n)then
                write(1,402) h,t(6),t(25),x(1,1,2),xb(2),l(1,2),qw,d(2),b(2),high(1),high(n),spcb,spct
                !write(1,402) H,M,J,TF,xb(1),xb(2),yb(1),yb(2),Tb,Pb,high(n),am(n,2),qr
                !else
                !WRITE(1,402) H,M,J,TF,x(1,j,2),x(2,j,2),y(1,j,2),y(2,j,2),T(J),P(J),high(J),am(J,2),denliq(j)
                !end if
                402 FORMAT(1i,2f20.1,15f20.4)
                !402 FORMAT(1I,1X,1I,1X,1I,1X,1I,1X,15F12.4)
                END If
                !END DO
                end do !m
        end do !h
end program

subroutine bubpt(pp,x1,x2,y1,y2,tt) !calculate temperature from bubble point equation
        integer i                               !index
        real(8)  df                                     !differential of function
        real(8)  f                                      !function
        real(8)  pp                                     !pressure (bar)
        real(8)  ps1,ps2                        !vapor pressure (bar)
        real(8)  tt                                     !temperature (K)
        real(8)  x1,x2                          !liquid composition
        real(8) y1,y2                           !vapor composition
        real(8) yy1,yy2
1       ps1=exp(-369.348/(tt-168.126)+5.23749)          !calculate vapor pressure of propane
        ps2=exp(-1275.718/(tt-59.782)+6.85137)          !calculate vapor pressure of butane
        y1=x1*ps1/pp    !calculate vapor composition
        y2=x2*ps2/pp
        if (abs(1-y1-y2).lt.0.00000001) goto 10    !find correct temperature
        f=1-y1-y2
        df=x1/pp*ps1*369.348/(tt-168.126)**2
        df=df+x2/pp*ps2*1275.718/(tt-59.782)**2
        tt=tt+f/df
        goto 1
10      return
end

subroutine enth(p,t,x3,x4,y3,y4,hl,ha) ! calculate liquid and vapor entralpy from pressure,temperature, and composition
        use numerical_libraries
        implicit real*8 (a-h,o-z)
        real(8)  t                      !temperature
        real(8) p               !pressure
        real(8) y3,y4           !vapor composition of propane and butane
        real(8) x3,x4           !liquid composition
        real(8) ha                      !total vapor enthalpy
        real(8) ha3                     !vapor enthalpy of propane
        real(8) ha4                     !vapor enthalpy of butane
        real(8) hll(2)          !liqid enthalpy of propane and butane
        real(8) hl                      !total liquid enthalpy
        common/blkd1/popv(5),hvc3(5),hvc4(5)
        data popv/1.,5.,10.,15.,20./
        parameter (korder=3,ndata=5,nknot=ndata+korder)
        dimension x1data(ndata),f1data(ndata)
        dimension x1knot(nknot),bscoef1(ndata)
        integer i

        !calculate vapor enthalpy
```

```
t=t-273.15
if (p.eq.1.or.p.eq.5.or.p.eq.10.or.p.eq.15.or.p.eq.20)then
    if (p.eq.1)then

ha3=0.00000243589743879133*t**3+0.0216068764561292*t**2+16.7600885781487*t+3948.29071794724
        ha4=5171.95353379809+22.7750602176193*t+0.0285385198127802*t**2-
0.0000006546231517426*t**3
    end if
    if (p.eq.5)then

ha3=3785.7155058276l+18.240793123538*t+0.0139970279720996*t**2+0.0000212237762234762*t**3
        ha4=13362.9290022956-614.055453861994*t+19.4411005643476*t**2-
0.305859930252696*t**3+0.00264210823154405*t**4-0.0000118981890756778*t**5+0.0000000218680429435476*t**6
    end if
    if (p.eq.10)then
        ha3=9299.88843643293-489.679087204064*t+18.2134871645406*t**2-
0.335630483024728*t**3+0.00337653409332662*t**4-0.0000176090629930964*t**5+0.0000000372728987837522*t**6
        ha4=52119.620884926-4542.38831847744*t+183.561795154405*t**2-
3.96420633705897*t**3+0.0496691999500929*t**4-0.000361742582892285*t**5+0.00000142214836684578*t**6-
0.00000000233518724898894*t**7
    end if
    if (p.eq.15)then
        ha3=3499.26966208774+10.0480539969921*t+0.235411990181417*t**2-
0.00185526320973007*t**3+0.00000546197552656038*t**4
        ha4=-41073.9677943845+4570.52957391954*t-
185.978489301388*t**2+4.09239659695254*t**3-0.0523767526218596*t**4+0.000390079118628205*t**5-
0.00000156690531090442*t**6+0.00000000262353582012308*t**7
    end if
    if (p.eq.20)then
        ha3=4127.1570396016+73.4391303904704*t-
4.99493677579601*t**2+0.125573969112786*t**3-0.00143072973061548*t**4+0.00000777934562O8826*t**5-
0.0000000164069371112414*t**6
        ha4=54716.6018791736-4931.18850411005*t+206.110049953317*t**2-
4.63591405624864*t**3+0.0608851762849367*t**4-0.000467220003840682*t**5+0.00000194083612282833*t**6-
0.00000000336865665585238*t**7
    end if
else
    do i=1,5
        x1data(i)=popv(i)
    end do
    do i=1,5
        if (i.eq.1)then
            hvc3(i)=2.43589743879133*10**(-
6)*t**3+0.0216068764561292*t**2+16.7600885781487*t+3948.29071794724
            hvc4(i)=5171.95353379809+22.7750602176193*t+0.0285385198127802*t**2-
0.0000006546231517426*t**3
        end if
        if (i.eq.2)then

hvc3(i)=3785.7155058276l+18.240793123538*t+0.0139970279720996*t**2+0.0000212237762234762*t**3
            hvc4(i)=13362.9290022956-614.055453861994*t+19.4411005643476*t**2-
0.305859930252696*t**3+0.00264210823154405*t**4-0.0000118981890756778*t**5+0.0000000218680429435476*t**6
        end if
        if (i.eq.3)then
            hvc3(i)=9299.88843643293-489.679087204064*t+18.2134871645406*t**2-
0.335630483024728*t**3+0.00337653409332662*t**4-0.0000176090629930964*t**5+0.0000000372728987837522*t**6
            hvc4(i)=52119.620884926-4542.38831847744*t+183.561795154405*t**2-
3.96420633705897*t**3+0.0496691999500929*t**4-0.000361742582892285*t**5+0.00000142214836684578*t**6-
0.00000000233518724898894*t**7
        end if
        if (i.eq.4)then
            hvc3(i)=3499.26966208774+10.0480539969921*t+0.235411990181417*t**2-
0.00185526320973007*t**3+0.00000546197552656038*t**4
            hvc4(i)=-41073.9677943845+4570.52957391954*t-
185.978489301388*t**2+4.09239659695254*t**3-0.0523767526218596*t**4+0.000390079118628205*t**5-
0.00000156690531090442*t**6+0.00000000262353582012308*t**7
        end if
        if (i.eq.5)then
            hvc3(i)=4127.1570396016+73.4391303904704*t-
4.99493677579601*t**2+0.125573969112786*t**3-0.00143072973061548*t**4+0.0000077793456208826*t**5-
0.0000000164069371112414*t**6
```

```
                                        hvc4(i)=54716.6018791736-4931.18850411005*t+206.110049953317*t**2-
4.63591405624864*t**3+0.0608851762849367*t**4-0.000467220003840682*t**5+0.00000194083612282833*t**6-
0.00000000336865665585238*t**7
                                end if
                                f1data(i)=hvc3(i)
                        end do
                        call dbsnak(ndata,x1data,korder,x1knot)
                        call dbsint(ndata,x1data,f1data,korder,x1knot,bscoef1)
                        ncoef=ndata
                        ha3=dbsval(p,korder,x1knot,ncoef,bscoef1)
                        do i=1,5
                                f1data(i)=hvc4(i)
                        enddo
                        call dbsint(ndata,x1data,f1data,korder,x1knot,bscoef1)
                        ha4=dbsval(p,korder,x1knot,ncoef,bscoef1)
                end if
                ha=4.186*(ha3*y3+ha4*y4)
                t=t+273.15
                ! calculate liquid enthalpy
                do i=1,2
                        check_component: select case (i) ! select composition
                        case (1)
                                if(t.le.373)then
                                        hll(1)=0.000198088*t**4-0.263253174*t**3+131.264949*t**2-
29069.26192*t+2410921.733
                                else
                                        hll(1)=0.0227*t**2+9.0203*t-2851.2
                                end if
                        case (2)
                                hll(2)=0.00000626941753153494*t**4-0.008361954*t**3+4.249105865*t**2-
936.7516086*t+74283.83672
                        end select check_component
                end do
                hl=4.186*(x3*hll(1)+x4*hll(2))
end

subroutine dliq(tt,x11,x22,denliq) !calculate density of liquid
                real(8) a(2)            !parameter
                real(8) avmw            !average molecular weight
                real(8) b(2)            !parameter
                real(8) den(2)          !liquid density of i component
                real(8) denliq          !mixture liquid density
                real(8) n(2)            !parameter
                real(8) m(2)            !molecular weight
                real(8) tt              !temperature
                real(8) tc(2)           !critical temperature
                real(8) x1,x11          !liquid propane composition
                real(8) x2,x22          !liquid butane composition
                data tc(1),tc(2)/369.82,452.15/ ! critical temperature
                data m(1),m(2)/44.097,58.124/  ! molecular weight
                data a(1),a(2)/0.22151,0.22827/ ! parameter for calculate liquid density
                data b(1),b(2)/0.27744,0.27240/ ! parameter for calculate liquid density
                data n(1),n(2)/0.28700,0.28630/ ! parameter for calculate liquid density
                if (x11.eq.0.and.x22.eq.0)then
                        denliq=0
                        return
                end if
                x1=x11/(x11+x22)
                x2=x22/(x11+x22)
                if (tt.gt.369.8)then
                        den(1)=a(1)*b(1)**(-1*(1-369.8/tc(1))**n(1))
                        den(2)=a(2)*b(2)**(-1*(1-tt/tc(2))**n(2))
                        goto 1
                end if
                do i=1,2  ! calculate density of component
                        den(i)=a(i)*b(i)**(-1*(1-tt/tc(i))**n(i))
                end do
1               avmw=x1*m(1)+x2*m(2) ! calculate average molecular weight
                denliq=1000*(x1*den(1)/m(1)+x2*den(2)/m(2)) ! calculate density of liquid mixture
end
```

```
subroutine cutdec1(dd) ! cut decimal
        real(8) dd,aa,bb,cc
        aa=(int(dd*1000))
        bb=(int(dd*100))
        cc=aa/1000-bb/100
        if (cc*1000.ge.5)then
                dd=bb/100+0.01d0
        else
                dd=bb/100
        end if
end

subroutine dcontrol(sph,h,dd,v2,d,l1,den,hold) ! control level in reflux drum (feed back)
        real(8) sph,h,k,tari,tard,dt,dd,dh,v2,d,l1,den,hold
        integer i
        k=0.6*15
        tari=18/2.
        tard=18/8.
        dt=1.
        if (den.eq.0)then
                dd=0
                return
        end if
        dh=(v2-d-l1)/(12.33*den)
        dd=k*((h-sph)+1/tari*(hold+dh*dt/2-sph)*dt+tard*dh)
end

subroutine l1control(sp,l1,dl1,l1o) ! control reflux flow rate
        real(8) sp,l1,k,tari,tard,dt,dl1,l1o
        integer i
        k=0.6*2
        tari=2/2.
        tard=2/8.
        dt=1.
        dl1=k*((sp-l1)+1/tari*(sp-l1o-dl1*dt/2)*dt-tard*dl1)
end

subroutine scontrol(sp,s,ds,so) ! control steam flow rate (feed forward)
        real(8) sp,s,k,tari,tard,dt,ds,so
        integer i
        k=0.6*2
        tari=2/2.
        tard=2/8.
        dt=1.
        ds=k*((sp-s)+1/tari*(sp-so-ds*dt/2)*dt-tard*ds)
end

subroutine bcontrol(sph,h,db,vn,b,lnm1,den,hold) ! control level in bottom column (feed back)
        real(8) sph,h,k,tari,tard,dt,db,dh,vn,b,lnm1,den,d2h,hold
        integer i
        k=0.6*15
        tari=17/2.
        tard=17/8.
        dt=1.
        if (den.eq.0)then
                db=0
                return
        end if
        dh=(lnm1-vn-b)/(12.33*den)
        db=k*((h-sph)+1/tari*(hold+dh*dt/2-sph)*dt+tard*dh)
end
```

Appendix K Compared Result of Depropanizer Column between results of ProII Program and Fortran Program

Results of liquid composition in table K.1 and Figure K.1 have low error at the top bottom tray. Tray that stays near the centre of the column will have the high error. Results of vapour composition in table K.2 and Figure K.2 have tend like the results of liquid composition. From the Figure K.1 and K.2, Tend of liquid and vapor composition are in the same tending of ProII program.

Table K.1 Liquid compositions (mole fraction) of distillation column at steady-state of ProII and Fortran (implicit method, IFP's method) programs

Tray No.	Fortran		ProII		% Error	
	Propane	Butane	Propane	Butane	Propane	Butane
1	1	0	1	0	0	0
2	1	0	1	0	0	0
3	0.9999	0.0001	0.9999	0.0001	0	0
4	0.9999	0.0001	0.9999	0.0001	0	0
5	0.9997	0.0003	0.9997	0.0003	0	0
6	0.9994	0.0006	0.9994	0.0006	0	0
7	0.9988	0.0012	0.9986	0.0014	0.02	-14.29
8	0.9974	0.0026	0.9969	0.0031	0.05	-16.13
9	0.9947	0.0053	0.9933	0.0067	0.14	-20.90
10	0.989	0.011	0.9856	0.0144	0.34	-23.61
11	0.9775	0.0225	0.9692	0.0308	0.86	-26.95
12	0.9547	0.0453	0.936	0.064	2.00	-29.22
13	0.9117	0.0883	0.8735	0.1265	4.37	-30.20
14	0.8376	0.1624	0.7711	0.2289	8.62	-29.05
15	0.7274	0.2726	0.6342	0.3658	14.70	-25.48
16	0.6828	0.3172	0.5944	0.4056	14.87	-21.79
17	0.6147	0.3853	0.5355	0.4645	14.79	-17.05
18	0.5224	0.4776	0.4573	0.5427	14.24	-12.00
19	0.4142	0.5858	0.3666	0.6334	12.98	-7.52
20	0.306	0.694	0.2754	0.7246	11.11	-4.22
21	0.2123	0.7877	0.1951	0.8049	8.82	-2.14
22	0.1404	0.8596	0.1319	0.8681	6.44	-0.98
23	0.0898	0.9102	0.0861	0.9139	4.30	-0.40
24	0.0562	0.9438	0.0549	0.9452	2.37	-0.15
25	0.0346	0.9654	0.0343	0.9657	0.87	-0.03
26	0.0211	0.9789	0.0211	0.9789	0	0
27	0.0128	0.9872	0.0128	0.9872	0	0
28	0.0076	0.9924	0.0077	0.9924	-1.2987	0
29	0.0045	0.9955	0.0044	0.9956	2.27273	-0.01
30	0.0025	0.9975	0.0025	0.9975	0	0

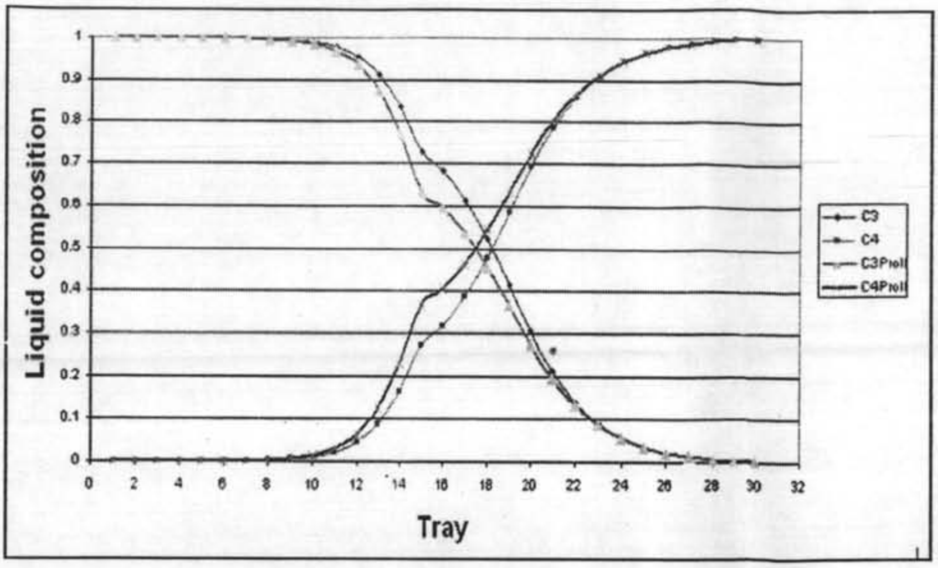

Figure K.1 Liquid composition (mole fraction) from Fortran (implicit method, IFP's method) program compared to one from ProII.

Table K.2 Vapor composition (mole fraction) of distillation column at steady-state from ProII and Fortran (implicit method, IFP's method) programs

Tray	Fortran		ProII		% Error	
No.	Propane	Butane	Propane	Butane	Propane	Butane
1	1	0	1	0	0	0
2	1	0	1	0	0	0
3	1	0	1	0	0	0
4	0.9999	0.0001	1	0.0001	-0.01	0
5	0.9999	0.0001	0.9999	0.0001	0	0
6	0.9998	0.0002	0.9998	0.0003	0	-33.333
7	0.9995	0.0005	0.9994	0.0006	0.01001	-16.667
8	0.9989	0.0011	0.9988	0.0012	0.01001	-8.3333
9	0.9977	0.0023	0.9973	0.0027	0.04011	-14.815
10	0.9953	0.0047	0.9942	0.0058	0.11064	-18.966
11	0.9903	0.0097	0.9875	0.0125	0.28354	-22.4
12	0.9801	0.0199	0.9733	0.0267	0.69865	-25.468
13	0.96	0.04	0.9446	0.0554	1.63032	-27.798
14	0.9223	0.0777	0.8909	0.1091	3.52453	-28.781
15	0.8579	0.1421	0.8038	0.1962	6.73053	-27.574
16	0.8284	0.1716	0.7744	0.2256	6.97314	-23.936
17	0.7793	0.2207	0.7273	0.2727	7.14973	-19.069
18	0.7035	0.2965	0.6569	0.3431	7.09393	-13.582
19	0.5993	0.4007	0.5624	0.4376	6.56117	-8.4324
20	0.4754	0.5246	0.4513	0.5487	5.34013	-4.3922
21	0.3505	0.6495	0.3388	0.6612	3.45337	-1.7695
22	0.2424	0.7576	0.2395	0.7605	1.21086	-0.3813
23	0.1598	0.8402	0.1614	0.8386	-0.9913	0.19079
24	0.1019	0.8981	0.105	0.895	-2.9524	0.34637
25	0.0636	0.9364	0.0665	0.9335	-4.3609	0.31066
26	0.039	0.961	0.0413	0.9587	-5.569	0.23991
27	0.0237	0.9763	0.0252	0.9748	-5.9524	0.15388
28	0.0142	0.9858	0.0151	0.9849	-5.9603	0.09138
29	0.0083	0.9917	0.0088	0.9912	-5.6818	0.05044
30	0.0047	0.9953	0.0049	0.9951	-4.0816	0.0201

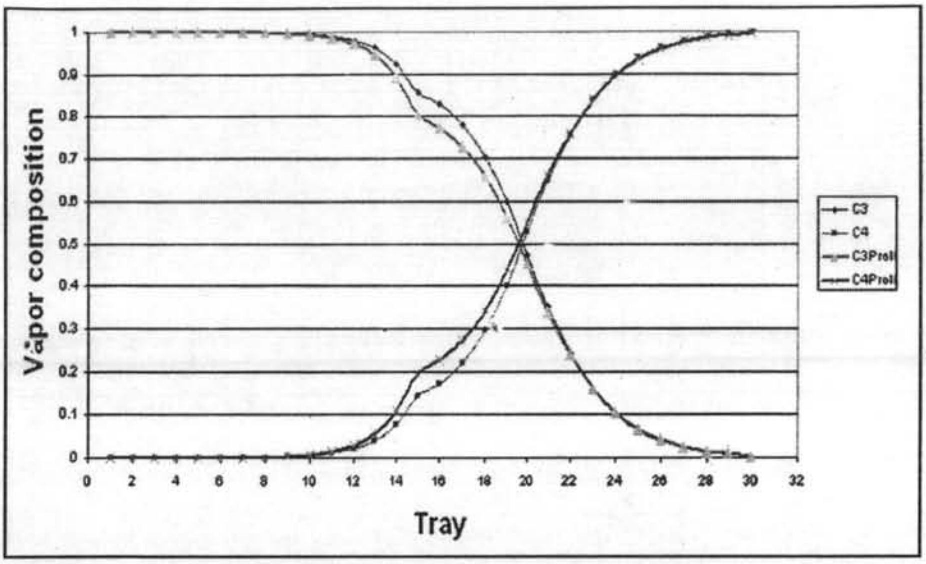

Figure K.2 Vapor composition (mole fraction) from Fortran (implicit method, IFP's method) program compared to ProII.

CURRICULUM VITAE

Name: Mr. Tharnuttarapamorn Sirithanonechai

Date of Birth: June 25, 1981

Nationality: Thai

University Education:

1999-2004 Bachelor Degree of Chemical Engineering, Faculty of Engineering, Thammasat University, Bangkok, Thailand

Working Experience:

2003	Position:	Student trainee
	Company name:	PTT Public Company Limited (PTT)