REFERENCES

Abdel-Aal, H.K., Aggour, M., and Fahim, M.A. (2003) Petroleum and Gas Field Processing. New York: Marcel Dekker, Inc.

Alkis, C. and Navid, M. (2000) Numerical Methods for Chemical Engineers with MATLAB Applications. New Jersey: Prentice-Hall Inc.

Baoyan, L., Zhangxin, C., and Guanren, H. (2003) The sequential method for the black-oil reservoir simulation on unstructured grids. Journal of Computational Physics, 192, 36-72.

Chamnakyut, K. (2004) A simulation of the underground storage of natural gas. M.S. Thesis, The Petroleum and Petrochemical Collage, Chulalongkorn University, Bangkok, Thailand.

Chapra, S.C. and Canale, R.P. (2002) Numerical Methods for Engineers. Boston: McGraw-Hill Companies, Inc.

Dale, H.B. (1991) Production Optimization Using NODAL Analysis. Oklahoma: OIL & GAS Consultants International Inc.

Dake, L.P. (1978) Fundamentals of Reservoir Engineering. Amsterdam: Elsevier Scientific Publishing Company.

Dawe, R.A. (2000) Modern Petroleum Technology Volume I Upstream. New York: John Wiley & Sons, LTD.

Goodarz, A., Chuang, J., and Duane, H.S. (2004) Numerical solution for natural gas production from methane hydrate dissociation. Journal of Petroleum Science and Engineering, 41, 269–285.

Henderson, N., Flores, E., Sampaio, M., Freitas, L., and Platt, G.M. (2005) Supercritical fluid flow in porous media: modeling and simulation. Journal of Chemical Engineering Science, 60, 1797-1808.

Khuzhayorov, B.Kh. and Burnashev, V.F. (2001) Modeling the multiphase flow of an oil–gas–condensate system in porous median. Journal of Petroleum Science and Engineering, 29, 67–82.

Ridha, B.C. (2004) Use of reservoir simulation for optimizing recovery performance. Journal of Petroleum Science and Engineering, 42, 183-194.

Ruben, J. (2004) A variational multiscale finite element method for multiphase flow in porous media. Finite Elements in Analysis and Design, 41, 763-777.

Sadooni, F.N. (2002) Reservoir Characterization. Department of Geology, United Arab Emirates University.

Suarez-Rivera, R., Begnaud, B.J., and Martin, W.J. (2004) Numerical analysis of open-hole multilateral completions minimizes the risk of costly junction failures. Rio Oil & Gas Expo and Conference 2004 Proceedings. Instituto Brasileiro de Petróleoe Gás, IBP096-04.

Ursin, J.R. (2004) Fluid flow in gas condensate reservoirs: the interplay of forces and their relative strengths. Journal of Petroleum Science and Engineering, 41, 253–267.

William, K.S. and Roland, W.L. (2002) Three-dimensional finite element simulation of three-phase flow in a deforming fissured reservoir. Comput. Methods Appl. Mech. Enrgy, 191, 2631-2659.

Wilkes, J.O. (1999) Fluid Mechanics for Chemical Engineers. New Jersey: Prentice-Hall Inc.

APPENDICES

APPENDIX A Fluid Flow from Reservoir into Well

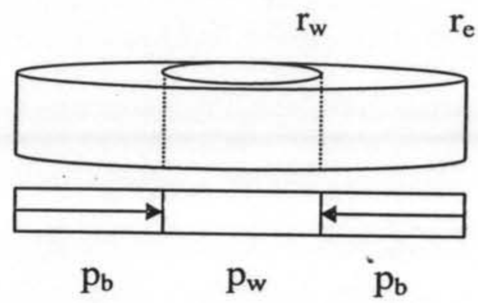

Figure A1 Radial flow system.

<u>**Assume**</u> Natural gas flow in reservoir behaves like flow in radial system

From Darcy's law

$$q = vA \tag{A-1}$$

$$q = -\frac{k}{\mu}\frac{dp}{dr} * 2\pi rh \tag{A-2}$$

Compare volumatic flow at standard condition,

$$Qi = \frac{\rho q}{\rho_{sc}} \tag{A-3}$$

When,

$$\frac{\rho}{\rho_{sc}} = \frac{pT_{sc}}{Zp_{sc}T} \tag{A-4}$$

Replace Eq. (A-4) into Eq. (A-3)

$$Q_i = -\frac{pT_{sc}}{Zp_{sc}T} * 2\pi rh * \frac{k}{\mu}\frac{dp}{dr} \qquad \text{(A-5)}$$

Integration from sandface (r_w) to any location (r)

BC. $r = r_w$, $p = p_{wi}$

$r = r$, $p = p$

$$\frac{-Q_i Zp_{sc}T\mu}{2\pi hkT_{sc}} \int_{r_w}^{r} dr / r = \int_{p_{wi}}^{p} pdp \qquad \text{(A-6)}$$

$$-\frac{Q_i TZp_{sc}\mu}{T_{sc}\pi hk} \ln\frac{r}{r_w} = (p^2 - p_{si}^2) \qquad \text{(A-7)}$$

$$p^2 = p_{si}^2 - \frac{Q_i TZp_{sc}\mu}{T_{sc}\pi hk} \ln\frac{r}{r_w} \qquad \text{(A-8)}$$

Get p_b^2 from the average of p^2 over radius r_w and r_e

$$p_b^2 = \frac{\int_{r_w}^{r_e} p^2 rdr}{\int_{r_w}^{r_e} rdr} \qquad \text{(A-9)}$$

$$p_b^2 = \frac{\int_{r_w}^{r_e} (p_{wi}^2 - \frac{Q_i TZp_{sc}\mu}{T_{sc}\pi hk} \ln\frac{r}{rw}) rdr}{\int_{r_w}^{r_e} rdr} \qquad \text{(A-10)}$$

$$p_b^2 = \frac{\left[\frac{r^2}{2}p_{wi}^2 - \left(\frac{Q_i TZp_{sc}\mu}{T_{sc}\pi hk}\times\frac{r^2}{2}(\ln\frac{r}{rw} - 0.5)\right)\right]_{r_w}^{r_e}}{\frac{r_e^{\ 2}}{2} - \frac{r_w^{\ 2}}{2}} \tag{A-11}$$

Gives, $r_e^2 - r_w^2 = r_e^2\,(1 - (r_w^2/\,r_e^2)) \approx r_e^2$

$$p_b^2 = \frac{2}{re^2}\left[\frac{r^2}{2}p_{wi}^2 - \left(\frac{Q_i TZp_{sc}\mu}{T_{sc}\pi hk}\times\frac{r^2}{2}(\ln\frac{r}{r_w} - 0.5)\right)\right]_{r_w}^{r_e} \tag{A-12}$$

$$p_b^2 = p_{wi}^2 - \frac{Q_i TZp_{sc}\mu}{T_{sc}\pi hk} * \frac{2}{r_e^{\ 2}}\left[\frac{r^2}{2}(\ln\frac{r}{r_w} - 0.5)\right]_{r_w}^{r_e} \tag{A-13}$$

$$p_b^2 = p_{wi}^2 - \frac{Q_i TZp_{sc}\mu}{T_{sc}\pi hk} * \frac{2}{r_e^{\ 2}}\left[\frac{r_e^{\ 2}}{2}\ln\frac{r_e}{r_w} - 0.5\frac{r_e^{\ 2}}{2} - \frac{r_w^{\ 2}}{2}\ln\frac{r_w}{r_w} + 0.5\frac{r_w^{\ 2}}{2}\right] \tag{A-14}$$

$$p_b^2 = p_{wi}^2 - \frac{Q_i TZp_{sc}\mu}{T_{sc}\pi hk} * \frac{2}{r_e^{\ 2}}\left[\frac{re^2}{2}\ln\frac{r_e}{r_w} - \frac{0.5}{2}(r_e^{\ 2} - r_w^{\ 2})\right] \tag{A-15}$$

$$p_b^2 = p_{wi}^2 - \frac{Q_i TZp_{sc}\mu}{T_{sc}\pi hk}(\ln\frac{r_e}{r_w} - 0.5) \tag{A-16}$$

$$p_{wi}^2 - p_b^2 = \frac{Q_i TZp_{sc}\mu}{T_{sc}\pi hk}(\ln\frac{r_e}{r_w} - 0.5) \tag{A-17}$$

Rearrange Eq. (A-17) into volume flow rate, Q_i ;

$$Q_i = \frac{T_{sc}\pi hk}{TZP_{sc}\mu}\frac{(p_{wi}^2 - p_b^2)}{\ln\frac{r_e}{r_w} - 0.5} \tag{A-18}$$

where, p_{wi}, is well pressure; p_b, the block average pressure; Qi, the volume flow rate; r_e, the equivalent radius of external boundary; r_w, the well radius; Z, the mean compressibility factor; μ, the gas viscosity; k, the rock permeability; and h, the reservoir thickness.

APPENDIX B Fluid Flow in Well

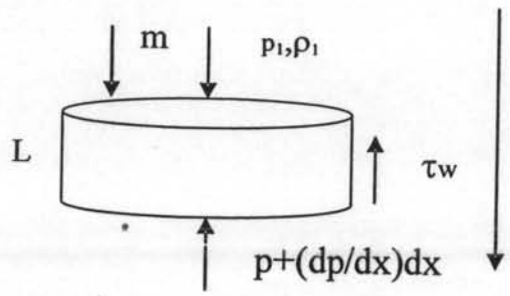

Figure B1 Well flow system.

Basis the steady flow of ideal gas at constant temperature (isothermal)
From momentum balance

$$\frac{\pi D^2}{4} dp = -\pi D \tau_w dx + \frac{\pi D^2}{4} \rho g_x dx \qquad \text{(B-1)}$$

Gives,

$$f_F = \frac{\tau_W}{0.5 \rho U^2} \qquad \textit{and} \qquad \rho = \frac{pMw}{RT}$$

Replace the fanning friction factor into Eq. (B-1),

$$\frac{dp}{\rho u^2} + \frac{2 f_F}{D} dx - \frac{g}{u^2} dx = 0 \qquad \text{(B-2)}$$

From continuity, mass flow rate (m = ρUA) is constant gives,

$$\frac{1}{\rho u^2} = \frac{\rho}{G^2} = \frac{\rho_1 p}{p_1 G^2} \qquad \text{and} \qquad \frac{1}{u^2} = \frac{\rho_1^2 p^2}{p_1^2 G^2}$$

Then,

$$\frac{\rho_1}{p_1 G^2} p dp + \frac{2 f_F}{D} dx - \frac{\rho_1^2 g}{p_1^2 G^2} p^2 dx = 0 \quad \text{(B-3)}$$

$$\frac{\rho_1}{p_1} p \frac{dp}{dx} - \frac{\rho_1^2 g}{p_1^2} p^2 + \frac{2 f_F G^2}{D} = 0 \quad \text{(B-4)}$$

Assume : $a = \frac{\rho_1}{p_1}$, $b = \frac{\rho_1^2 g}{p_1^2}$ and $c = \frac{2 f_F G^2}{D}$

Replace variables a, b, c into Eq. (B-4)

$$ap \frac{dp}{dx} - bp^2 + c = 0 \quad \text{(B-5)}$$

Solved Variable '*p*' in Eq. (B-5)

$$p = \pm \frac{1}{b} \sqrt{b(c + \exp(\frac{2bx}{a}) * c_1 * b)} \quad \text{(B-6)}$$

$$p^2 = \frac{c}{b} + c_1 \exp(\frac{2bx}{a}) \quad \text{(B-7)}$$

From B.C.1 x = 0 , $p = p_t$

$$pt^2 = \frac{c}{b} + c_1 \exp(\frac{2b(0)}{a}) \quad \text{(B-8)}$$

$$p^2 = \frac{c}{b} + \frac{1}{b}(-c + pt^2 b) * \exp(\frac{2bx}{a}) \quad \text{(B-9)}$$

Next, B.C.2 $x = L$, $p = p_{wi}$

$$pwi^2 = \frac{c}{b}(1 - \exp(\frac{2bL}{a})) + pt^2 \exp(\frac{2bL}{a}) \tag{B-10}$$

$$pt^2 \exp(\frac{2bL}{a}) - pwi^2 = \frac{c}{b}(\exp(\frac{2bL}{a}) - 1) \tag{B-11}$$

Substitute variables a, b, c into Eq. (B-11),

$$pt^2 \exp(\frac{2\frac{\rho_1^2 g}{p_1^2}L}{\frac{\rho_1}{p_1}}) - pwi^2 = \frac{\frac{2f_F G^2}{D}}{\frac{\rho_1^2 g}{p_1^2}}(\exp(\frac{2\frac{\rho_1^2 g}{p_1^2}L}{\frac{\rho_1}{p_1}}) - 1) \tag{B-12}$$

$$pt^2 \exp(\frac{2\rho_1 gL}{p_1}) - pwi^2 = \frac{\frac{2f_F G^2}{D}}{\frac{\rho_1^2 g}{p_1^2}}(\exp(\frac{2\rho_1 gL}{p_1}) - 1) \tag{B-13}$$

Rearrange Eq. (B-13) into volume flow rate, Q_i, by

$$Q_i = \frac{GA}{\rho}, \quad A = \frac{\pi D^2}{4}$$

Then,

$$Q_i^{\,2} = \left(\frac{\pi D^2}{4\rho_s}\right)^2 \frac{\rho_1^2 gD}{2f_F P_1^2} * \frac{1}{(\exp(\frac{2p_1^3}{\rho_1^3 gL}) - 1)}\left[pt^2 \exp(\frac{2\rho_1 gL}{p_1}) - pwi^2\right] \tag{B-14}$$

Finally,

$$Q_i = \pm \frac{\pi MwD^2}{4RT\rho_s}\left(\frac{gD}{2f_F} * \frac{1}{(\exp(\frac{2MwgL}{RT_1})-1)}\right)^{1/2} \sqrt{\pm\left(pt^2\exp(\frac{2MwgL}{RT_1}) - pwi^2\right)} \qquad \text{(B-15)}$$

** For upwards flow, minus sign are obtained.

Where, mass velocity (G) = ρU; pt is well head pressure; p_{wi}, the well pressure; Mw, the molecular weight; Q_i , the volume flow rate; ρ, the gas density; R, the gas constant; T, the mean temperature; D, the well diameter; f_F, the fanning friction; L, the well depth; and g, the gravitational acceleration.

APPENDIX C Harmonic Average in Transmissibilities

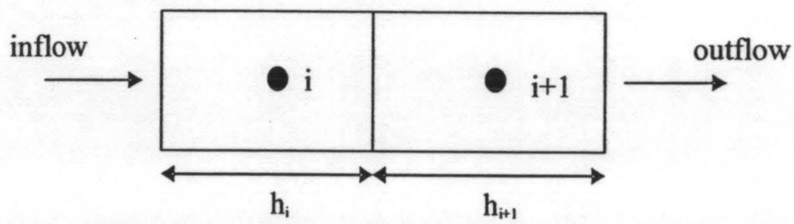

Figure C1 Gas flow between two blocks.

__Assume__ the gas flow in 2 blocks

Consider between two blocks (i,i+1) with length (h_i, h_{i+1}) and permeabilities (k_i, k_{i+1}) separate by edge i+1/2

From Darcy's law

$$v = -\frac{k}{\mu}\nabla p \qquad \text{(C-1)}$$

Assume

$$\tilde{v} = -\nabla p \qquad \text{(C-2)}$$

Then, Eq. (C-1) becomes

$$v = \frac{k}{\mu}\tilde{v} \qquad \text{(C-3)}$$

If $\tilde{v}^-_{i+1/2}, \tilde{v}^+_{i+1/2}$ denote the discrete values in block i, i+1, respectively.

Substitute into Eq. (C-3)

$$v_{i+1/2} = \frac{k_i}{\mu} \tilde{v}^{-}_{i+1/2} \tag{C-4}$$

$$v_{i+1/2} = \frac{k_{i+1}}{\mu} \tilde{v}^{+}_{i+1/2} \tag{C-5}$$

$$\frac{h_i}{2} \tilde{v}^{-}_{i+1/2} + \frac{h_{i+1}}{2} \tilde{v}^{+}_{i+1/2} = -(p_{i+1} - p_i) \tag{C-6}$$

Substitute Eqs. (C-4 and 5) into Eq.(C-6) to eliminate $\tilde{v}^{-}_{i+1/2}$, $\tilde{v}^{+}_{i+1/2}$

$$v_{i+1/2} = -\frac{2k_i k_{i+1}}{\mu(h_i k_i + h_{i+1} k_{i+1})}(p_{i+1} - p_i) \tag{C-7}$$

If $h_i = h_{i+1}$, We can arrange into;

$$v_{i+1/2} = -\frac{2k_i k_{i+1}}{(k_i + k_{i+1})} \frac{(p_{i+1} - p_i)}{\mu h_i} \tag{C-8}$$

APPENDIX D Effect of Reservoir Temperature

The reservoir temperature was investigated by using the energy balance (convection and conduction) equation as shown in Eq. (D-1). Energy balance equation was solved along with the governing equation in Eq. (3-25). The regular case is used to study this effect based on the data from Table 4.4. Carbonate reservoir (limestone) is assumed in this study.

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \bullet (-k\nabla T) = -\rho C_p u \bullet \nabla T \qquad \text{(D-1)}$$

when, ρ is density of gas (dependent of p and T); C_p, the heat capacity of methane (0.035 kJ/mol.K.); T, reservoir temperature; t, operation time; k, thermal conductivity of limestone (0.5 W/m.K.); and u, velocity of gas in reservoir (related with Darcy's law).

The reservoir behaviors after the gas is withdrawn are depicted in Figs. D1(a) and (b). It is observed that reservoir pressure gradually decreases at the withdrawal point. On the contrary, reservoir temperature does not change with the reservoir pressure because during fluids are produced, any change in temperature due to production is compensated by heat from cap or base rocks (Richard, 2000). Therefore, the reservoir temperature is assumed constant along the reservoir.

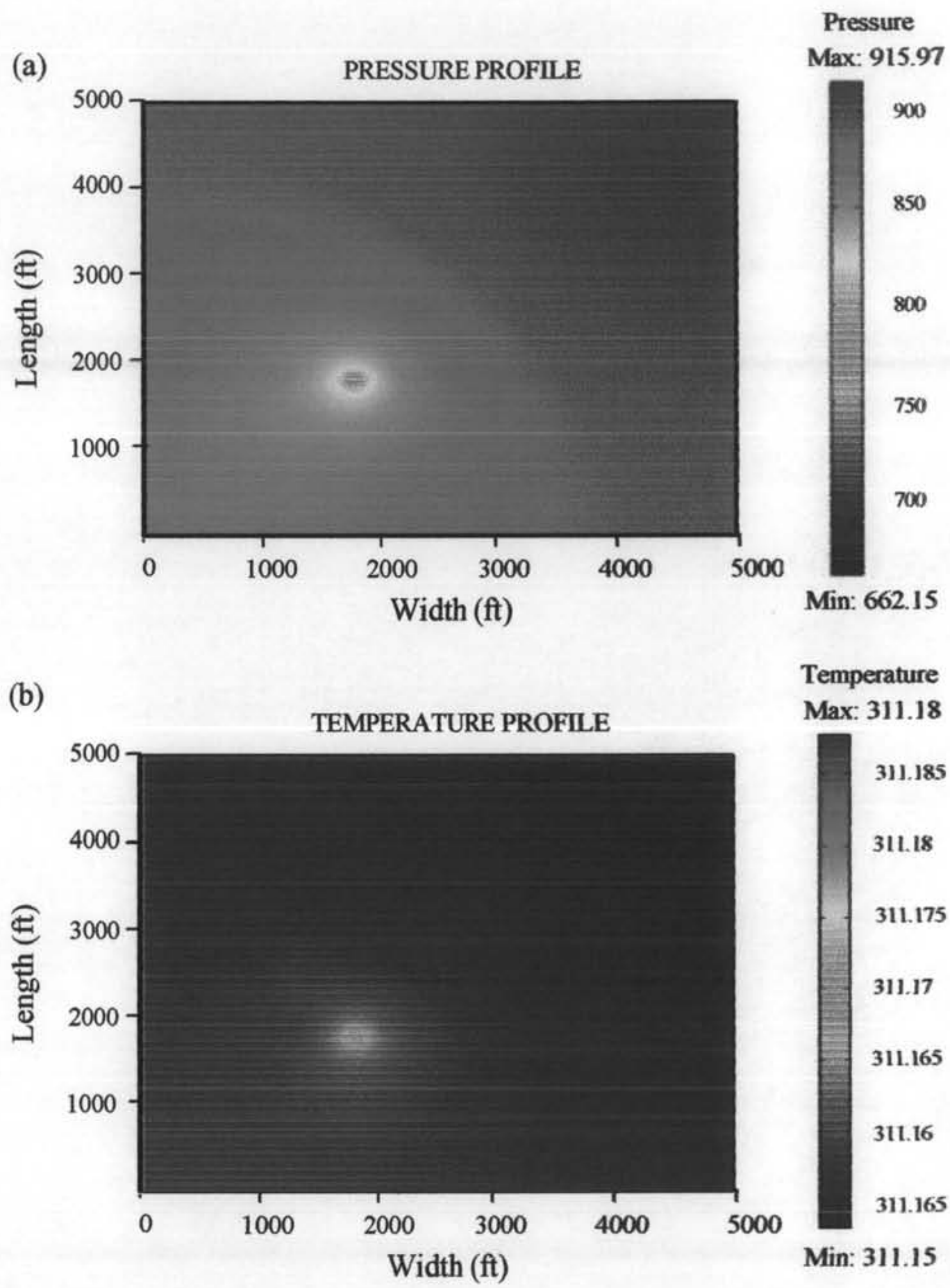

Figure D1 Reservoir behaviors after natural gas withdrawal at time 500 days, (a) pressure profile, (b) temperature profile.

APPENDIX E Fortran Code for Computing Pressure Profile in Reservoir

```
PROGRAM GAS STORAGE
C       COMPLETE VERSION
C       BIGQS1      Current gas withdrawal rate per well, SCF/day
C       BIGQS2      Current gas injection rate per well, SCF/day
C       C           Conversion Factor, 6.327E-3 cp sq ft/md day psia
C       COUNT       Counter number of time steps
C       DELTA(I,J)  Array of gas withdrawal or injection..
C       DT          Time step, days
C       DX,DY       Grid spacing in the x and y direction, ft
C       EPS         Porosity
C       FREQ        Frequency of output data
C       FF          Fanning friction factor
C       G           Gravity force, ft/s^2
C       H           Reservoir thickness, ft
C       I,J         Column and row indicates (x and y direction)
C       IA,JA       Array of wells
C       IDF         Individual flow in each well
C       IW,JW       Indicates of block in which well is located
C       K           Permeability, md
C       L           Length of storage field, ft
C       M           Number of increments in x direction
C       MP1         Number of grid in x direction
C       MU          Gas viscosity, cp
C       MW          Molecular weight of methane
C       N           Number of increments in y direction
C       NP1         Number of grid in y direction
C       NW          Number of well
C       P           Pressure, psia
C       PB          Block average pressure, psia
C       PD          Delivery pressure, psia
C       PHI         Gas potential,(psia)^2/cp
C       PS,TS       Standard pressure (psia), standard temperature (R)
C       PT          Well bore pressure, psia
C       PZERO       Initial Pressure (uniform).(psia)
```

```
C     QI          Total injection rate, SCF/day
C     QMAX1       Gas withdrawal rate per well, SCF/day
C     QMAX2       Gas injection rate per well, SCF/day
C     QS1         Gas withdrawal rate per volume, SCF/day.cu ft =1/day
C     QS2         Gas withdrawal rate per volume, SCF/day.cu ft =1/day
C     QW          Total withdrawal rate, SCF/day
C     R           Gas constant
C.    RE          Effective drainage radius of well, ft
C     RW          Wellbore radius, ft
C     T           Time, day
C     TI          Injection periods, days
C     TO          Operation periods, days
C     TW          Withdrawal periods, day
C     TEMP        Reservoir temperature, R
C     TMAX        Total simulation time, days
C     W           Width of storage field, ft
C     Z           Well height, ft
C     **********Declarations**********

      IMPLICIT NONE
      INTEGER  COUNT,FREQ,I,IW,J,JW,M,N,MP1,NP1,NW,IA,JA,U
      INTEGER  TW,TI,TO
      REAL   A,B,ALPHA,BETA,BIGQS1,BIGQS2,C,CO,CX,CY, DELF,DELTA1
      REAL   DELTA2,DT,DX,DY,EPS, EX,FF,G,H, IDF, K, L,MU, MW, P,PB,
      REAL   PD,PHI,PI,PS, PT,PW PZERO,QI,QW,QMAX1,QMAX2,QS1,QS2
      REAL   R,RE,RW,SF,T,TEMP,TMAX,TS,W, Z
      DIMENSION CX(401,401),CY(401,401),DELTA1(401,401),DELTA2(401,401)
      DIMENSION K(401,401),P(401,401),PHI(401,401),IA(400),JA(400)
      DIMENSION EX(400),PT(400), B(400),DELF(400),PW(400)
      DIMENSION IW(400),JW(400),RW(400),Z(400),PB(400),IDF(400),CO(400)
      OPEN   (4, FILE='Input Data2.dat')
      OPEN   (6, FILE='Checked Input Data IRRE .XLS')
      OPEN   (7, FILE='TestIRRE.XLS')
C     ***********READ INPUT DATA&PARAMETERS***********
      READ(4,*)DT,EPS,FF,FREQ,G,H,L,M,MU,MW,N,NW,PD,PS,PZERO,QI,QW,
*     TEMP,TS,TMAX,TI,TW,W
```

```
      MP1 = M+1
      NP1 = N+1
      DX = L/M
      DY = W/N
      RE = SQRT(DX*DY/3.1416)
      WRITE (6,201)DT,EPS,FF,FREQ,G,H,L,M,MU,MW,N,NW,PD,PS,
     *      PZERO,QI,QW,TEMP,TS,TMAX,TI,TW,W
      WRITE (6,202) DX,DY,RE

      IF (NW.NEQV.0) THEN
            WRITE (6,*) 'LOCATION OF WELL'
            WRITE(6,*) 'NW   IW    JW      RW(ft)      Z(ft)'
      END IF

      DO 101 I =1,NW
            READ(4,*) IW(I),JW(I),RW(I),Z(I)
            WRITE (6,203) I,IW(I),JW(I),RW(I),Z(I)
 101  CONTINUE
      DO 102 I=1,NW
       IA(I)= IW(I)
       JA(I)= JW(I)
 102  CONTINUE

C     *******INITIAL VALUES********
       PI = 3.14159
       C = 6.327E-3
       COUNT = 0
       A = PI*86400*TS/5.656/PS/TEMP
       QS1 = 0.
       QS2 = 0
       PA = 0
       R = 4.971E4
       ALPHA = TEMP*PS/TS
       BETA = EPS*SQRT(MU/2.)
       T = 0
       TO = TI+TW
```

```
      DO 103 I=1,MP1
        DO 104 J=1,NP1
              CX(I,J)=C*K(I,J)*DT/(2*BETA*DX**2)
              CY(I,J)=C*K(I,J)*DT/(2*BETA*DY**2)
              DELTA1(I,J) = 0
              DELTA2(I,J) = 0.
              P(I,J)=PZERO
              PHI(I,J)=PZERO**2/(2.*MU)
              EX(I) = 0
              IDF(I) = 0
              PB(I) = 0
              PT(I) = 0
104     END DO
103   END DO
      READ(4,*) ((K(I,J),I=1,MP1),J=NP1,1,-1)

C   *************SET PRESSURE IN IRREGULAR SHAPE****************
      DO 105 I=1,MP1
        DO 106 J=1,NP1
             IF (K(I,J).EQ.0) THEN
               P(I,J) = 0
               PHI(I,J)= 0
             END IF
106     END DO
105   END DO

      CALL PRINT (1,M,N,K)
      WRITE (6,*) 'T=',T ,'DAYS'
      CALL PRINT (2,M,N,P)
      CALL PRINT (3,M,N,PHI)

C    ***********CALCULATION OVER SUCCESSSIVE TIME STEPS**********
107   COUNT=COUNT+1
      T=T+DT
      WRITE (*,*) 'T=',T
      IF (T.LE.TW) THEN
```

```
            QMAX1 = QW/(NW+1E-9)
            QMAX2 = 0
      ENDIF

      IF (T.GT.TW) THEN
            QMAX1 = 0
            QMAX2 = (-QI)/(NW+1E-9)
      ENDIF

      IF (T.GE.TO) THEN
            QMAX1 = 0
            QMAX2 = 0
      ENDIF

C     ************UPDATE WITHDRAWAL / INJECTION RATE************
      BIGQS1 = QMAX1*(1. - ABS(2.*T/TW - 1.))
      BIGQS2 = QMAX2*(1. - ABS(2.*(T-TW)/TI - 1.))
      QS1 = BIGQS1/(DX*DY*H)
      QS2 = BIGQS2/(DX*DY*H)

      DO 108 I=1,NW
            DELTA1(IA(I),JA(I)) = ALPHA*SQRT(PHI(IA(I),JA(I)))*QS1*DT
     *      /(2*BETA)
108   CONTINUE

      DO 109 I=1,NW
            DELTA2(IA(I),JA(I)) = ALPHA*SQRT(PHI(IA(I),JA(I)))*QS2*DT
     *      /(2*BETA)
109   CONTINUE

C     *************Update potentials*************
      CALL IAD (CX,CY,DELTA1,DELTA2,M,N,PHI)

C     ....Print pressure and potential fields when request,
C       first converting potentail to pressure...............
      DO 110 I=1,MP1
```

```
          DO 111 J=1,NP1
                P(I,J)=SQRT(2.*MU*PHI(I,J))
111       CONTINUE
110     CONTINUE

        IF (COUNT/FREQ*FREQ.EQ.COUNT) THEN
                WRITE (6,*) 'T=',T ,'DAYS',' QW=',BIGQS1*NW/1E6,'MMSCFD',
*               ' QI=',BIGQS2*NW/1E6,'MMSCFD'
                CALL PRINT (2,M,N,P)
                CALL PRINT (3,M,N,PHI)
        ENDIF

        WRITE (6,*) 'TIME =',T,'DAYS'

        DO 112 I = 1,NW
                PB(I)=(P(IA(I),JA(I))+P(IA(I),JA(I)+1)+P(IA(I),JA(I)-1)
*               +P(IA(I)+1,JA(I))+P(IA(I)-1,JA(I)))/5
                WRITE (6,*) 'PB','(',I,')= ',PB(I),'psi'
112     CONTINUE

C       *************WITHDRAWAL PERIOD*************
        IF (T.LE.TW) THEN
        DO 113 U=1,20
                PT(1)=PD
                SF = 0
          DO 114 I=1,NW
                EX(I) = EXP(2*MW*G*Z(I)/R/TEMP )
                B(I)= G*((2*RW(I))**5)/FF/(EX(I)-1)
                CO(I) = PS*TEMP*MU*(ALOG(RE/RW(I))-0.5)/TS/PI/H/C/K(IA(I),JA(I))
                IDF(I)= A*(-(0.5*A*B(I)*CO(I))+0.5*((A*B(I)*CO(I))**2-
*               4*B(I)*(EX(I)*PT(U)**2-PB(I)**2))**0.5)
                SF= SF+IDF(I)
114       CONTINUE
                DELF(U)=NW*BIGQS1-SF
                PT(U+1)=(PT(U-1)*DELF(U)-PT(U)*DELF(U-1))/(PT(U-1)-DELF(U-1)-
*                PT(U)+DELF(U))
```

```
            IF (PT(U+1).EQ.PT(U)) THEN
                WRITE (6,*) 'PT=',PT(U),'psi'
            DO 115 I=1,NW
                IDF(I)= A*(-(0.5*A*B(I)*CO(I))+0.5*((A*B(I)*CO(I))**2-
     *          4*B(I)*(EX(I)*PT(U)**2-PB(I)**2))**0.5)
                PW(I) = SQRT(PB(I)**2 - MU*IDF(I)*ALPHA/(PI*K(IA(I),JA(I))*H)*
     *           (ALOG(RE/RW(I)) - 0.5)/C)
              * WRITE (6,*) 'PW=',PW(I),'psi'
                WRITE (6,*) 'INDIVIDUAL FLOW',I,'=>  ',IDF(I)/1E6,'MMSCFD'
115         END DO
          GOTO 116
          END IF
113       CONTINUE
          END IF

C         *************INJECTION PERIOD*************
          IF (T.GT.TW) THEN
           DO 117 U=1,20
                PT(1)=PD
                SF = 0
            DO 118 I=1,NW
                EX(I)  = EXP(2*MW*G*Z(I)/R/TEMP )
                B(I)= G*((2*RW(I))**5)/FF/(EX(I)-1)
                CO(I) = PS*TEMP*MU*(ALOG(RE/RW(I))-0.5)/TS/PI/H/C/K(IA(I),JA(I))
                IDF(I)= A*(-(0.5*A*B(I)*CO(I))+0.5*((A*B(I)*CO(I))**2+
     *          4*B(I)*(EX(I)*PT(U)**2-PB(I)**2))**0.5)
                SF= SF+IDF(I)
118         CONTINUE
                DELF(U)=NW*BIGQS2+SF
                PT(U+1)=(PT(U-1)*DELF(U)-PT(U)*DELF(U-1))/(PT(U-1)-DELF(U-1)-
     *          PT(U)+DELF(U))
            IF (PT(U+1).EQ.PT(U)) THEN
                WRITE (6,*) 'PT=',PT(U),'psi'
            DO 119 I=1,NW
                IDF(I)= A*(-(0.5*A*B(I)*CO(I))+0.5*((A*B(I)*CO(I))**2-
     *          4*B(I)*(EX(I)*PT(U)**2-PB(I)**2))**0.5)
```

```
            PW(I) = SQRT(PB(I)**2 - MU*IDF(I)*ALPHA/(PI*K(IA(I),JA(I))*H)*
     *      (ALOG(RE/RW(I)) - 0.5)/C)
            WRITE (6,*) 'PW=',PW(I),'psi'
            WRITE (6,*) 'INDIVIDUAL FLOW',I,'=>  ',IDF(I)/1E6,'MMSCFD'
119       END DO
        GOTO 116
        END IF
117     CONTINUE
      ENDIF

C     ************CHECKING CONDITIONS**************
116   IF (T.GT.TMAX-DT/2.) THEN
            STOP
      ELSE
            GOTO 107
      END IF

C     ************FORMAT OF OUTPUT STATEMENT***********
201   FORMAT (1X,'Simulation of gas-storage reservoir with'/
     *      'DT    =',F10.3,2X,'days'/
     *      'EPS   =',F10.3/
     *      'FF    =',F10.3/
     *      'FREQ  =',I6/
     *      'G     =',F10.3,2X,'ft/s^2'/
     *      'H     =',F10.3,2X,'ft'/
     *      'L     =',F10.3,2X,'ft'/
     *      'M     =',I6/
     *      'MU    =',F10.3,2X,'cp'/
     *      'MW    =',F10.3,2X,'lb/lbmole'/
     *      'N     =',I6/
     *      'NW    =',I6/
     *      'PD    =',F10.3,2X,'psia'/
     *      'PS    =',F10.3,2X,'psia'/
     *      'PZERO=',F10.3,2X,'psia'/
     *      'QI    =',E10.3,2X,'SCF/days'/
     *      'QW    =',E10.3,2X,'SCF/days'/
```

```
*              'TEMP  =',F10.3,2X,'R'/
*              'TS    =',F10.3,2X,'R'/
*              'TMAX  =',F10.3,2X,'days'/
*              'TI    =',I4,2X,'days'/
*              'TW    =',I4,2X,'days'/
*              'W     =',F10.3,2X,'ft')

 202    FORMAT ('DX  =',F10.3,2X,'ft'/
*               'DY  =',F10.3,2X,'ft'/
*               'RE  =',F10.3,2X,'ft')

 203    FORMAT (I2,5X,I4,4X,I4,5X,F10.3,5X,F10.3)
  STOP
END

        SUBROUTINE IAD (CX,CY,DELTA1,DELTA2,M,N,PHI)
C   Updates the gas potentials across a time step. Variables are same
C   as in main program, with addition of:
C    V =   Vector of solutions returned by TRIDAG

    IMPLICIT NONE
    INTEGER  I,J,MP1,NP1,M,N
    REAL     A,B,C,D,CX,CY,DELTA1,DELTA2,PHI,PHISTAR,V,LAMBDAX,LAMBDAY
*            ,LHX,LHY
    DIMENSION  A(401),B(401),C(401),CX(401, 401),
*              CY(401, 401),D(401),DELTA1(401, 401),DELTA2(401, 401),
*              PHI(401, 401),PHISTAR(401, 401),V(401),LHY(401,401),
*              LAMBDAX(401,401), LAMBDAY(401,401),LHX(401,401)
        MP1 = M+1
        NP1 = N+1

        DO 301 I= 1,MP1
          DO 302 J= 1,NP1
              LAMBDAX(I,J) = CX(I,J)*SQRT(ABS(PHI(I,J)))
              LAMBDAY(I,J) = CY(I,J)*SQRT(ABS(PHI(I,J)))
302       CONTINUE
301     CONTINUE
```

```
      DO 303 I=2,M,1
        DO 304 J= 1,NP1
              LHX(I,J) = (2*LAMBDAX(I-1,J)*LAMBDAX(I+1,J))
*              /(LAMBDAX(I-1,J)+LAMBDAX(I+1,J)+1e-9)
304     CONTINUE
303   CONTINUE
      DO 305 J=2,N,1
        DO 306 I= 1,MP1
              LHY(I,J) = (2*LAMBDAY(I,J-1)*LAMBDAY(I,J+1))
*             /(LAMBDAY(I,J-1)+LAMBDAY(I,J+1)+1e-9)
306     CONTINUE
305   CONTINUE

C     **COMPUTE PRESSURE FOR FIRST HALF TIME STEP (IMPLICIT BY ROWS)**
      DO 307 J=1,NP1
        DO 308 I=1,MP1
          IF (LAMBDAX(I-1,J).EQ.0) THEN
              B(I)=2.0*(1+LAMBDAX(I,J))
              C(I)=-2.0*LAMBDAX(I,J)
                IF (LAMBDAY(I,J-1).EQ.0) THEN
                      D(I) = 2.0*(1-LAMBDAY(I,J))*PHI(I,J)
*                     +2.0*LAMBDAY(I,J)*PHI(I,J+1)-DELTA1(I,J)-DELTA2(I,J)
                ELSEIF (LAMBDAY(I,J+1).EQ.0)THEN
                      D(I)=2.0*(1-LAMBDAY(I,J))*PHI(I,J)
*                     +2.0*LAMBDAY(I,J)*PHI(I,J-1)-DELTA1(I,J)-DELTA2(I,J)
                ELSE
                      D(I)=LAMBDAY(I,J)*PHI(I,J-1)+2*(1-LAMBDAY(I,J))*PHI(I,J)
*                     +LAMBDAY(I,J)*PHI(I,J+1)-DELTA1(I,J)-DELTA2(I,J)
                ENDIF
          ELSEIF (LAMBDAX(I+1,J).EQ.0)THEN
              A(I)=-2.0*LAMBDAX(I,J)
              B(I)=2.0*(1+LAMBDAX(I,J))
                IF (LAMBDAY(I,J-1).EQ.0) THEN
                      D(I) = 2.0*(1-LAMBDAY(I,J))*PHI(I,J)
*                     +2.0*LAMBDAY(I,J)*PHI(I,J+1)-DELTA1(I,J)-DELTA2(I,J)
                ELSEIF (LAMBDAY(I,J+1).EQ.0)THEN
```

```
                    D(I)=2.0*(1-LAMBDAY(I,J))*PHI(I,J)
     *              +2.0*LAMBDAY(I,J)*PHI(I,J-1)-DELTA1(I,J)-DELTA2(I,J)
                ELSE
                    D(I)=LAMBDAY(I,J)*PHI(I,J-1)+2*(1-LAMBDAY(I,J))*PHI(I,J)
     *              +LAMBDAY(I,J)*PHI(I,J+1)-DELTA1(I,J)-DELTA2(I,J)
                ENDIF
          ELSE
             A(I)=-LAMBDAX(I,J)
             B(I)=2.0*(1+LAMBDAX(I,J))
             C(I)=-LAMBDAX(I,J)
             D(I)=LAMBDAY(I,J)*PHI(I,J-1)+2*(1-LAMBDAY(I,J))*PHI(I,J)
     *       +LAMBDAY(I,J)*PHI(I,J+1)-DELTA1(I,J)-DELTA2(I,J)
            IF (LAMBDAY(I,J-1).EQ.0) THEN
                    D(I) = 2.0*(1-LAMBDAY(I,J))*PHI(I,J)
     *               +2.0*LAMBDAY(I,J)*PHI(I,J+1)-DELTA1(I,J)-DELTA2(I,J)
            ELSEIF (LAMBDAY(I,J+1).EQ.0)THEN
                    D(I)=2.0*(1-LAMBDAY(I,J))*PHI(I,J)
     *               +2.0*LAMBDAY(I,J)*PHI(I,J-1)-DELTA1(I,J)-DELTA2(I,J)
            ENDIF
         ENDIF
308      ENDDO
         CALL TRIDAG (1,MP1,A,B,C,D,V)
         DO 309  I=1,MP1
             PHISTAR(I,J)=V(I)
309      CONTINUE
307     CONTINUE

C       **COMPUTE PRESSURE FOR SECOND HALF TIME STEP (IMPLICIT BY
        COLUMNS)**
        DO 310 I=1,MP1
         DO 311 J=1,NP1
           IF (LAMBDAY(I,J-1).EQ.0) THEN
               B(J)=2.0*(1+LAMBDAY(I,J))
               C(J)=-2.0*LAMBDAY(I,J)
                 IF (LAMBDAX(I-1,J).EQ.0) THEN
                     D(J) = 2.0*(1-LAMBDAX(I,J))*PHISTAR(I,J)
```

```
*           +2.0*LAMBDAX(I,J)*PHISTAR(I+1,J)-DELTA1(I,J)-DELTA2(I,J)
          ELSEIF (LAMBDAX(I+1,J).EQ.0)THEN
            D(J)=2.0*(1-LAMBDAX(I,J))*PHISTAR(I,J)
*           +2.0*LAMBDAX(I,J)*PHISTAR(I-1,J)-DELTA1(I,J)-DELTA2(I,J)
          ENDIF
        ELSEIF (LAMBDAY(I,J+1).EQ.0)THEN
          A(J)=-2.0*LAMBDAY(I,J)
          B(J)=2.0*(1+LAMBDAY(I,J))

          IF (LAMBDAX(I-1,J).EQ.0) THEN
            D(J) = 2.0*(1-LAMBDAX(I,J))*PHISTAR(I,J)
*           +2.0*LAMBDAX(I,J)*PHISTAR(I+1,J)-DELTA1(I,J)-DELTA2(I,J)
          ELSEIF (LAMBDAX(I+1,J).EQ.0)THEN
            D(J)=2.0*(1-LAMBDAX(I,J))*PHISTAR(I,J)
*           +2.0*LAMBDAX(I,J)*PHISTAR(I-1,J)-DELTA1(I,J)-DELTA2(I,J)
          ENDIF
        ELSE
          A(J)=-LAMBDAY(I,J)
          B(J)=2.0*(1+LAMBDAY(I,J))
          C(J)=-LAMBDAY(I,J)
          D(J)=LAMBDAX(I,J)*PHISTAR(I-1,J)+2*(1-LAMBDAX(I,J))*PHISTAR(I,J)
*         +LAMBDAX(I,J)*PHISTAR(I+1,J)-DELTA1(I,J)-DELTA2(I,J)
          IF (LAMBDAX(I-1,J).EQ.0) THEN
            D(J) = 2.0*(1-LAMBDAX(I,J))*PHISTAR(I,J)
*           +2.0*LAMBDAX(I,J)*PHISTAR(I+1,J)-DELTA1(I,J)-DELTA2(I,J)
          ELSEIF (LAMBDAX(I+1,J).EQ.0)THEN
            D(J)=2.0*(1-LAMBDAX(I,J))*PHISTAR(I,J)
*           +2.0*LAMBDAX(I,J)*PHISTAR(I-1,J)-DELTA1(I,J)-DELTA2(I,J)
          ENDIF
        ENDIF
311   ENDDO
      CALL TRIDAG (1,NP1,A,B,C,D,V)
       DO 312 J=1,NP1
          PHI(I,J)=V(J)
312    CONTINUE
310  CONTINUE
```

```
      RETURN
      END

      SUBROUTINE PRINT (CODE,M,N,X)
      IMPLICIT NONE
      INTEGER CODE,I,J,M,N,MP1,NP1
      REAL X
      DIMENSION X(401,401)
      MP1 = M+1
      NP1 = N+1
      SELECT CASE (CODE)
       CASE(1)
           WRITE (6,401)
401        FORMAT (' The permeability field md'/
*          'standting with the row J=NP1 is:'/)
         DO J=NP1,1,-1
           WRITE (6,402)(X(I,J),I=1,MP1)
402        FORMAT ('',401F7.1)
         END DO
       CASE(2)
           WRITE (6,403)
403        FORMAT (' The current pressure field (psia) is:'/)
         DO J=NP1,1,-1
           WRITE (6,402)(X(I,J),I=1,MP1)
         END DO
       CASE(3)
           WRITE (6,405)
405        FORMAT (' The current potential field,MM(psia^2/cp)is:'/)
         DO J=NP1,1,-1
           WRITE (6,402)(X(I,J)/1.E6,I=1,MP1)
         END DO
      END SELECT
      RETURN
      END
```

```
      SUBROUTINE TRIDAG (FIRST,LAST,A,B,C,D,V)
C     Procedure for solving a system of simultaneous
C     linear equation with a triagonal coefficient matrix
      IMPLICIT NONE
      INTEGER FIRST,I,LAST
      REAL A,B,BETA,C,D,GAMMA,V
      DIMENSION A(301),B(301),BETA(301),C(301),D(301)
      DIMENSION GAMMA(301),V(301)
C     ...........Compute intermediate arrays BETA and GAMMA ...............
      BETA(FIRST)=B(FIRST)
      GAMMA(FIRST)=D(FIRST)/BETA(FIRST)
        DO 501 I=FIRST+1,LAST
              BETA(I)=B(I)-((A(I)*C(I-1))/BETA(I-1))
              GAMMA(I)=(D(I)-(A(I)*GAMMA(I-1)))/BETA(I)
501     CONTINUE
      V(LAST)=GAMMA(LAST)
        DO 502 I=LAST-1,FIRST,-1
              V(I)=GAMMA(I)-(C(I)*V(I+1)/BETA(I))
502     CONTINUE
      RETURN
      END
```

APPENDIX F Input Parameters in FEMLAB Software

Computer Specification : Pentium 4 CPU 2.4 GHz, Ram 2.0 GHz.

Software version : FEMLAB 3.1

Governing equation

Table F1 Governing equations in FEMLAB software

<table>
<tr><th>Location</th><th>Equations</th><th>Description</th></tr>
<tr><td>In the reservoir</td><td>Darcy' law (transient flow)
Variable: p
$\varepsilon\frac{\partial(p/T)}{\partial t}=\frac{\partial}{\partial x}(\frac{p}{T}\frac{k}{\eta}\frac{\partial p}{\partial x})+\frac{\partial}{\partial y}(\frac{p}{T}\frac{k}{\eta}\frac{\partial p}{\partial y})$</td><td rowspan="2">ε = porosity
k = permeability
η = viscosity
p = pressure
p_s = standard pressure
q_s = volume flow rate per volume
t = time
T = temperature
T_s = standard temperature
*All variables are in SI units.</td></tr>
<tr><td>In the drainage area</td><td>Darcy' law (transient flow)
Variable: p
$\varepsilon\frac{\partial(p/T)}{\partial t}=\frac{\partial}{\partial x}(\frac{p}{T}\frac{k}{\eta}\frac{\partial p}{\partial x})$
$+\frac{\partial}{\partial y}(\frac{p}{T}\frac{k}{\eta}\frac{\partial p}{\partial y})-\frac{q_s p_s}{T_s}$</td></tr>
</table>

Subdomain setting

Table F2 Subdomain setting in FEMLAB software

Item (unit)	Symbol	Value
Operating condition Gas withdrawal rate per volume (s^{-1})	q_s	1.473
Production time (days)	T	500
Reservoir pressure (Pa)	p_{re}	6.9e6
Reservoir temperature (K)	T_{re}	311
Properties of gas reservoir Fanning friction factor	f_F	0.0047
Gas Viscosity (Pa.s)	η	5e-5
Permeability (m^2)	k	1e-13
Porosity	ε	0.148
Standard pressure (Pa)	p_{sc}	1.013e5
Standard temperature (K)	T_{sc}	273
Reservoir geometry Reservoir length (m)	L	1524
Reservoir thickness (m)	H	15.24
Reservoir width (m)	W	1524
Well depth (m)	wd	1220
Well radius (m)	r_w	0.152

Procedure of Programming

1. From Model Navigator, choosing the solving equation , (Figure F1), *i.e.*, 2 D → Chemical Engineering Module → Momentum balance → darcy's law → transient analysis .

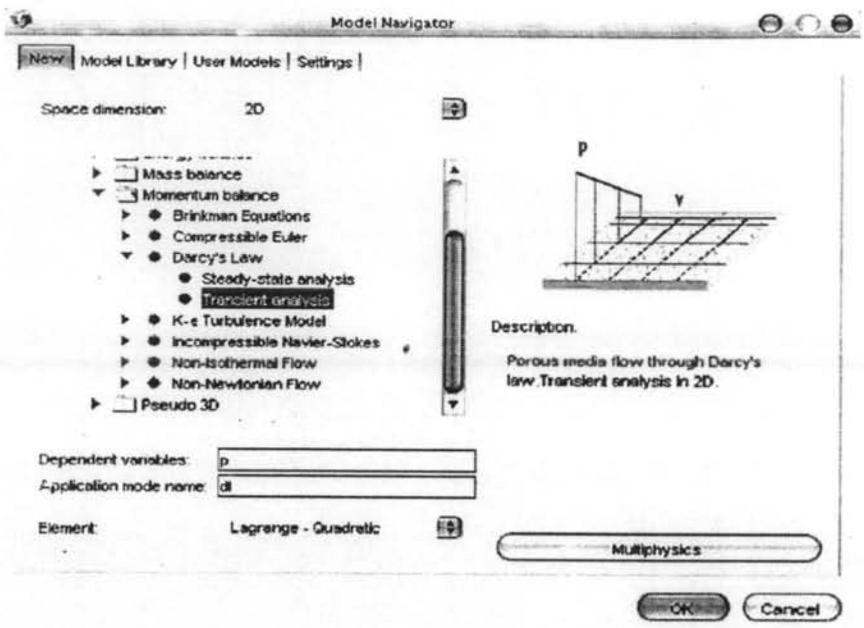

Figure F1 Model navigator interface.

2. Drawing reservoir shape and withdrawal well by using drawing tools (Figure F2).

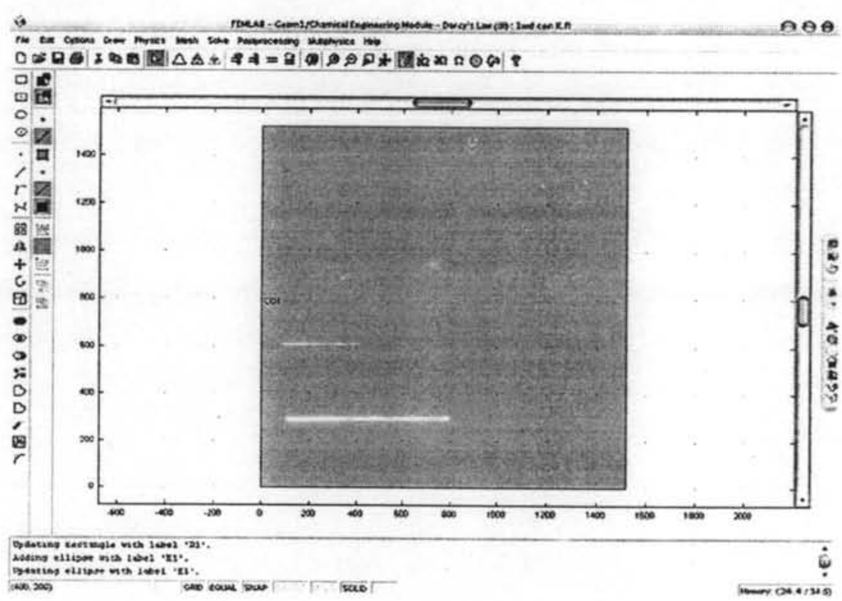

Figure F2 The graphical interface with the reservoir shape.

3. Setting Subdomain condition in the model (Figure F3) :
   - Subdomain 1 (reservoir)

$\rho \quad = p\varepsilon/T_{re}$

$K \quad = k/\varepsilon$

$\eta \quad = \eta$

$F \quad = 0$

$p(t_0) \quad = \exp(-1e9{*}x^2) + p_{re}$

   - Subdomain 2 (withdrawal well)

$\rho \quad = p\varepsilon/T_{re}$

$K \quad = 1e\text{-}12/\varepsilon$

$\eta \quad = \eta$

$F \quad = q_s p_{sc}/T_{sc}$

$p(t_0) \quad = \exp(-1e9{*}x^2) + p_{re}$

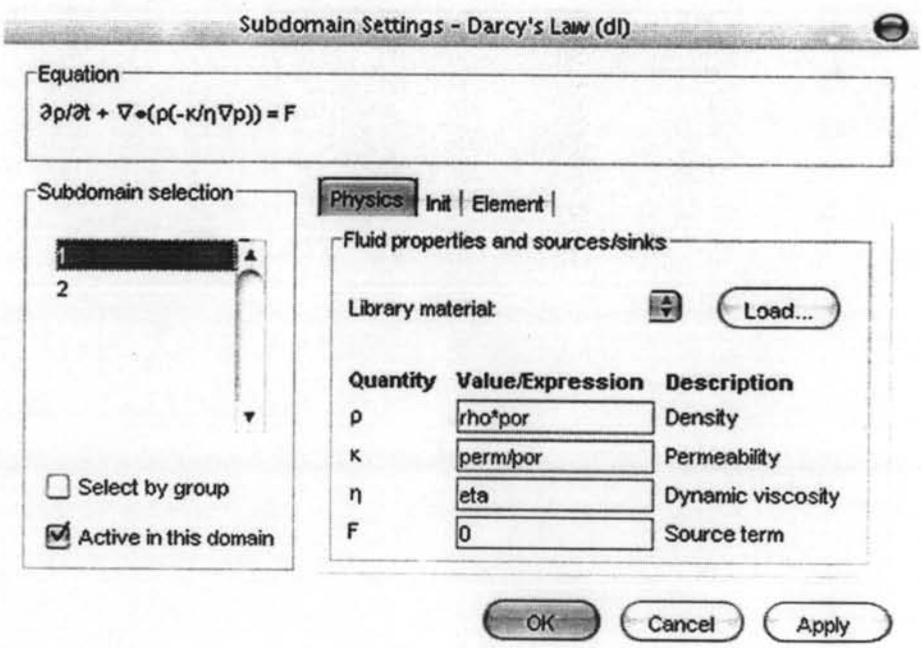

Figure F3 The subdomain-settings dialog box.

4. Setting boundary condition in the model (Figure F4, 5) : reservoir boundary (1-2-3-4) are insulation, $\mathbf{n} \bullet \mathbf{u} = 0$, $\mathbf{u} = -k/\eta(\nabla p)$.

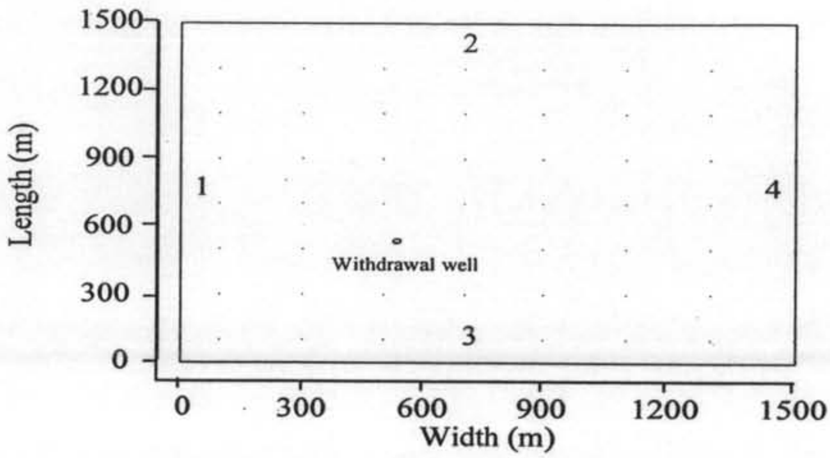

Figure F4 Boundary conditions in model.

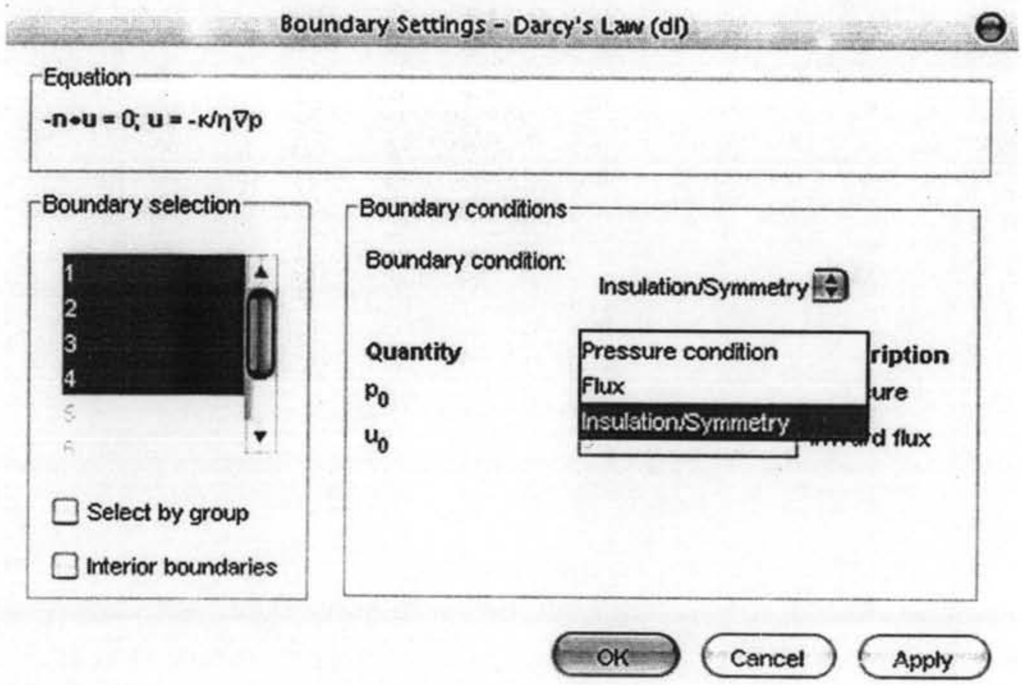

Figure F5 The boundary-settings dialog box.

5. Setting solver parameters (Figure F6) :

   Solver : Time Dependent

   Times : 0 : 86400 : 4.32e7

   Linear system solver : Direct (UMFPACK)

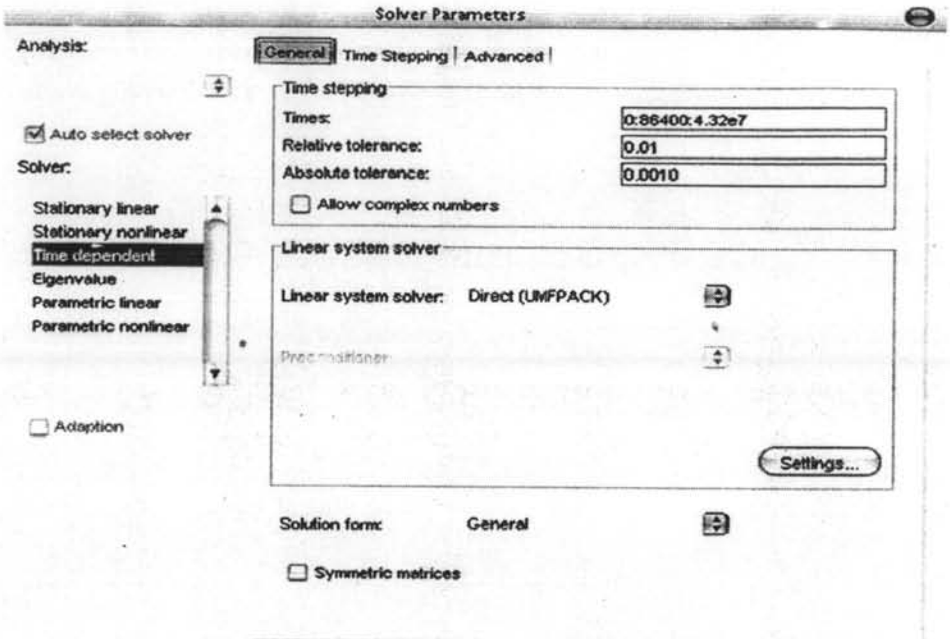

Figure F6 The solver parameters dialog box.

6. Generate the elements on the model until the mesh content reach 10000 elements (Figure F7).

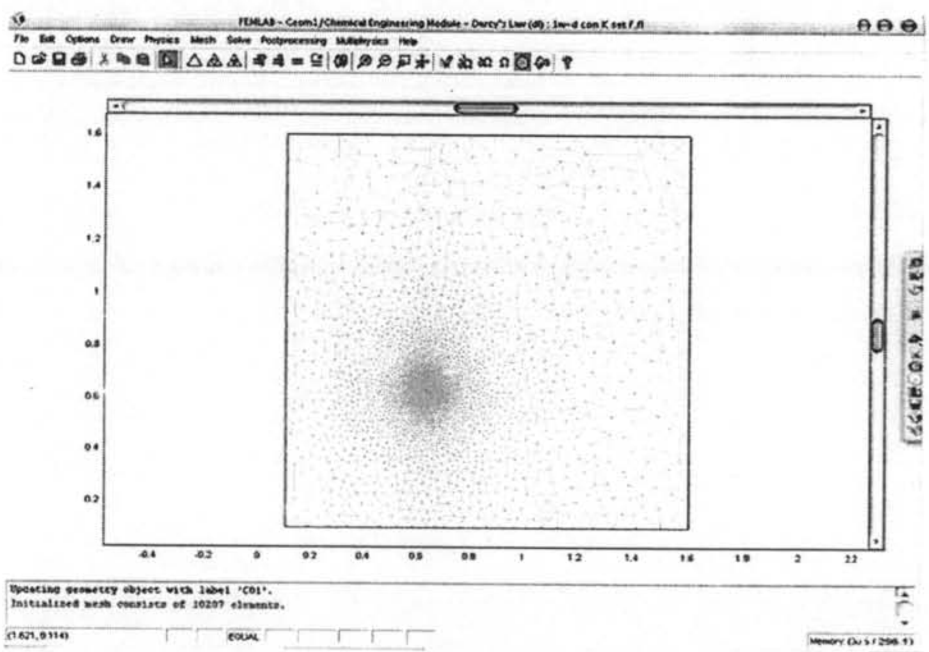

Figure F7 The finite-element grid.

CURRICULUM VITAE

Name: Mr. Chaiwat Assawaphomthada

Date of Birth: June 14, 1982

Nationality: Thai

University Education:

2000-2004 Bachelor Degree of Science, Faculty of Applied Science, King Mongkut's Institute of Technology North Bangkok, Bangkok, Thailand