Proc. 12th New Zealand Geothermal Workshop 1990

COMPUTER MODELLING OF A PRODUCTION/INJECTION DOUBLET SYSTEM

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ABSTRACT

Analytical methods for solving both one-dimensional and two-dimensional geothermal doublet problems are described in the paper. They can be used to calculate the travel time of tracer and heat from the injection well to the production well and the tracer concentration and temperature changes with time at the production well. The results are compared with two other methods: a fully numerical method (MULKOM) and a semi-analytical method (RESSQ).

1. INTRODUCTION

The term doublet applies to a system which includes two wells, the first for production and the second one for injection of the water after extraction of its heat. Fig. 1.1 shows a diagram of a typical doublet system. The first development of such a doublet scheme took place in 1969 at Melun, a town of 50,000 inhabitants 50 km south east of Paris (Coudert 1985).

There are two advantages of a doublet system:
(i) It maintains pressure in the geothermal field throughout the production period and thereby maintains the yield
(ii) It disposes of saline water which cannot be discharged into the surface environment.

More than 40 doublets have been drilled and are exploited in the Paris Basin. These are all of the low temperature (T<100°C) type. Generally. one geothermal doublet provides heat for 1000 to 5000 housing units (or their equivalent in hospitals, schools, swimming pools or greenhouses). A housing unit has a consumption of 1 to 1.5 tons of oil per year, or the equivalent in natural gas, coal or electricity (Coudert 1984).

Around the injection well of a doublet system a colder zone is mated which spreads gradually, and ultimately reaches the production well. The distance between the two wells must therefore be calculated beforehand so that the decrease in temperature does not affect the production well for a period at least as long as the pay back period of the installation (generally it is much longer). This period must be compatible with the accepted service life of a borehole.

In France. the interval of time for the cold injected water to first reach the production well is normally planned to be about 30 years. But it does not mean that when the cold zone arrives at the production well the operation must be closed down. In fact the geothermal doublet can continue to operate beyond this deadline as long as the production temperature remains high enough for the installation concerned and the state of the boreholes is satisfactory. The decrease in temperature is estimated in normal exploitation conditions as 2° C each five years.

Several doublet system are used for space heating in Klamath Falls, Oregon, USA. The hot water is pumped from the production well and then cooled in a surface heat exchanger. The wells in the doublet systems in Klamath Falls are all of similar depth and design and they are closely spaced (Sammel 1984 & Gudmundsson et al 1983).

About 20 doublet systems are operating in Rotorua, New Zealand. The flow of geothermal fluid used by these doublet system is estimated to be 1500 tonnes per day in the winter. Even though no detailed work has been done on these doublet systems they appear to work well and have very few problems. (Ministry of Energy 1985b)

The objective of this research project is an assessment of the characteristics and performance of doublet systems in the Rotorua geothermal field. This is considered to be one option which will enable a more efficient use of the resource as it is a zero mass removal system.

This research work has been divided into three stages. The first stage is a theoretical study which is aimed at finding better analytical and numerical methods for simulation of doublets. The second stage will be to carry out a tracer test in the Rotorua geothermal field. The third stage will be an analysis of the tracer test results and an assessment of doublet systems for the Rotorua geothermal field. The present paper discusses part of the first stage of the work.

From the information currently available, it appears that the geothermal reservoir underneath Rotorua city is a relatively thin confined aquifer (Donaldson and Grant 1981; Ministry of Energy 1985a). Therefore the doublet system considered for this analysis is assumed to be two-dimensional. One-dimensional and two-dimensional doublet simulations are described in the next two sections of this paper. The results labeled ID-MODEL and 2D-MODEL are obtained using analytical methods developed by the authors of this paper. Other results are obtained using the geothermal reservoir simulation package MULKOM (Pruess 1988) and the semi-analytical RESSQ programme (Javandel et al.1984).

For complex geothermal reservoirs which are not homogeneous or are not thin or where boiling occurs then analytic solution techniques will not work and MULKOM must be used. Therefore it is important to carry out numerical experiments and to compare the numerical results from MULKOM with analytic results for simple problems in order to determine what kind of block structures may be required for the more complex problems.

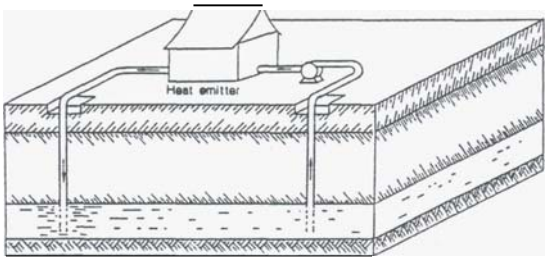

Fig. 1.1 Typical Geothermal Doublet System

2. ONE DIMENSIONAL DOUBLET MODELLING

A one dimensional doublet model (1D-Model), was investigated first in order to evaluate the MULKOM program on a very simple doublet system. An idealized one-dimensional isothermal reservoir is considered. The vertical cross-section of the reservoir is assumed to be a square with an edge of 100 m. The length of the reservoir is 1000 meters.

The reservoir is divided into 10 blocks with the production and injection wells located at each end of the reservoir. The reservoir flow consists of the steady movement of cold injected water along the reservoir. This movement of cold water gradually "sweeps" the heat out of the reservoir. For the analytical method, the density ρ and specific heat C (both for water and rock) are assumed to be constant. For small temperam changes, the energy equation can be written as (OSullivan and McKibbin, 1989)

$$[(1-n)\rho_r C_r + n\rho_l C_l]\frac{\partial T}{\partial t} + Q_m C_l \frac{\partial T}{\partial x} = K\frac{\partial^2 T}{\partial x^2} \qquad (2.1)$$

or

$$\frac{\partial T}{\partial t} + V\frac{\partial T}{\partial x} = D\frac{\partial^2 T}{\partial x^2} \qquad (2.2)$$

Here V is the velocity of movement of the thermal front and D is the effective thermal diffusion coefficient given by:

$$V = \frac{Q_m C_l}{[(1-n)\rho_r C_r + n\rho_l C_l]} \qquad (2.3)$$

and

$$D = \frac{K}{[(1-n)\rho_r C_r + n\rho_l C_l]} \qquad (2.4)$$

It is assumed that the reservoir is initially at a temperature To everywhere and the injected water has temperature T_1. These conditions are expressed mathematically as an initial condition

$$T(x,0) = T_0,$$

and a boundary condition

$$T(0,t) = \begin{cases} T_0 & t < 0 \\ T_1 & t > 0 \end{cases}$$

The equation (2.2) is known as the advection-diffusion equation. It governs processes where heat or chemicals are moved by movement of the medium and by diffusion.
If we put $\theta = T - T_0$ and $\theta_0 = T_1 - T_0$, equation (2.2) can be rewritten as

$$\frac{\partial \theta}{\partial t} + V\frac{\partial \theta}{\partial x} = D\frac{\partial^2 \theta}{\partial x^2}, \qquad (2.5)$$

with initial condition $\theta(x,0) = 0$,

and boundary condition $\theta(0,t) = \begin{cases} 0 & t < 0 \\ \theta_0 & t > 0 \end{cases}$

The boundary condition at the production well is approximated by a condtion at infinity. It is assumed that as x moves toward infinity, the temperature remains unchanged, ie

$$T_1 \to T_0 \text{ or } \theta \to 0 \text{ as } (x \to \infty)$$

In the reservoir considered here, the injection and the production well are located at x=0 and x=1000 meters respectively.

This problem can be solved using the Laplace transform technique. The transform of (2.5) is

$$s\bar{\theta} - \theta(x,0) + V\frac{d\bar{\theta}}{dx} = D\frac{d^2\bar{\theta}}{dx^2} \qquad (2.6)$$

This can be solved using the boundary condition at x=0 and the decay condition as $x \to \infty$:

$$\bar{\theta} = \frac{\theta_0}{s}\, e^{-\sqrt{s+\frac{v^2}{4D}}\,\frac{x}{\sqrt{D}}}\, e^{\frac{v}{2D}x} \qquad (2.7)$$

Inverting (2.7) gives the solution:

$$\theta = \frac{\theta_0}{2}\left\{ e^{\frac{xv}{D}}\,\mathrm{erfc}\left(\frac{x+vt}{2\sqrt{Dt}}\right) + \mathrm{erfc}\left(\frac{x-vt}{2\sqrt{Dt}}\right)\right\} \qquad (2.8)$$

or

$$T = T_0 + \frac{T_1 - T_0}{2}\left[e^{\frac{xv}{D}}\,\mathrm{erfc}\left(\frac{x+vt}{2\sqrt{Dt}}\right) + \mathrm{erfc}\left(\frac{x-vt}{2\sqrt{Dt}}\right)\right] \qquad (2.9)$$

Normally D is very small and (2.9) can be approximated by:

For $x > vt$

$$T = T_0 + (T_1 - T_0)\sqrt{\frac{Dt}{\pi}}\, e^{-\left(\frac{x-vt}{2\sqrt{Dt}}\right)^2}\frac{2x}{x^2 - v^2t^2} \qquad (2.10)$$

For $x < vt$

$$T = T_0 + (T_1 - T_0)\left[\sqrt{\frac{Dt}{\pi}}\, e^{-\left(\frac{x-vt}{2\sqrt{Dt}}\right)^2}\left(\frac{2x}{x^2 - v^2t^2}\right) + 1\right] \qquad (2.11)$$

Equation (2.10) and (2.11) are used in the 1D-MODEL programme to calculate the temperature profile in the x direction.

The assumed values of parameters for both the MULKOM and 1D-MODEL input data are listed in Table 2.1.

Table 2.1 One-dimensional modelling input data

reservoir temperature	T_0=100°C
injection temperature	T_1=20°C
injection/production mass flow rate	Q_m=30.0 kg/s
porosity	n=0.15
density of rock	ρ_r=2670 kg/m^3
specific heat of rock	C_r=900 J/kg K
rock heat conductivity	K=2.5 W/K

The calculated velocity of the thermal front V is 4.7 16E-06meter per second, and the thermal diffusion coefficient D is 8.355E-07 square meter per second.

Fig. 2.1 shows 1D-MODEL output at different times. For comparison, the reservoir is divided into 10, 20 and 50 blocks and the thennal front is calculated using the MULKOM package. The MULKOM results are shown in Fig. 2.2, 2.3 and 2.4. It is obvious that artificial numerical dispersion is present in the MULKOM results. This numerical dispersion is not unique to MULKOM. All common numerical techniques, especially those using upstream differencing, have the same problem. The exact solution obtained using the analytical method (1D-MODEL) shows the expected sharp thennal front. Fig. 2.2, 2.3 and 2.4 demonstrate that the numerical dispersion gets smaller when the reservoir is divided into more blocks.

3. TWO DIMENSIONAL DOUBLET MODELLING

Da Casta and Bennett (1960) mathematically modelled the underground flow of cold water between two wells. Their analysis considered the relation between porosity, recharge-dischargerate, regional flow, and magnitude of the velocity of regional flow. Grove et al (1970) expanded on the studies of Da Casta and Bennett and calculated actual travel time for water moving from one well to the other well along various streamlines. These results were presented in the form of dimensionless groups for various angles of regional flow. Their solution of the fluid particle travel time between a well doublet is numerical.

A semi-analytical method is described by Javandel I. et al (1984) in which the travel time for a doublet system in a uniform reservoir can be calculated.

Mercer et al (1982) presents an analytical solution for a recharge - discharge pair (well doublet).The analysis, which is based on the work of Davis and Dewiest (1966), only gives the solution for the rise or fall of water level in the wells .

In later work Javandel and Tsang (1986); Shafer (1987) simultaneously calculated approximate streamline positions and approximate travel times. Analytical and numerical calculation of the travel time for tracer movement along streamlines, including a high permeability fracture or a barrier fracture, is described by Bullivant (1988).

In this section, the travel time integral along the streamline for a doublet system is derived analytically. It can be used to calculate the travel time of tracer or heat from the injection well to the production well and changes in the tracer concentration or temperature with time at the production well. The assumptions used in the study of doublets in a two-dimensional reservoir are listed below:

(i) The aquifer is a homogeneous, isotopic and constant thickness;
(ii) The top and bottom of the reservoir are confined;
(iii) The porosity is constant and permeability are constant ;
(iv) Regional flow is negligible.

In most studies of doublets two-dimensional steady incompressible flow is assumed and it can be described by a complex potential

$$W(x+iy) = \phi(x,y) + i\psi(x,y) \qquad (3.1)$$

Where ϕ is the velocity potential and ψ is the stream function. Javandel et al(1984) and Bullivant (1988) both use this formulation. Javandel et al follow the streamlines approximately by calculating the velocity at a point and moving in that direction for a time step. Bullivant uses an inversion technique to exactly follow the streamlines. In the present work Bullivant's technique is followed.

Curves of velocity potentials ϕ = constant, and streamlines ψ = constant (shown in Fig. 3.1) intersect each other at right angles.

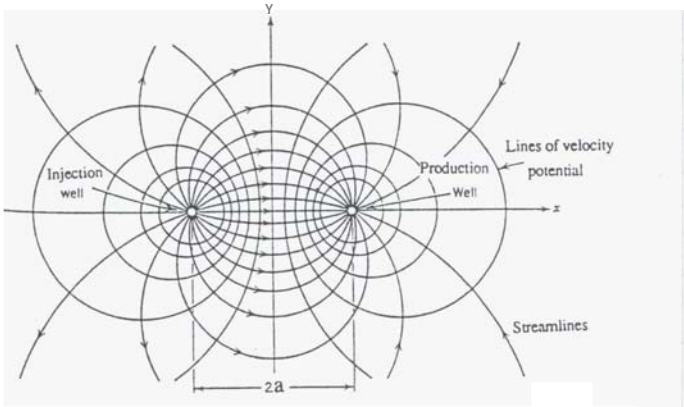

Fig 3.1 Streamlines and velocity potential lines for a balanced doublet (modified from Davis and DeWiest,1966)

The components of the fluid particle velocity, u_x(x direction) and u_y(y direction), are given by

$$u_x = \frac{\partial \phi}{\partial x} = \frac{\partial \psi}{\partial y} \qquad (3.2)$$

$$u_y = \frac{\partial \phi}{\partial y} = -\frac{\partial \psi}{\partial x} \qquad (3.3)$$

So that the fluid volume flux is given by

$$q = nu = n \nabla \phi \qquad (3.4)$$

Since the flow is incompressible, Vq =0, and it follows that both ϕ and ψ are harmonic functions, ie they satisfy Laplace's equation

$$\nabla^2\phi = \nabla^2\psi = 0 \qquad (3.5)$$

The dispersion of tracer (or heat) along the sueamline has been approximated by a number of models. Javandel et al (1984) described how to incorporate a retardation factor which models the effect of water trapped in the rock matrix, assuming instantaneous concentration equilibrium between the stagnant and moving fluid. Gringarten and Sauty (1975) included diffusion of heat into the rock matrix. Abbaszadeh-Dehghani and Brigham (1984) allowed for velocity dependent diffusion along the streamline. All these mechanisms for dispersion have been detailed in chapter 2 of Bullivant (1988). The tracer particles move exactly with the fluid particles and the tracer mass flux is Cq, where C is mass fraction of tracer in unit fluid volume.

Conservation of mass of tracer gives rise to the advection equation

$$n\frac{\partial C}{\partial t} + V.(Cq) = 0 \qquad (3.6)$$

Using (3.4) and (3.5), then (3.6) becomes

$$\frac{\partial C}{\partial t} + VC.\nabla\phi = 0 \qquad (3.7)$$

and transforming equation (3.7) using ϕ and ψ as independent variables gives

$$\frac{\partial C}{\partial t} + |\nabla\phi|^2\frac{\partial C}{\partial \phi} = 0 \qquad (3.8)$$

If conduction is neglected similarly equation (2.2) becomes

$$\frac{\partial T}{\partial t} + \alpha\,|\nabla\phi|^2\frac{\partial T}{\partial \phi} = 0 \qquad (3.9)$$

where T is temperature and

$$\alpha = \frac{n\,\rho_f C_f}{(1-n)\rho_r C_r + n\rho_f C_f} \qquad (3.10)$$

Bachmat and Bear (1964) have expressed the advection dispersion equation in (ϕ,ψ) coordinates and equation (3.9) is a special case of their expression.

The rate of change of $C(\phi,t)$ along a characteristic curve defined by $t = t(s), \phi = \phi(s)$ is

$$\frac{dC}{ds} = \frac{\partial C}{\partial \phi}\frac{d\phi}{ds} + \frac{\partial C}{\partial t}\frac{dt}{ds} \qquad (3.11)$$

Comparing (3.1 1) and (3.8) we can write

$$\frac{dC}{ds} = 0 \qquad (3.12)$$

On the curves defined by

$$\frac{dt}{ds} = 1 \text{ and } \frac{d\phi}{ds} = |\nabla\phi|^2$$

These equation can be combined to give

$$\frac{d\phi}{dt} = |\nabla\phi|^2$$

This equation can be integrated to calculate travel times

$$t = \int_{-\infty}^{\phi} \frac{1}{|\nabla\phi|^2}\,d\phi \qquad (3.13)$$

The dimensionless time t taken for the tracer to travel all the way from the injection to the production well is calculated by integrating from $-\infty$ to ∞.

Equation (3.13) becomes

$$t = \int_{-\infty}^{\infty} \frac{1}{|\nabla\phi|^2}\,d\phi \qquad (3.14)$$

Similarly for heat (3.14) can be rewritten

$$t = f\int_{-\infty}^{\infty} \frac{1}{|\nabla\phi|^2}\,d\phi \qquad (3.15)$$

$$f = \begin{cases} 1 & \text{for tracer} \\ \frac{1}{c} & \text{for heat} \end{cases}$$

For doublet flow, the geometry of the velocity potential and stream function at a certain point with a radius vector r and angle θ .and the position of injection - production well doublet is shown in Fig. (3.2)

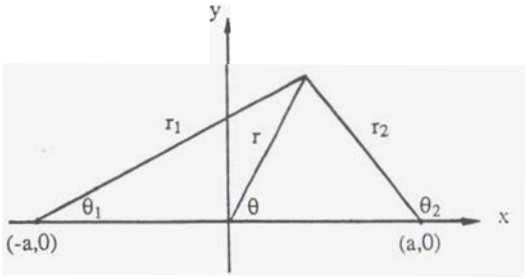

Fig 3.2 Position of injection - production doublet with respect of a typical point with a radius vector and angle

The potential and stream function for doublet flow are given by

$$\phi = \ln r_1 - \ln r_2 = \frac{1}{2}\ln[(x+a)^2+y^2] - \frac{1}{2}\ln[(x-a)^2+y^2] \qquad (3.16)$$

$$\psi = \theta_1 - \theta_2 = \tan^{-1}\left(\frac{y}{x+a}\right) - \tan^{-1}\left(\frac{y}{x-a}\right) \qquad (3.17)$$

From (3.16)

$$|\nabla\phi|^2 = \left(\frac{\partial\phi}{\partial x}\right)^2 + \left(\frac{\partial\psi}{\partial y}\right)^2 = \frac{4a^2}{[(x+a)^2+y^2]\,[(x-a)^2+y^2]} \qquad (3.18)$$

Introducing the complex potential, (3.1) becomes

$$\phi + i\psi = W(x+iy) = \ln[(x+a)+iy] - \ln[(x-a)+iy] \qquad (3.19)$$

or

$$e^{\phi+i\psi} = e^{\phi}[\cos\psi+i\sin\psi] = \frac{x+a+iy}{x-a+iy} \qquad (3.20)$$

Rearranging (3.20) gives:

$$x = \frac{e^{2\phi}-1}{e^{2\phi}-2e^{\phi}\cos\psi+1} \qquad (3.21)$$

$$y = \frac{-2e^{\phi}\sin\psi}{e^{2\phi}-2e^{\phi}\cos\psi+1} \qquad (3.22)$$

Then (3.21). (3.22) can be used to rewrite (3.15) in terms of ϕ,ψ. First:

$$|\nabla\phi|^2 = \frac{e^{-2\phi}}{4a^2}(e^{2\phi}-2e^{\phi}\cos\psi+1)^2 \qquad (3.23)$$

Then substituting (3.23) into (3.15) and integrating gives:

$$t = \frac{2f}{\sin^2\psi}\left\{\frac{e^{\phi}\cos\psi-1}{e^{2\phi}-2e^{\phi}\cos\psi+1} + 1 + \cot\psi\left[\tan^{-1}\left(\frac{e^{\phi}}{\sin\psi}\right) - \cot\psi\right]\cot\psi\left(\psi-\frac{\pi}{2}\right)\right\} \qquad (3.24)$$

For the travel time t to the production well, the velocity potential ϕ will go to infinity, Equation (3.24) becomes

$$t_{\phi\to\infty} = \frac{2a^2f}{\sin^2\psi^*}[1+(\pi-\psi^*)\cot\psi^*] \qquad (3.25)$$

Here ψ^* indicates the stream function value for the streamline along which either tracer ($f=1$) or heat ($f=1/\alpha$) has just arrived at the production well at time t.

The tracer concentration and the temperature at the production well depends on their arrival time along various streamlines from the injection well. However, the tracer velocity is the same as the fluid particle velocity which is much faster then the velocity of heat movement. So the tracer arrival occurs much earlier than the arrival of cold water. The amval of cold water and tracer can be approximately illustrated as in Fig 3.3

Here ψ^*_C and ψ^*_T are the solution of (3.25) for

$f = 1$ and $f = \frac{1}{a}$ respectively.

For temperature at the production well,

$$T(t) = T_0 + \frac{\Delta T}{\pi}[\pi - \psi^*_T(t)]$$

where ψ^*_T is the stream function satisfying $(0 < \psi^*_T < \pi)$

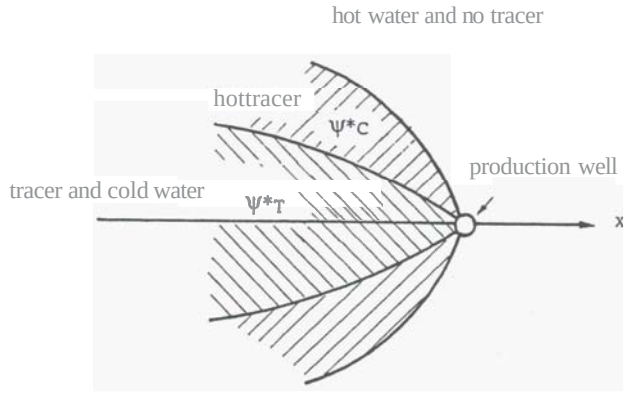

Fig 3.3 Illustration of the difference between pacer and heat arrival at the production well

Similarly for tracer concentration

$$C(t) = C_0 + \frac{\Delta C}{\pi}[\pi - \psi^*_C(t)]$$

All the equations above are dimensionless. For comparison of the 2D-MODEL developed and described in this paper with the MULKOM package and the semi-analytical RESSQ results, the real units have to be used. Dimensional quantities $\Phi, \Psi, X, Y, U, V, \tau$ arc defined in terms of dimensionless quantities ϕ,ψ,x,y,u,v,t as follows:

$$\Phi = \phi\frac{Q}{2\pi bn}$$

$$\Psi = \psi\frac{Q}{2\pi bn}$$

$$X = ax$$

$$Y = ay$$

$$U = u\frac{Q}{2\pi bna}$$

$$V = v\frac{Q}{2\pi bna}$$

$$\tau = t\frac{2\pi bna^2}{Q}$$

4. RESULTS OF 2D-MODELS

In order to calculate the shape of the cold injected water at any time (3.21) is used. For a particular value of t, (3.21) is solved for ϕ for a number of different ψ values. To calculate the temperature or tracer response at the production well (3.25) is used. For a particular time (3.25) is solved for ψ^*_C and ψ^*_T, for f=1 (for tracer) or f=(1/α) (for heat) respectively.

Table 3.1 below shows the model parameters. These parameters are used as input data for the comparison of the MULKOM, RESSQ and 2D-MODEL programs.

The RESSQ programme (Javandel et al, 1984) was developed at the Lawrence Berkeley Laboratory University of California, USA, based on a solution procedure used by Gringarten and Sauty (1975). The computer programme RESSQ can be applied to two-dimensional

Table 3.1 Example model parameters	
Reservoir temperature	$T_0 = 100\ ^{\circ}C$
Injection temperature	$T_1 = 20^{\circ}C$
Injection / production flow rate	$Q_m = 50.0\ m^3/h$
Tracer concentration of injected	$C_1 = 100\ \%$
Tracer concentration of reservoir	$C_0 = 0.0\ \%$
Thickness of the aquifer	b = 10.0 m
Length of the aquifer	L = 10.0 km
Width of the aquifer	W = 8.0 km
Porosity of the aquifer	n = 25.0 %
Density of reservoir rock	$\rho_r = 2670\ kg/m^3$
Specific heat of rock	$C_r = 900\ J/kg.K$
Conductivity of rock	K=O

contaminant transport by advection (no dispersion or diffusion) in a homogeneous, isotopic confined aquifer of uniform thickness when regional flow, sources and sinks create a steady state flow field. It calculates the streamline pattern in the aquifer, the location of contaminant fronts around sources at various times, and the variation of contaminant concentration with time at sinks.

The MULKOM package was also developed by the same group at the Lawrence Berkeley Laboratory. It is a fully numerical programme.

Tracer concentration versus time at the production well are shown in Fig 3.4. It indicates that the semi-analytical RESSQ program output gives a good match to the 2D-MODEL, but it is not quite as smooth as the 2D-MODEL. However, the fully numerical MULKOM output shows about 10% difference compared to these two programs as a result of the numerical dispersion;

Fig 3.5 shows a plot of temperature with time at the production well. The percentage of temperature difference between MULKOM and 2D-MODEL is of the same order as shown in Fig. 3.4 for the tracer concentration.

5. COMMENTS

The 2D-MODEL program gives the expected good results. However there are some limitations:
(i) it may not produce good results if the reservoir area is a finite one bounded by impermeable strata because the analytical method assumes an infinite region;
(ii) it cannot simulate a reservoir with more than two wells and / or with regional flow.
The program will be extended to allow for a regional flow across the doublet system.

The semi-analytical method (RESSQ) does not consider heat movement in the reservoir. Therefore it cannot be used to calculate the production well temperature change for a doublet. However, the RESSQ programme is a valuable tool for comparison with other programs which calculate tracer concentration in the production well.

In many respects. the MULKOM package is much more powerful than the RESSQ and the 2D-MODEL programme. It can be used to simulate a three-dimensional, multi-layer, reservoir with many production and injection wells. A deficiency is that it does not produce highly accurate results, because of numerical dispersion, for problems like doublet flow where there is movement of sharp fronts. The one-dimensional doublet modelling discussed in section 2 indicated that the numerical dispersion gets smaller when the reservoir is divided into more blocks. This should also be applicable to the two-dimensional doublet simulation. Further two-dimensional doublet modelling using MULKOM investigating the effect of block size and layout will be carried out.

NOTATION

a	half distance between production and injection wells, m
b	reservoir thickness, m
C	dimensionless concentration
C	specific heat, kJ/kg K
D	diffusion coefficient, m^2s^{-1}
f	conversion factor
H	step function
K	rock thermal conductivity, W/m K
L	length, m
n	Porosity
q	fluid volume flux, ms^{-1}
Q	volume flow rate m^3s^{-1}
r	radial coordinate
t	dimensionless time or time, s
T	temperature, ^0C
u	fluid velocity ms^{-1}
v	speed of thermal / tracer front, ms^{-1}
W	complex potential m^2s^{-1}
w	width, m
x	cartesian coordinate m
y	cartesian coordinate m
ϕ	dimensionless velocity potential
Φ	velocity potential, m^2s^{-1}
θ	radial coordinate angle
e	density, $kg\ m^3$
ψ	dimensionless stream function
Ψ	stream function, m^2s^{-1}
τ	times

Subscripts

1	injected fluid condition
0	original reservoir condition
l	fluid
r	rock
x	x coordinate direction
y	y coordinate direction
c	tracer concentration
T	temperature

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FIG. 2.1 THERMAL FRONT CALCULATION USING 1D-MODEL (20 BLOCKS)

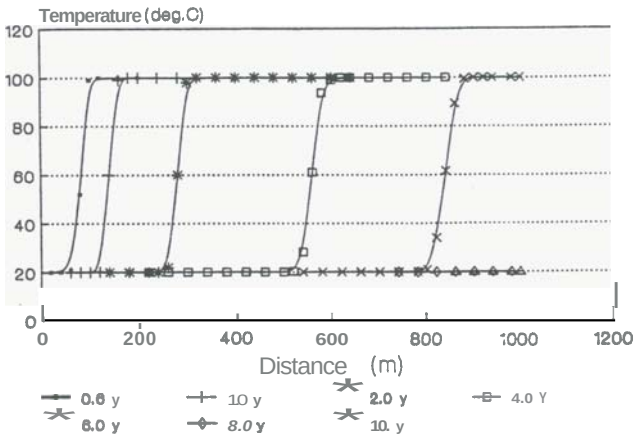

FIG 2.2 THERMAL FRONT CALCULATION USING MULKOM (10 BLOCKS)

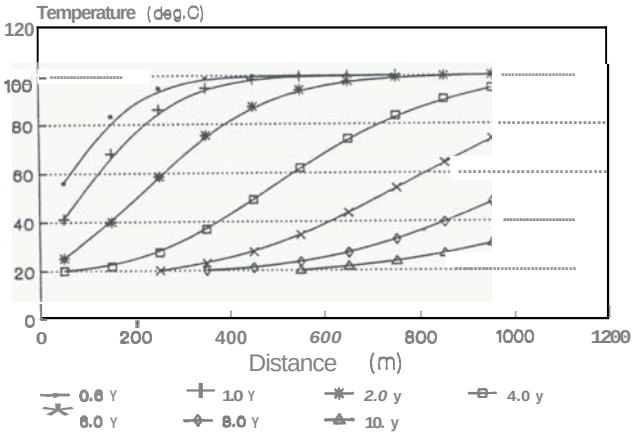

FIG. 2.3 THERMAL FRONT CALCULATION USING MULKOM (20 BLOCKS)

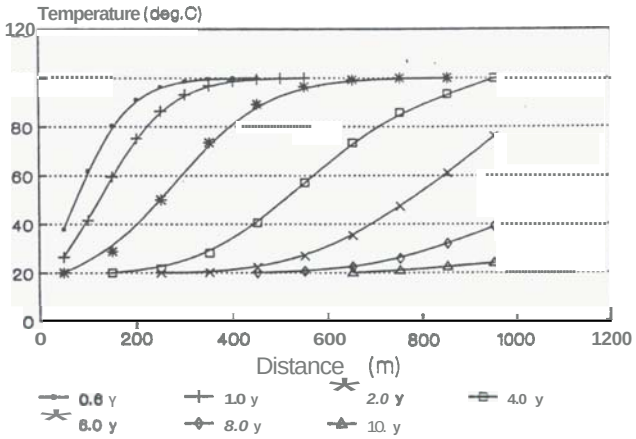

FIG. 2.4 THERMAL FRONT CALCULATION USING MULKOM (60 BLOCKS)

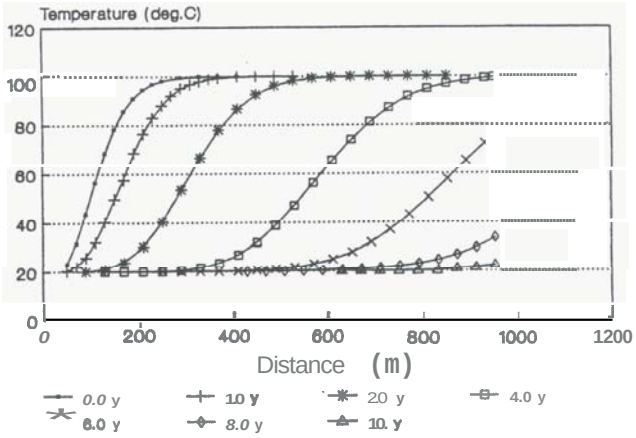

FIG.3.4 TRACER CONCENTRATION AT THE PRODUCTION WELL

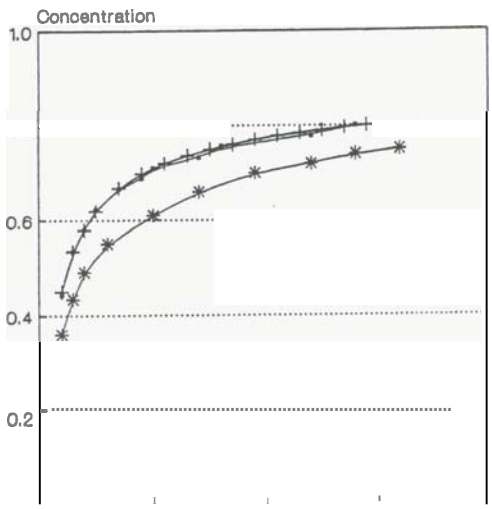

FIG. 3.6 TEMPERATURE WITH TIME AT THE PRODUCTION WELL