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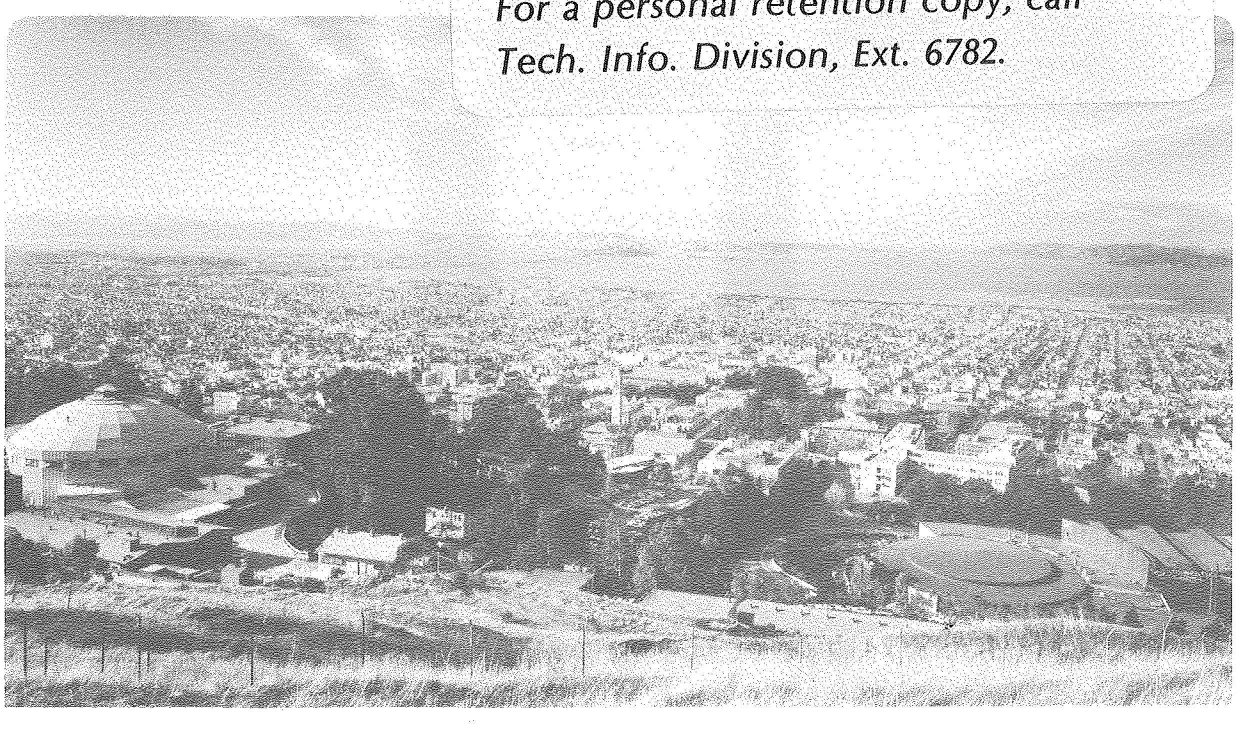

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ABSTRACT

Recent interest in geothermal energy development has contributed to the advance in the modeling of non-isothermal flows, especially of the two-phase, steam-water phenomena. In this paper, the key processes associated with a geothermal energy reservoir are described and the current approaches are pointed out. The state-of-the-art of geothermal modeling is reviewed by comparing the governing equations, numerical methods, code availability, validations and applications of several selected major existing models. The needs for further studies are discussed.

NOMENCLATURE

a	upstream weighting factor for convective terms
H	enthalpy, m^2/sec^2
k	permeability, m^2
k_r	relative permeability
k_{rr}	k_r at the residual saturation
n	exponent in k_r function
P	pressure, $kg/m/sec^2$
S	saturation
$\bar{S}$	normalized saturation
T	temperature, ^oC
U	internal energy, m^2/sec^2
λ	time differencing implicit factor
ρ	density, kg/m^3
σ	stress, $kg/m/sec^2$
ϕ	porosity

SUPERSCRIPTS

f	fractures
m	rock medium

INTRODUCTION

Geothermal reservoirs are sometimes classified into two categories on the basis of their fluid composition. The first categories are those that primarily produce steam. Examples are the Geysers in California, Larderello in Italy and Matsukawa in Japan. Though these reservoirs have been used to produce steam and generate electricity for many years, their occurrence is relatively rare. The majority of geothermal reservoirs are in the second category which are reservoirs whose fluid is predominately water in the liquid phase. These hot water reservoirs are found at New Zealand, Mexico, Iceland, El Salvador and other locations worldwide. A few of these reservoirs have been exploited for power production and several for space heating or industrial processing. Recently the U.S. Department of Energy began a demonstration experiment in cooperation with industry at the Baca site in New Mexico and a second DOE demonstration experiment was also under negotiation for the Heber, California reservoir. Both these systems are considered to be liquid-dominated reservoirs. In many cases, as a hot water reservoir is being produced and fluid pressure is reduced, the reservoir will turn two-phase. For example, this is believed to be already happening in Wairakei, New Zealand.

With such interest and activities in the geothermal energy development over the years, analytic and numerical models to simulate the system are quite well advanced. Much work has been done in this area and many models were developed. Recent review papers include Wang, Sterbentz and Tsang (1980), Pinder (1979), and Sudol, Harrison and Ramey (1979). The latter two are results of work performed under the DOE Geothermal Reservoir Engineering and Subsidence Research Management Programs managed by the Lawrence Berkeley Laboratory. However, there still remain key areas that require further understanding and study.

In the next section the major processes in geothermal reservoir engineering will be briefly explained and some open questions pointed out. Then in the following section a few models will be selected for a comparative review. Emphasis will be on two-phase models which can, of course, also handle single (water) phase as a special case. After this review, key problems requiring further investigation will be listed. A summary will conclude the paper.

KEY PROCESSES

The key processes involved in geothermal reservoir engineering include fluid and energy flows. Subsidence effects associated with reservoir fluid depletion may also be important in some cases. Chemical reactions, rock-water interaction and chemical transport and dispersion will be of significance, especially in cases where reinjection is or will be carried out. The couplings among the key processes are shown schematically in Figure 1.

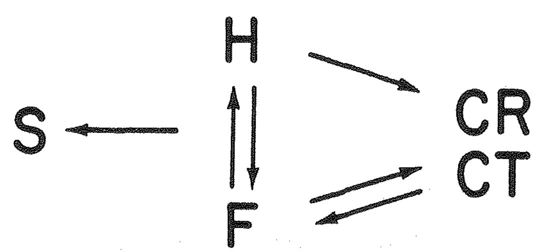

Fig. 1 Couplings among the fluid flow (F), heat flow (H), subsidence (S), chemical reactions (CR) and chemical transport and dispersion (CT).

Fluid Flow

In geothermal reservoir engineering, Darcy's law is usually assumed, implying a laminar flow. This is reasonable for fluid flow in porous medium and in tight fractures. The assumption will not hold for many well-bore fluid-flow problems. With the presence of heat, many parameters associated with fluid flow will be affected. The viscosity parameter is strongly temperature dependent, varying by a factor of 3 over a 200°C temperature difference for the liquid phase, while the density varies by approximately 20%. These parameters will vary even more drastically when two-phase condition sets in. Thus, much of the reservoir behavior will be outside of isothermal hydrology or petroleum engineering experience. The dependence of permeability of a rock sample on temperature has been observed in the laboratory. However, its significance in large scale field condition is not clearly understood, and in nearly all the geothermal models this effect has not been taken into account. Under two-phase conditions, the fluxes of steam and liquid are reduced from the corresponding single-phase fluxes. In most studies, these flux reductions are modeled by using the relative permeability functions.

Energy Flow

The heat flow is mainly by conduction and convection. Except for numerical problems, these are well understood in the single phase case. For two phase problems considerable work has also been done. The pressure work and the viscous dissipation have been shown to be negligible in most cases. However much care has to be exercised in the modeling of boiling and natural convection, expecially in the sensitivity of these phenomena on mesh choice (unphysical) and on local geological inhomogeneity (physical). The geological inhomogeneity also induces thermal dispersion. This has been noticed in some experiments, but has not been properly understood and modeled. Another area requiring further studies is the problem of fluid and heat flow in fractured rock masses. Though several authors have addressed the problem of isothermal fracture flow, a basic formulation of two-phase 2- or 3-dimensional fracture-porous flow is still lacking.

Subsidence

With depletion of reservoir fluid, the pressure in the reservoir will decrease and the formation may deform under the overburden pressure. Land subsidence may thus occur. This was observed in hydrology and petroleum production cases, and also at Wairakei geothermal field. Much less work has been done in the modeling of this phenomenon. One liquid phase model CCC assumes one dimensional reservoir compaction based on the Terzaghi theory coupled with a deformable overburden model. It has been applied to simulate subsidence of systems similar to that at Wairakei. We are not aware of any two-phase models that calculate deformation simultaneously. Together with the lack of modeling there is also a lack of understanding of the associated basic parameters such as the elasticity-plasticity property and the effective stress formulation.

Chemical Transport and Dispersion

A number of models have included simple solute transport and dispersion. The usual assumptions include the solute moving with the fluid, and dispersive effects represented by a simple dispersive coefficient that is a linear function of velocity. Source and sink terms are also included in the models. The modeling of gases (CO_2, H_2S, methane, etc.) in two-phase flow is of great interest in the development of geothermal and geopressured reservoirs from both environmental and energy extraction considerations.

Chemical Reactions and Rock-water Interactions

Scaling and corrosion are major problems in the development and use of geothermal energy. Many experiments were made to study the chemical reactions of geothermal fluid with the well casing, fluid pipelines, and power generation systems. Empirical understanding and remedial procedures have been developed, but it may be difficult to model these phenomena in detail as a function of temperature, pressure, and time. Rock-water interaction may be important when cooled water or water with a chemical composition different from the native water is injected. Much work has been done in modeling chemical reactions. However, the modeling of coupled fluid flow and chemical reactions is still in a primitive state.

COMPARATIVE REVIEW OF MODELS

As discussed in the previous section, most of the models have been developed for fluid and energy flows. Some have included solute transport and dispersion. In this section we shall select a few key models for a comparative review to illustrate the present state-of-the-art. This selection is not intended to be complete, but represents the models we have some familiarity with. Analytic and zero-dimensional lumped models are not considered here.

Table 1 lists the models reviewed. The emphasis is on two-phase models, including those of Coats, Faust and Mercer, Pritchett and Garg, Pruess, Thomas and Pierson, Voss and Pinder, and Toronyi and Ali. There are many more single-phase models, but we have chosen only one for illustration. This is the model developed by Lippmann, and is one of the most well-validated and well-used single-phase non-isothermal models currently available. For fractured systems, the modeling of heat and fluid flow is still in an unsatisfactory state. One approach is the double porosity model, in which two porosities simultaneously exist and interact with each other, one corresponding to the porous medium porosity, and the other to the fracture porosity. For this approach we have selected the one developed initially by O'Neill.

The main features of these selected models are summarized in Table 1, which indicates that many of these are three-dimensional models; and numerical approaches used include finite-difference (FD), finite-element (FE) and integrated-finite-difference (IFD) methods. Some characteristics of the governing equations of these models are compared with each other in Table 2. The thermodynamic variables employed are either pressure-temperature, pressure-enthalpy or density-internal energy. Toronyi and Ali's model assumes as its variables pressure and vapour-saturation, and is thus limited to the study of two-phase systems. Most of the two-phase models have similar approaches in the formulation of the governing equations, and they all assume the same relative permeability functions---the Corey's formula. The relative permeability function of steam-water flow in porous medium has not been well established. Most of the recent measurements were carried out at Stanford, and more work is needed not only in the measurement but also to understand the physics of the phenomenon and its proper inclusion into a numerical model.

Table 3 compares the numerical methods used in the models. A major numerical problem encountered is the very non-linear coefficients in the governing equations, especially in cases of phase transition. Most of the models use the Newton-Raphson method to overcome this problem. Table 4 summarizes the status of the computer codes and some key references.

A good model that can be used with some confidence requires proper validations against field data. Unfortunately not too many long term case histories in geothermal energy development are available. In the United States, the major case history should be that of The Geysers geothermal reservoir. However, it is not in the public domain. So far the best available data are those from Wairakei field in New Zealand. Data from Cerro Prieto, Mexico, and the Italian geothermal fields are also being compiled and organized and will be of considerable use in the validation of numerical models. Table 5 summarizes the field validation and applications of the major model selected. Obviously more validations are needed and further generic studies will be useful.

NEEDS FOR FURTHER STUDIES

As remarked earlier, one of the major needs for further work is the validation of currently available models. Not only should they be validated against special cases where analytic solutions are available, but they should also be validated against field data. Another validation that should be done is to verify the models against each other. Currently the Department of Energy (SAN office) has published a Request for Proposal (DOE, 1980) in which six problems are formulated and suggested for proposers to solve with their numerical models. The DOE hopes to make 6-12 awards for this work. Thus 6-12 models could be compared for consistency among each other. No development work is expected under the guidelines of this request for proposals.

However, development and study are necessary for the further understanding and better simulation of geothermal reservoirs. This may be listed below under two categories: (a) conceptual model and physical formulation, and (b) constitutive equation and numerical solution:

Problems in Conceptual Models and Physical Formulation

(1) The conceptual models for most currently studied geothermal fields are generally well constructed. However, in many cases the fluid recharge and heat source are not well known. In general, boundary conditions are hard to determine. Sensitivity studies will be needed.

(2) Many geothermal reservoirs such as The Geysers and the Baca field are fracture systems. However, basic formulation of heat and fluid flow in two or three-dimensional fracture systems are still lacking. The fracture-porous relationships are not clear. Currently two approaches may be taken. The first considers discrete fractures and models the system in detail. This is only possible for systems involving only a few major fractures. Otherwise the computational time will be formidable. Furthermore, it is probably impossible to obtain such detailed fracture mapping in the field. A second approach is to "smear out" all the fractures into a secondary porosity in addition to the porous medium porosity. This double porosity model has been formulated and constructed. However, such averaging may not be valid, especially near any point of observation which is strongly affected by nearby discrete fractures. A hybrid of the two may be the proper approach.

(3) Tracer dispersivity has been much studied. However, thermal dispersion requires further study. The effect of molecular dispersion or fluid-path tortuousity dispersion is probably unimportant. The major part would probably be due to geological inhomogeneity. A proper formulation has to be made and one should question the validity of the simple linear-velocity dependence of the dispersivity coefficient.

(4) The dependence of permeability on temperature also needs to be studied and understood.

Table 1. Summary of Some of the Models

Model	Current Development	Main Characteristics
CCC	M. Lippmann, LBL	flow-heat-consolidation. 3D, IFD, geothermal, aquifer storage, waste isolation.
O'Neill	K. O'Neill, CRRE A. Shapiro, Princeton	flow-heat, double-porosity, 3D, FE, geothermal.
Coats	K. Coats, Intercomp	flow-heat, two-phase, 3D, FD, geothermal, petroleum
Faust-Mercer	C. Faust, J. Mercer, Geotrans	flow-heat, two-phase, 3D, FD, geothermal
MUSHRM	J. Pritchett, S. Garg, S^3	flow-heat-solute, two-phase, 3D, FD, geothermal, geopressure
SHAFT79	K. Pruess, LBL	flow-heat, two-phase, 3D, IFD, geothermal, waste isolation
Thomas-Pierson	L. Thomas R. Pierson, Phillips	flow-heat, two-phase, 3D, FD, geothermal
Voss-Pinder	C. Voss G. Pinder, Princeton	flow-heat, two-phase, 3D, FE geothermal
Toronyi-Ali	R. Toronyi, Chevron S.M. Farouq Ali, Alberta	flow-heat, two-phase, 2D, FD geothermal

Table 2. Governing Equations

Model	Variables	Fluid Properties	Formation Properties
CCC	P,T	formula and tables	$\phi(\sigma-P)$ $k(\phi)$
O'Neill	P,T^f,T^m	formula	ϕ^f, ϕ^m, k^f, k^m
Coats	P,T or P,S	formula and steam tables	$k_r = k_{rr}\bar{S}^n$
Faust-Mercer	P,H	formula	Corey's k_r
MUSHRM	ρ,U	formula	Corey's k_r
SHAFT79	ρ,U	steam tables	Corey's k_r
Thomas-Pierson	P,T	formula and steam tables	Corey's k_r
Voss-Pinder	P,H	formula, or package	Corey's or Arihara's k_r
Toronyi-Ali	P,S	formula	Corey's k_r

Table 3 Numerical Methods

Model	Upstream weighting	Implicit factor	Non-linear coefficients	Matrix solver
CCC	$0.5 \leq a \leq 1$	$\lambda=0,0.5,1$ (0.57-1.)		Direct (Duff)
O'Neill		$\lambda=0.5,1.$		Direct (Eisenstat and Sherman)
Coats	a=1	$\lambda=1$	Newton-Raphson	Direct (Price and Coats)
Faust-Mercer	a=1	$\lambda=1$	Newton-Raphson	Direct (Price and Coats)
MUSHRM	a=1	$\lambda=1$	Newton-Raphson	alternating direction implicit
SHAFT79	$0.5 \leq a \leq 1$	$\lambda=1$	Newton-Raphson	Direct (Duff)
Thomas-Pierson	a=1	$\lambda=1$	implicit pressure -explicit saturation	Direct (Price and Coats)
Voss-Pinder	asymmetric weighting function	$0.5 \leq \lambda \leq 1$	total increment method (semi-implict)	Block interative (BIFEPS)
Toronyi-Ali	a=1	$\lambda=1$	Newton-Raphson	Direct (Varga)

Table 4. Computer Codes

Model	Code Listing	User's Manual	Computer Systems	References
CCC	yes	yes	CDC, IBM	Lippmann et al., 1977 Mangold et al., 1979 Bodvarsson et al, 1979
O'Neill	yes	yes	IBM	O'Neill, 1978
Coats	Intercomp			Coats, 1977 Coats et al, 1977
Faust-Mercer	USGS			Faust & Mercer, 1979a,b Mercer & Faust, 1979
MUSHRM	S^3			Pritchett et al., 1975, 1980 Garg et al., 1977
SHAFT79	yes	yes	CDC	Pruess et al., 1979a,b Pruess & Schroeder, 1979
Thomas-Pierson	Phillips			Thomas and Pierson, 1978
Voss-Pinder	yes	yes	IBM	Voss, 1978 Voss and Pinder, 1977
Toronyi-Ali	Penn State			Toronyi, 1974 Toronyi & Ali, 1977

Table 5. Model Field Validation and Applications

Models	Field Validations	Applications
CCC	Auburn, Aquifer Storage	Cerro Prieto, reinjection; generic studies: aquifer storage, geothermal, repository; well testing
O'Neill		Hot water injection
Coats		Two-phase flow in fractures; convection
Faust-Mercer	Wairakei, Geothermal	Steam near canister
MUSHRM	Wairakei, Geothermal	Gulf Coast, geopressure; Salton Sea, precipitation
SHAFT79	Serrazzano, Geothermal	Krafla, geothermal; reservoir depletion; Sandia, repository
Thomas-Pierson		Stanford depletion experiment; production studies
Voss-Pinder		Stanford depletion experiment; production studies
Toronyi-Ali		production studies

Problems in Constitutive Equations and Numerical Solutions

(1) Relative permeability curves for steam and water need to be better determined.

(2) Capillary effects and steam-water interface thermodynamics in two-phase systems should be understood.

(3) Modeling of phase change, we believe, is still in an early stage of development.

(4) Elasticity-plasticity behavior of the fractured-porous systems requires further investigation.

(5) Modeling of coupled fluid flow and chemical reactions is still primitive.

(6) Development of modeling methods for parameter uncertainties is needed to provide confidence limits for all the modeling results, even if the model is assumed to be mathematically correct.

Many other problems may be listed whose solutions will improve our modeling capability in geothermal reservoir engineering.

SUMMARY

In this paper the state-of-the-art of modeling geothermal reservoir responses is reviewed. First, key processes in geothermal energy development are described and current approaches are pointed out. Then some of the major existing models are selected for detailed comparison according to the governing equations, numerical method, code availability, validations and applications. Finally important problems yet to be solved are listed. In general, the state-of-the-art is relatively advanced for heat and fluid flow in porous media, and generally, modelers have some confidence that current models will be able to simulate the major behaviors of geothermal reservoirs, given adequate reservoir parameters. However, many problems still remain which require careful investigation. The solution of these problems may yet prove to be of great importance in the future development of geothermal energy.

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