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Henry J. Ramey, Jr., Roland N. Horne,
Paul Kruger, Frank G. Miller,
William E. Brigham, Jean W. Cook
Stanford Geothermal Program
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HEAT DELIVERABILITY OF HOMOGENEOUS GEOTHERMAL RESERVOIRS

Eduardo R. Iglesias and Sara L. Moya

Instituto de Investigaciones Electricas

Apartado Postal 475, Cuernavaca 96000, Mexico

ABSTRACT

For the last two decades, the petroleum industry has been successfully using simple inflow performance relationships (IPR's) to predict oil deliverability. In contrast, the geothermal industry lacked a simple and reliable method to estimate geothermal wells' heat deliverability. To addres this gap in the standard geothermal-reservoir-assessment arsenal, we developed generalized dimensionless geothermal inflow performance relationships (GIPR's). These "reference curves" may be regarded as an approximate general solution of the equations describing the practically important case of radial 2-phase inflow. Based on this approximate solution, we outline a straightforward approach to estimate the reservoir contribution to geothermal wells' heat and mass deliverability for 2-phase reservoirs. This approach is far less costly and in most cases as reliable as numerically modelling the reservoir, which is the alternative for 2-phase inflow.

INTRODUCTION

For the last few decades, the petroleum industry has been successfully using inflow performance relationships (IPR's) to predict well productivities. These IPR's relate the volumetric oil flow rate q_o of a well to the corresponding sandface flowing pressure p. For liquid inflow the relationship between these variables is a straight line. In this case one can define a unique productivity index $J = q_o/(p - p_R)$, where p_R is the average reservoir pressure.

For 2-phase inflow the relationship between q_o and p is non-linear, as first pointed out by Evinger and Muskat (1942). Thus, a unique productivity index cannot be defined for this case. Gilbert (1954) was the first to propose methods of well analysis to use the information of the nonlinear relationships, and named these curves IPR's. Vogel (1968) numerically synthesized the IPR's corresponding to a broad set of different oil properties, formation properties, initial conditions and cumulative recovery, for solution-gas-drive reservoirs. In this work Vogel demonstrated that, normalizing q_o to the maximum flow rate $q_{o(max)}$ and p to the average reservoir pressure, the resulting dimensionless IPR's are remarkably similar to each other. Taking advantage of this approximate self-similarity, he proposed his now famous "reference curve"

$$q_o/q_{o(max)} = 1 - 0.2(p/p_R) - 0.8(p/p_R)^2, \qquad (1)$$

widely used in the oil industry since then. Vogel's seminal work has been extended, refined and variously applied by numerous authors (e.g., Standing, 1970; Al-Saadoon, 1980; Weiss et al., 1981; Dias-Couto and Golan, 1982; Mishra and Caudle, 1984; Kelkar and Cox, 1985; Camacho and Raghavan, 1989).

In contrast, the geothermal industry has made scant use of inflow performance relationships. Examples in the literature of IPR's applied to geothermal problems are few. They include assessment of productivity index and of reservoir parameters for wells fed by single-phase water and steam (Iglesias et al. 1983a, 1983b), and optimization of development strategy for liquid-dominated reservoirs (Marcou, 1985).

The scarce application of IPR's to geothermal problems reveals an important gap in the standard reservoir-assessment arsenal.

This work contributes generalized dimensionless IPR's appropriate for geothermal use. These geothermal IPR's (GIPR's) address geothermal heat deliverability, while reflecting that geothermal heat mining is inextricably linked to fluid production. Thus, the new GIPR's relate fluid production, heat production and reservoir pressure. In this contribution we examine the practically important case of 2-phase inflow.

GEOTHERMAL DELIVERABILITY

The main geothermal commodity is heat. However, heat is extracted via fluid production. Thus, to describe geothermal productivity it is necessary to relate fluid and heat production. Moreover, geothermal heat production is determined by reservoir and wellbore characteristics. There are good conceptual and practical reasons to differentiate these contributions. In this paper we concentrate on the reservoir contribution.

For 2-phase inflow, heat production is determined by reservoir temperature, pressure and shape, permeability (k), relative permeability (k_{rel}), fluid thermophysical properties and skin factor. The same variables control mass production. A distinct trait of 2-phase inflow is that the specific enthalpy of the fluid discharge increases with mass flow rate. This trait reflects heat transfer from the formation to the fluid, associated with boiling.

Heat deliverability also depends on reservoir history, mainly because the average reservoir pressure generally decreases with cumulative mass production (M_C). Additionally, the rate of decrease of p_R depends on whether the reservoir is closed or recharged (either naturally or by reinjection). Recharge also impacts on heat deliverability via the temperature of the recharged fluids. For simplicity, this work is restricted to characterizing heat deliverability in closed reservoirs with no reinjection.

METHOD

To characterize geothermal heat and fluid deliverabilities for 2-phase inflow, we assessed their dependence on unperturbed reservoir initial conditions, on cumulative mass production and on fluid and formation properties. We accomplished this by numerically modeling a number of relevant cases, which are summarized in Table 1.

The model is a closed, cylindrical, homogeneous reservoir with a fully penetrating well at its center. No skin effects were accounted for. We neglected vertical components of fluid flow. The reservoir is bounded above and below by impermeable formations. Conductive heat flow from the overlying and underlying formations was also neglected.

The computational work was done with a reliable numerical reservoir simulator (Pruess and Schroeder, 1980). The model neglects effects associated with dissolved gases or solids: the thermophysical properties of pure water substance are assumed for the fluid. All the cases of Table 1 were simulated using a 28 zone radial grid. The positions of the nodes are given by $r_n = 0.1(2)^{(n-1)/2}$, which locates the last node at 1158.52 m from the origin. Reservoir thickness is 100 m. Table 2 summarizes the assumed formation properties.

The cases of Table 1 include Corey-type and linear (also termed X-type) relative permeabilities. These are the most widely used in the geothermal literature. For both types, the residual saturations were assumed equal to 0.3 for liquid and to 0.05 for steam.

The initial temperature of the unperturbed reservoir (T_{init}) is also shown in Table 1, along with the assumed permeability and the computed cumulative mass produced (percent of initial fluid mass in-place), for each case.

In every case, the unperturbed initial conditions were pure liquid at the saturation pressure corresponding to T_{init}. Therefore, 2-phase inflow sets in as soon as production begins, and average reservoir pressure and temperature decrease with cumulative mass production.

RESULTS AND DISCUSSION

We computed geothermal inflow performance curves for each value of M_C, for all cases in Table 1. These curves relate sandface flowing pressure, discharge thermal power P (= Wh, where h is the specific enthalpy of the total discharge) and mass flow rate. Figures 1-3 illustrate these results for T_{init} = 250°C, k_{rel} = Corey, k = 10 mD, M_C = 5-35%.

Then, we normalized these curves to the corresponding maximum values of mass flow rate W_{max}, thermal power P_{max} and reservoir pressure p_R. The resulting dimensionless GIPR's corresponding to the cases shown in Figs. 1-3 are presented in Figs. 4-6. It is readily apparent that the pseudo-data[1] points tend to collapse into relatively narrow strips, in the dimensionless form. Since

[1]We refer to our computed results as pseudo-data to distinguish them from true data, as recommended by the American Geophysical Union.

T_{init}, k and k_{rel} are fixed for Figs. 4-5, the spread of the pseudo-data points reflects the effect of reservoir depletion on heat and mass deliverability, for this particular reservoir. Note also the tight non-linear correlation between heat and mass deliverability (Fig. 6). Though not shown here, similar effects are present for all reservoirs listed in Table 1.

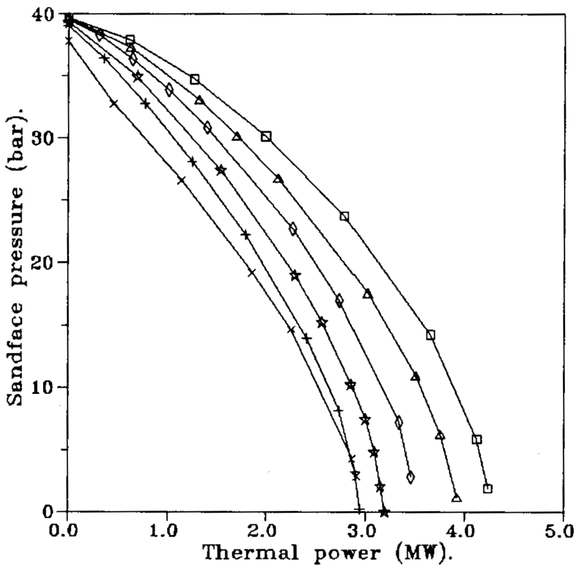

Fig. 1. Pressure - power relationships for T_{init} = 250°C, k_{rel} = Corey, k = 10 mD, M_C = 5, 10, 15, 20, 25, 35%. M_C increases towards lower curves.

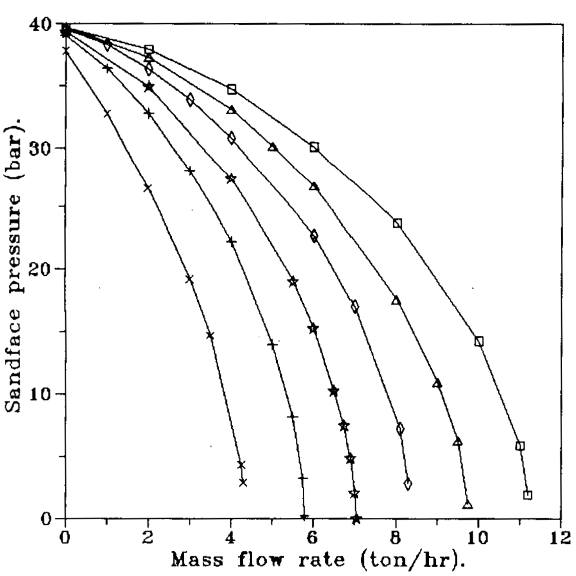

Fig. 2. Pressure - flow rate relationships for T_{init} = 250°C, k_{rel} = Corey, k = 10 mD, M_C = 5, 10, 15, 20, 25, 35%. M_C increases towards lower curves.

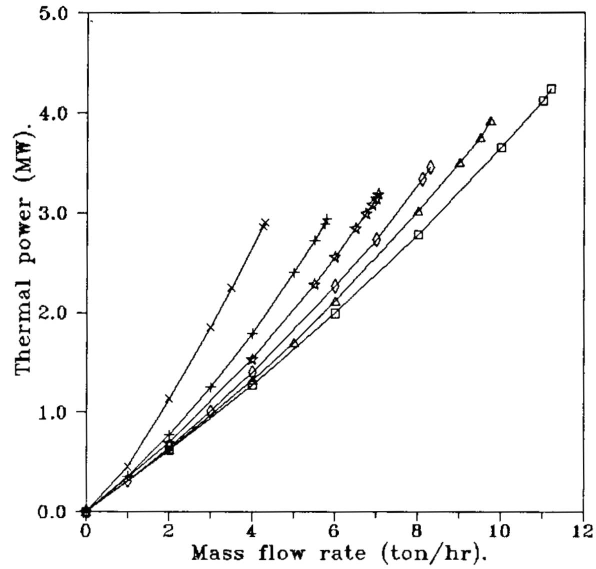

Fig. 3. Power - flow rate relationships for T_{init} = 250°C, k_{rel} = Corey, k = 10 mD, M_C = 5, 10, 15, 20, 25, 35%. M_C increases towards upper curves.

Table 1. Cases studied

k_{rel}	T_{init} (°C)	k (md)	Cumulative mass produced (%)
Corey	250	10	5 10 15 20 25 35
Corey	250	100	5 35
Corey	250	1000	4 20 29 33
Corey	350	10	5 35
Corey	350	100	5 35
Linear	250	10	5 35
Linear	250	100	5 35
Linear	250	1000	4 20 33
Linear	350	10	5 35
Linear	350	100	5 35

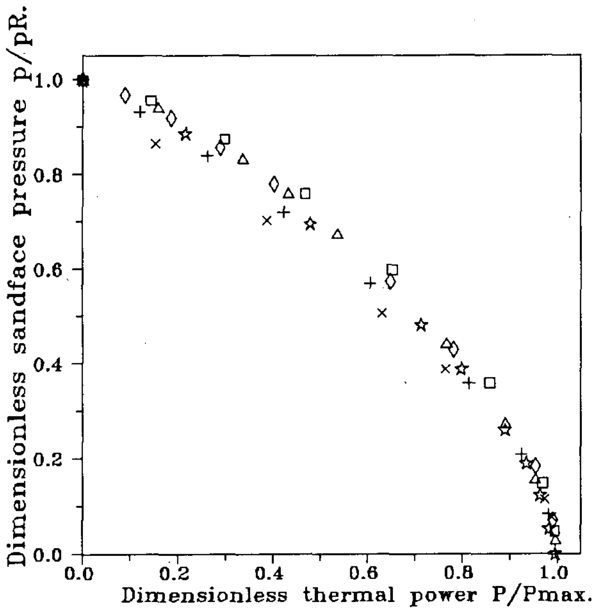

Fig. 4. Dimensionless relationships corresponding to Fig. 1 (same simbols).

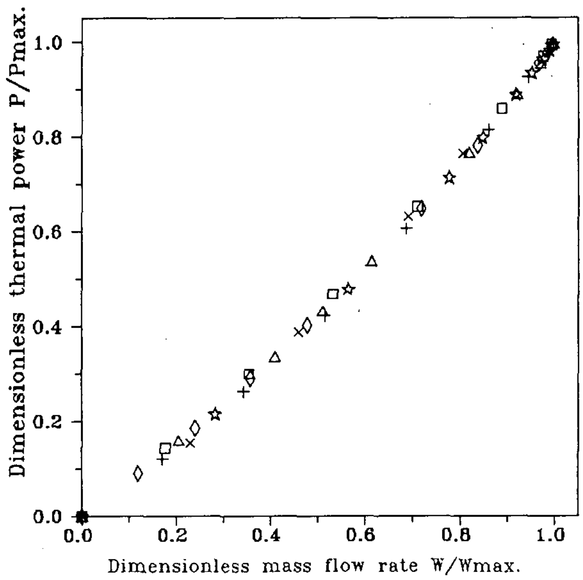

Fig. 6. Dimensionless relationships corresponding to Fig. 3 (same simbols).

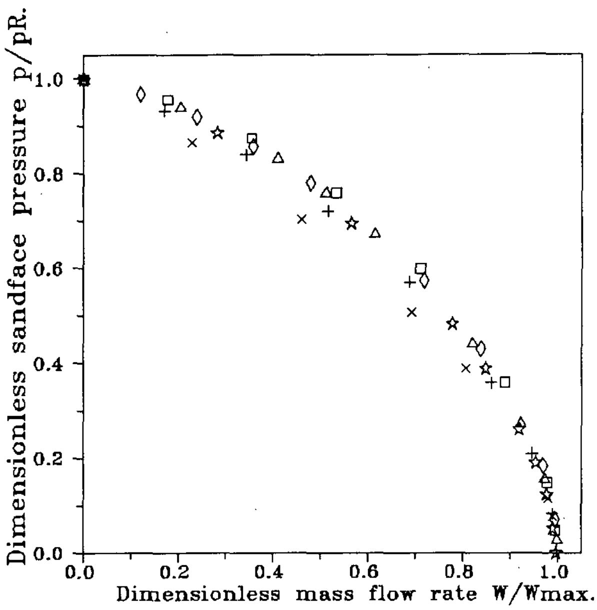

Fig. 5. Dimensionless relationships corresponding to Fig. 2 (same simbols).

The combined effects of reservoir initial conditions, permeability, relative permeability and reservoir depletion on dimensionless heat and mass deliverability are shown in Figs. 7-9. These figures summarize the results corresponding to all cases of Table 1. Note that despite the wide range of reservoir parameters, fluid properties and cumulative production covered, the relatively tight grouping of the computed results persists. As demonstrated by Vogel's dimensionless IPR's succes, this approximate self-similarity can be exploited for practical engineering purpouses.

We fitted the "reference curves" shown as continuous lines in Figs. 7 and 8 to the dimensionless heat deliverability results and thermal power - mass flowrate correlation, respectively. Thus, we exploited the close correlation between dimensionless thermal power and mass flowrate demonstrated in Fig. 8, while directly addresing geothermal heat deliverability. These reference curves may be regarded as an approximate general solution of the equations describing radial 2-phase geothermal inflow.

Table 2. Formation properties.

Porosity	0.10
Bulk density	2,700 kg/m^3
Thermal conductivity	2.0 $W^{m-1}{}^{\circ}C^{-1}$
Specific heat	1,000 $Jkg^{-1}{}^{\circ}C^{-1}$

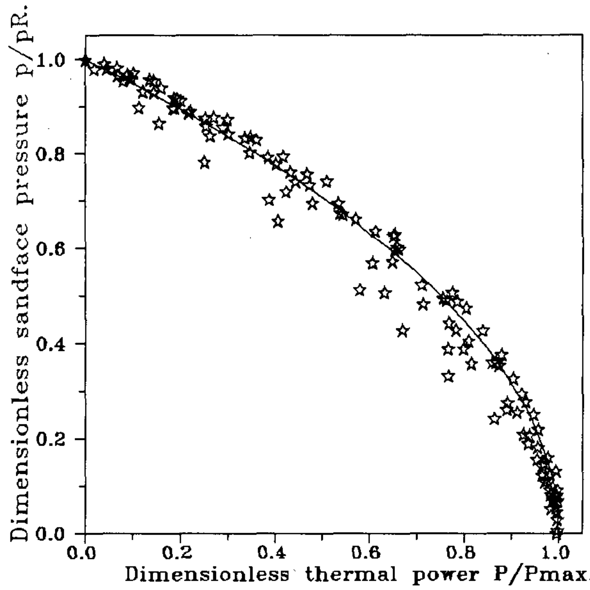

Fig. 7. Dimensionless pressure - power relationships including all cases in Table 1. The continuous line is the reference curve of eq. (2).

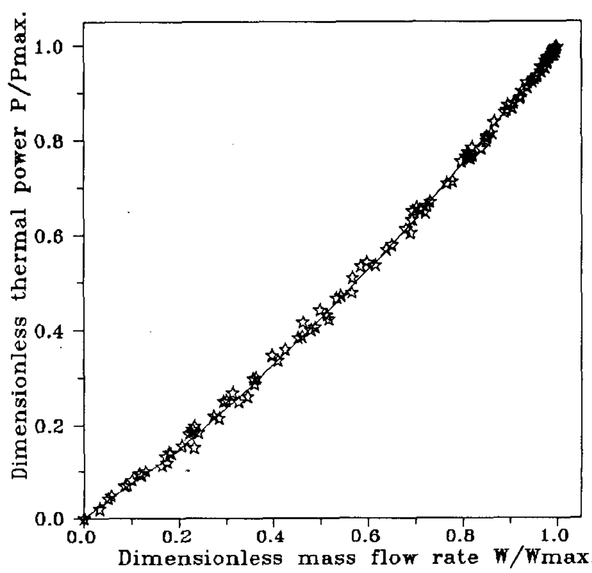

Fig. 8. Dimensionless power - flowrate relationships including all cases in Table 1. The continuous line is the reference curve of eq. (3).

For expediency we chose simple empirical expressions to fit to our results. Thus, the dimensionless heat deliverability results were fitted with

$$P_D = 1 - p_D^2, \quad (2)$$

where $P_D = P/P_{max}$ and $p_D = p/p_R$, and the dimensionless power - flow rate relationship by

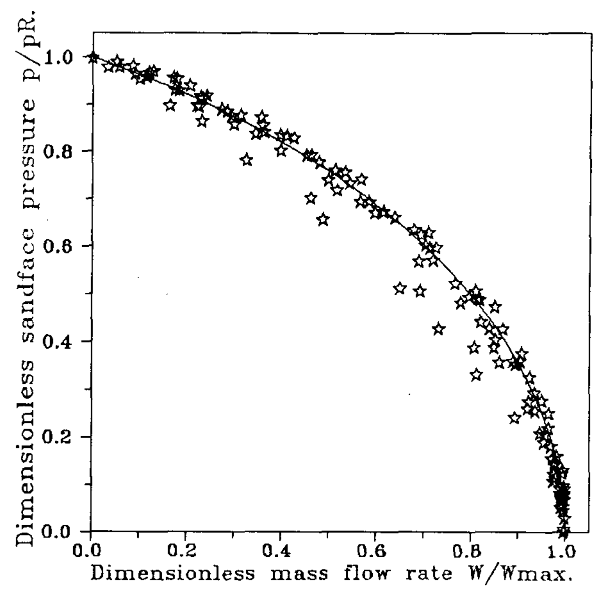

Fig. 9. Dimensionless pressure - flow rate relationships including all cases in Table 1. The continuous line is the reference curve of eqs. (3) or (4).

$$P_D = 0.7W_D + 0.3W_D^2, \quad (3)$$

where $W_D = W/W_{max}$.

From (2) and (3) follows

$$p_D = (1 - 0.7W_D - 0.3W_D^2)^{0.5}, \quad (4)$$

or

$$W_D = [- 0.7 + (1.69 - 1.2p_D^2)^{0.5}]/0.6 \quad (5)$$

which is plotted in Fig. 9 as a solid line. This "derived" fit looks reasonably satisfying to us.

Expressions (2)-(5), together with the definitions of the dimensionless variables may be used to estimate the reservoir contribution to geothermal wells' heat and mass deliverability. This straightforward approach is far less costly and probably as reliable as numerically modelling the reservoir. A further advantage of this approach stems from the simplicity and low cost associated with the input data necessary to estimate heat and mass deliverability with it. The necessary data may be gathered by simple wellhead measurements of mass flowrate and total discharge enthalpy, plus one downhole pressure measurement. This compares favorably with the expense and complication involved in gathering reliable information about reservoir parameters (e.g., permeability, relative permeabilities, thermal conductivity, average pressure) necessary for numerically modelling the reservoir.

SUMMARY AND CONCLUSIONS

Until present, the geothermal industry lacked a simple and reliable method to estimate the reservoir contribution to geothermal wells' heat deliverability.

To addres this gap in the standard geothermal-reservoir-assessment arsenal we developed generalized dimensionless geothermal inflow performance relationships (GIPR's). These "reference curves" may be regarded as an approximate general solution of the equations describing radial 2-phase geothermal inflow. They relate dimensionless thermal power, sandface pressure and mass flow rate, for the practically important case of 2-phase inflow in closed reservoirs. Our results include the effects of unperturbed reservoir initial conditions, fluid and formation properties and history of reservoir production. Effects associated with skin, reservoir shape, reinjection and dissolved gases and solids, were neglected.

The "reference curves" presented here provide a straightforward approach to estimate the reservoir contribution to geothermal wells' heat and mass deliverability for 2-phase reservoirs. This approach is far less costly and in most cases as reliable as numerically modelling the reservoir, which is the alternative for 2-phase inflow.

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