NUMERICAL SIMULATION OF CARBON DIOXIDE EFFECTS IN GEOTHERMAL RESERVOIRS

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ABSTRACT. We developed and coded a new equation of state (EOS) for water-carbon dioxide mixtures and coupled it to the TOUGH numerical simulator. This EOS is valid up to 350°C and 500 bar. Unlike previous thermodynamical models, it rigorously considers the non-ideal behavior of both components in the gaseous mixture and formally includes the effect of the compressibility of the liquid phase. We refer to the coupling of this EOS with TOUGH as TOUGH-DIOX. To complement this enhancement of TOUGH, we added indexed output files for easy selection and interpretation of results. We validated TOUGH-DIOX against published results. Furthermore we used TOUGH-DIOX to explore and compare mass and energy inflow performance relationships of geothermal wells with/without carbon dioxide (CO_2). Our results include the effects of a broad range of fluid and formation properties, initial conditions and history of reservoir production. This work contributes with generalized dimensionless inflow performance relationships appropiate for geothermal use.

INTRODUCTION

Many geothermal reservoirs contain considerable amounts of noncondensible gases, specially CO_2. A small fraction of this gas changes the thermodynamics and transport properties of the geothermal fluid. For this reason, is important to include in the geothermal simulators, a suitable Equation Of State (EOS) for the binary mixture H_2O-CO_2, in order to determine with confidence the mass and energy transport in the geothermal reservoirs. This in addition to the numerical qualities that the geothermal simulators must to have (e.g. Pruess, 1988; Pritchett, 1994).

We developed a new EOS for the binary mixture H_2O-CO_2 (Moya and Iglesias, 1992; Moya, 1994) valid up to 350°C and 500 bar. This new EOS is different that of O'Sullivan et al. (1985) and that one of Sutton (1976). Our EOS included the recent virial formulation of Spycher y Reed (1988) for the realistic determination of the fugacity coefficients of each component in the gaseous mixture. It also included the correlation of Andersen et al. (1992) for the evaluation of the enthalpy of the CO_2 gas.

Taking advantage of the efficiency and modular structure of the TOUGH geothermal simulator (Pruess, 1987) we coupled it our new EOS for the H_2O-CO_2 system. This coupling is refered as the TOUGH-DIOX simulator which included also index output files for easy selection and interpretation of the numerical results. We validated TOUGH-DIOX against published results.

As one applying of the TOUGH-DIOX simulator, we explored the mass and energy productivities of the geothermal wells for a broad range of reservoir parameters, in order to obtain a dimensionless model of productivities. Various numerical studies have been published on the behavior of the flowing enthalpy in relation to the reservoir parameters (Sorey et al., 1980; Pritchett et al., 1981; Grant y Glover, 1984; Bodvarsson, 1984; O'Sullivan et al., 1985; Pruess et al., 1985; Lippmann et al., 1985; Gaulke, 1986; Bodvarsson y Gaulke, 1987; among others). However, up to now, there's no a numerical methodology in the geothermal literature which permits estimate the mass and energy productivities of geothermal wells, with independence of the transport and thermophysical parameters of the reservoir. In the petroleum industry this has been performed over twenty years ago through the use of dimensionless inflow performance relationships (IPR).

The IPR curves were suggested by Gilbert (1954) as an analysis method of oil wells. The pioneer work of Muskat (1937) and later on of Vogel (1968) gave a great impulse to the use of dimensionless IPR curves in order to estimate the mass productivity of oil wells. Vogel (1968) proposed his famous "reference curve" (dimensionless IPR curve) widely used in the oil industry since then. Our preliminary results for a case of pure water in a homogenous porous media (Iglesias y Moya, 1990) and even in a fracturated porous media (Iglesias y Moya, 1993) showed that this also is possible for geothermal wells.

Considering the effect of CO_2, in this work we presented IPR curves and GIPR curves (Geothermal Inflow Performance Relationships) inherents to geothermal reservoirs. Two dimensionless "reference curves" are proposed in order to estimate geothermal heat deliverability, one for mass productivity (dimensionless IPR curve) and another one for thermal productivity (dimensionless GIPR curve). These two reference curves are independent of the reservoir parameters, the initial conditions and stage of explotation of this.

EQUATION OF STATE

Figure 1 shows the values of Henry's constant obtained with our EOS (Moya e Iglesias, 1992) for the solubility of carbon dioxide in water, compared with those of previous thermodynamical models. It is seen that they differ for temperatures of geothermal interest. The main source of error for the earlier solubility models is the choice of the Lewis fugacity rule (values of Majumdar and Roy, 1956) which estimates the fugacity coefficient of a component in a gas mixture as the fugacity coefficient of the pure component at the same temperature and pressure of the mixture. This idealization is obviously inconvenient for geothermal systems due to the both components are present in significant amounts (Takenouchi and Kennedy, 1965). We chose the important and recent virial formulation of Spycher and Reed (1988) to compute reliable fugacity coefficients. The formulation of Spycher and Reed involves up to the third virial coefficient necessary at temperatures and pressures of geothermal interest. Another important improvement in our EOS is the rigorous consideration of the compressibility effect of the liquid phase named Poynting correction (Prauznitz, 1969) necessary for high pressures. Finally, our EOS doesn't present the severe conflict between the linearity of the model and the lack of linearity of the experimental data, evident in previous thermodynamical models.

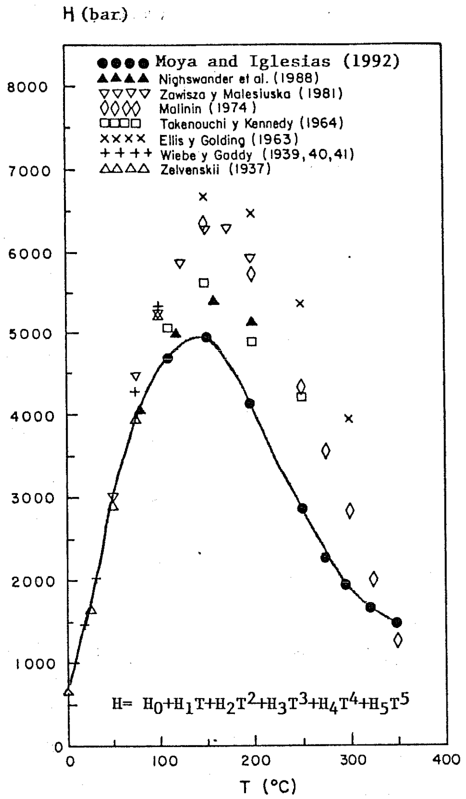

Fig. 1 Values of Henry's law constant by different authors. $H_0=666.128$, $H_1=37.084$, $H_2=0.325$, $H_3=4.273\times10^{-3}$, $H_4=1.344\times10^{-5}$, $H_5=1.343\times10^{-8}$.

TOUGH-DIOX SIMULATOR

The TOUGH-DIOX simulator is the coupling of the TOUGH simulator (Pruess, 1987) and of a new equation of state (EOS) for H_2O-CO_2 mixtures (Moya e Iglesias, 1992), valid until 350°C and 500 bar. Furthermore, the TOUGH-DIOX simulator generates indexed output files that permit, through an interactive program (Moya, 1989), to process the required information by the user for a fast selection and interpretation of the numerical results. We validated TOUGH-DIOX against published results for two geothermal studies with CO_2. The comparison with one of this studies (Suárez et al., 1989) is detailed in Figure 2. It is seen that our results agree well with those of the MULKOM simulator (Pruess, 1988). Although we no know with detail the EOS employed in MULKOM, the range of pressures involved (up to 80 bar), doesn't require very strict considerations in the thermodynamic model. That's why we don't expect that the values obtained with both simulators be very different.

NUMERICAL METHODOLOGY

The radial inflow model is used. A cylindrical reservoir is considered with radio and width of approximately 1000 and 100 m, respectively, limited above and below by impermeable and adiabatic formations. In the center there is a fully penetrating well with constant rate production. The rock-fluid media is constituted of homogenous porous rock and two-phase water with CO_2 representing the effect of noncondensable gases. The fluid flow in the reservoir is governing under Darcy law without gravity effect (unidirectional radial flow). Local thermodynamical equilibrium is established. The numerical grid employed has a nodal distribution of $r_n=0.1(2)^{(n-1)/2}$ showing higher finesse in adjacent area of the well where strong pressure and temperature gradients are present.

The cases under study are summarized in Table 1 and the constant assumed formation properties in Table 2. Each case involves a range of accumulated produced mass between five and thirty-five per cent of the total mass of initial geothermal fluid (*in situ*). The residual saturations are the usual ones of 0.30 for the liquid and 0.05 for

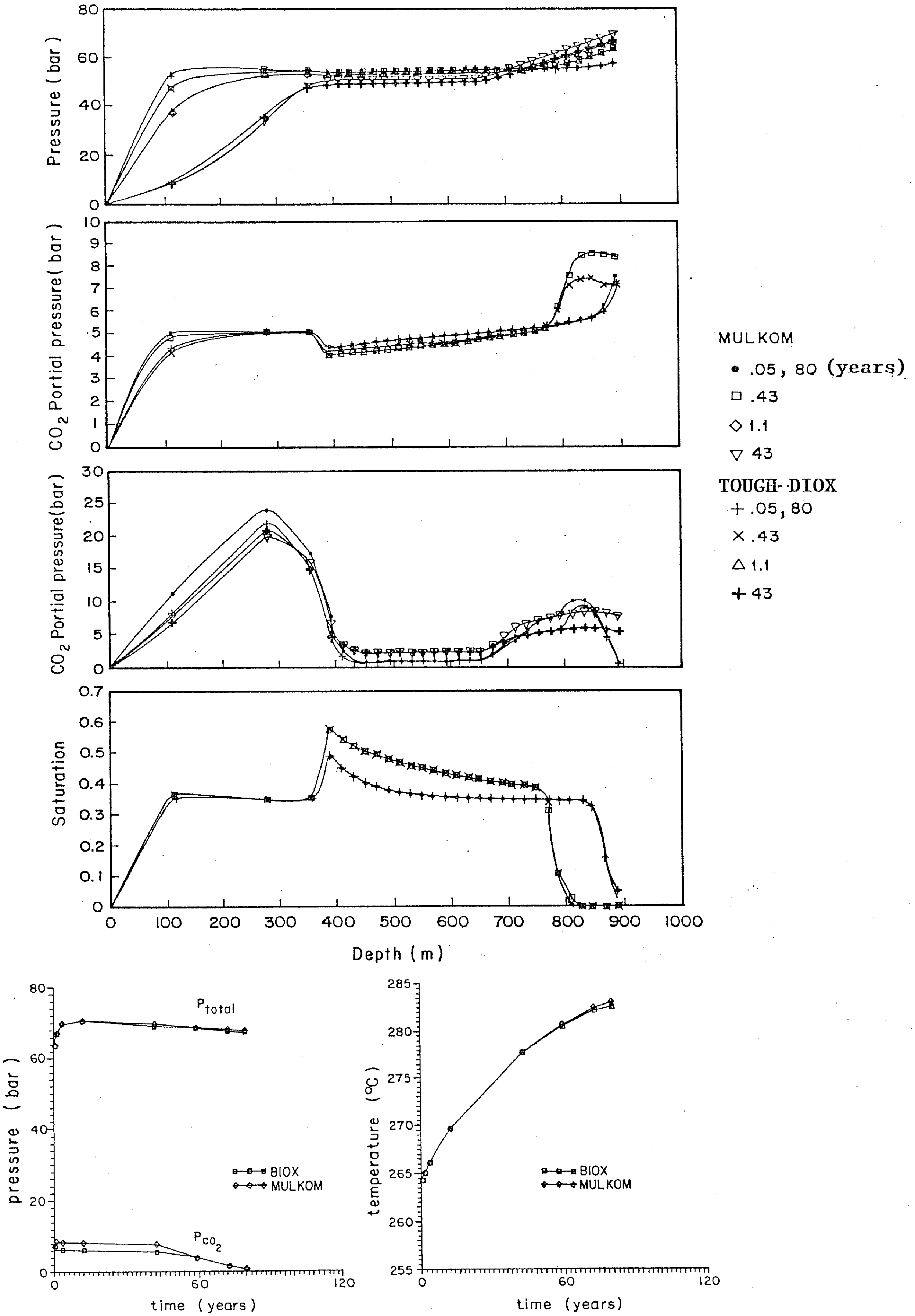

Figure. 2 Validation of the TOUGH- DIOX simulator.

the steam, as much as for the relative permeabilities of the Corey type as for those of the lineal type. The initial conditions correspond to a non-perturbed reservoir by the production under compressed liquid state almost boiling, containing 0.5% of CO_2 mass. Two initial temperatures are under analysis: 250 y 350°C that imply, at the beginning of production, partial pressures of CO_2 of 7 and 4 bar, respectively. The corresponding total pressures are of 50 and 170 bar, in accordance with the diagram of liquid-steam phases of a H_2O-CO_2 binary system containing 0.5% of CO_2 mass.

Each one of the indicated cases in Table 1 is numerically carried out to constant mass production until the quantity of accumulated produced mass reaches a thirty-five per cent of the initial total mass of the geothermal fluid *in situ*. During the transient simulation, the information of pressures is recorded in the reservoir-well interface as well as of the produced fluid enthalpy (flowing enthalpy). This, for the different percentages of accumulated produced mass. The procedure is repeated for other constant mass flows of the production, from the condition on non-perturbed reservoir for the production to the condition of maximum possible mass flow.

Table 1. Cases studied

Initial Temperature (°C)	Absolute Permeability (mD)	Relative Permeability	Cumulative mass produced %
250	10	Corey	5,10,15,20,25, 35
250	10	Lineal	idem
250	100	Corey	idem
250	100	Lineal	idem
350	10	Corey	idem
350	10	Lineal	idem
350	100	Corey	idem
350	100	Lineal	idem

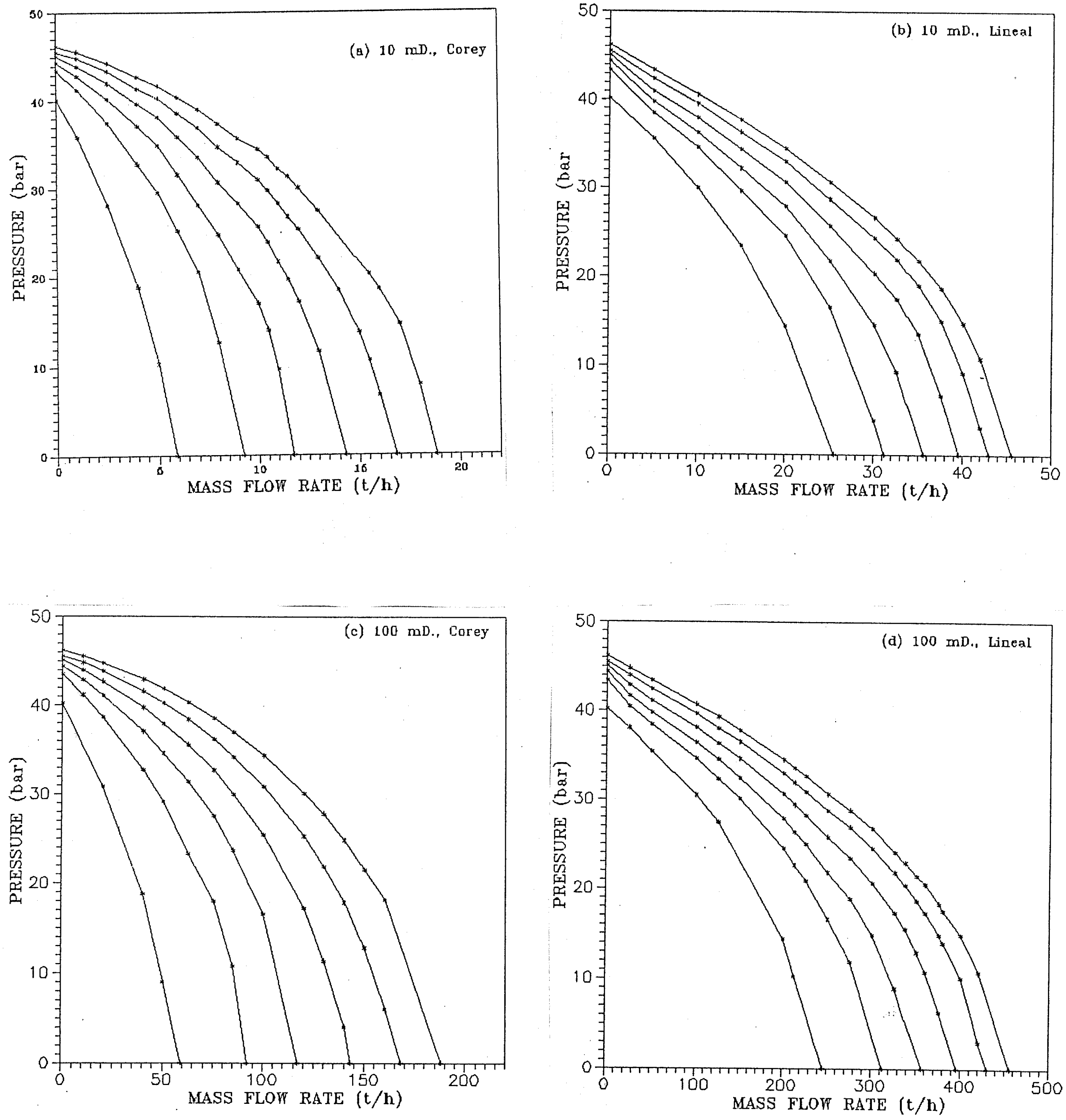

Fig. 3 Inflow performance relationships(IPR) for To=250°C, Po= 50 bar, 0.5% CO_2 initial mass.

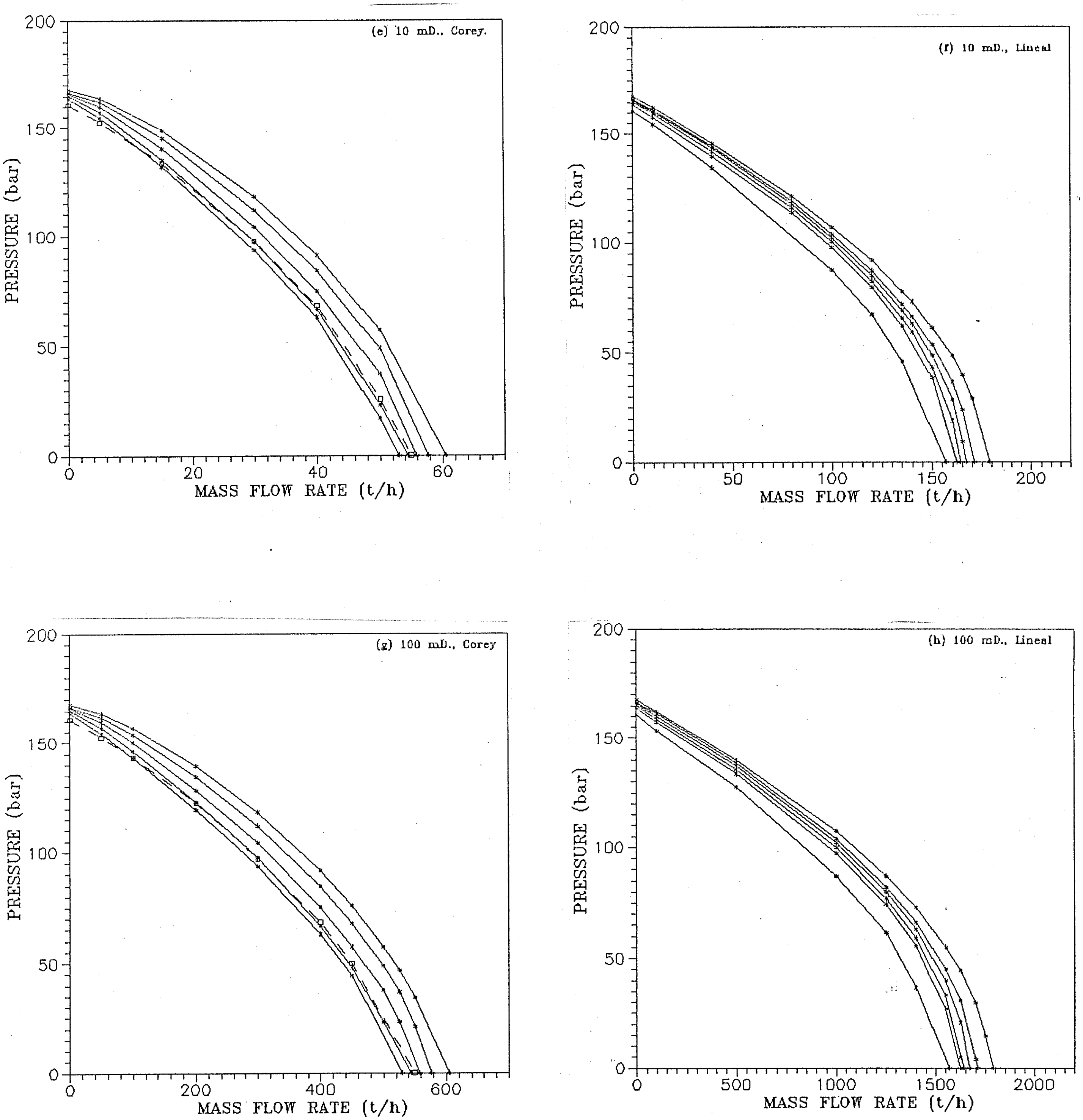

Fig. 3 Inflow performance relationships (IPR) for To=350°C, Po= 170 bar, 0.5% CO_2 initial mass.

Table 2. Formation properties

Porosity	0.10
Density	2,700 kg/cm^2
Thermal conductivity	2.00 W/(m °C)
Specific heat	1,000 J/(kg °C)

RESULTS AND DISCUSSION

Reservoir contribution to the mass productivity

Figures 3(a-h) show IPR curves in the indicated order in Tabla 1. These denote the relation between the pressure in the reservoir-well interface and the produced mass flow for the different percentages of accumulated produced mass. The curves present a non-lineal behaviour as expected for 2-phase flows (Muskat, 1937). Some general conclusions can be established: a) the IPR curves for the 10 and 100 mD cases (keeping the other constant parameters) show self-similarity in scale of 10 in accordance with the Darcy law. b) The relative permeability cases of the lineal type allow higher mass flow with respect to the Corey type, between 2 and 3 times more, due to a smaller interference between the liquid and gaseus phases. c) The effect of a higher initial temperature is to permit higher mass flow and with less dependency of the accumulated produced mass.

Adimensional model of mass productivity

On normalizing each IPR curve with the corresponding maximum values of pressure and mass flow, we obtained the dimensionless values shown in figure 4 for all Table 1 cases. The narrow grouping of the dimensionless data outline one curve which we propose as "reference curve" in order to estimate the mass productivity of geothermal wells. This dimensionless reference curve is independent from thermophysical and transport parameters of the reservoir, of the initial conditions and of the grade of explotation of the same. This is the first one that is proposed for geothermal reservoirs containing CO_2.

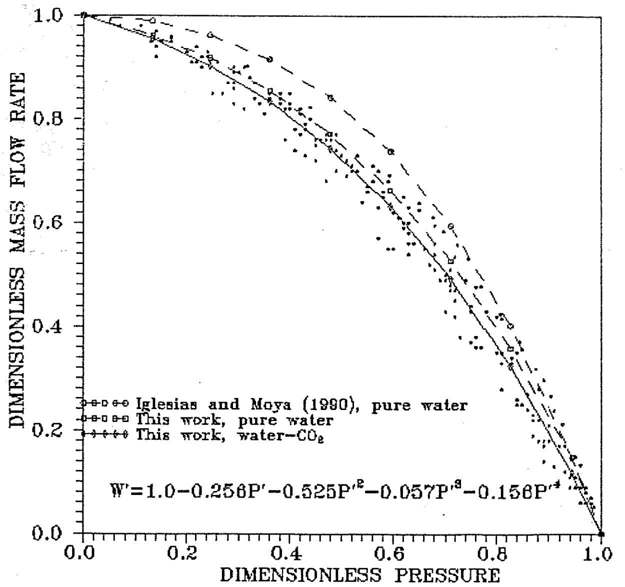

Fig. 4 Comparation of reference curves

Gunn and Freeston (1991) found a mistake of up to 30% on applying the former IPR (Iglesias and Moya, 1990), for the pure water system, to the Broadlands 13 well in New Zealand. This error could notoriously decrease if corresponding IPR to binary system would be applied. As it is wellknown, significative CO_2 amounts are found in Broadlands.

Reservoir contribution to the thermal productivity

Unlike the Oil Industry, the main geothermal recourse is the heat. The geothermal productivity is referred to the speed with which energy can be extracted as heat. It is necessary to produce fluid in order to extract heat. Consequently, heat and fluid productivities must be related with each other. The thermal power is the speed with which energy can be extracted as heat and it is the product of the specific enthalpy and the mass flow of the discharge. The Figure 5 shows, as an example, the GIPR curve corresponding to the IPR curve of the figure 3.a (for 250°C, 10 mD and relative permeability of Corey type). As it is seen, the thermal power is higher if mass flow is higher. On the other hand, the more advanced is the explotation range of the reservoir, the more effective is the thermal power obtained. This is as a consequence of the increase in the produced steam saturation and, consequently, of the flowing enthalpy. It must be reminded that no recharges are considered in this study. The GIPR curves reflect in general that the explotation of the geothermal energy is intimately linked with the extraction of the geothermal fluid.

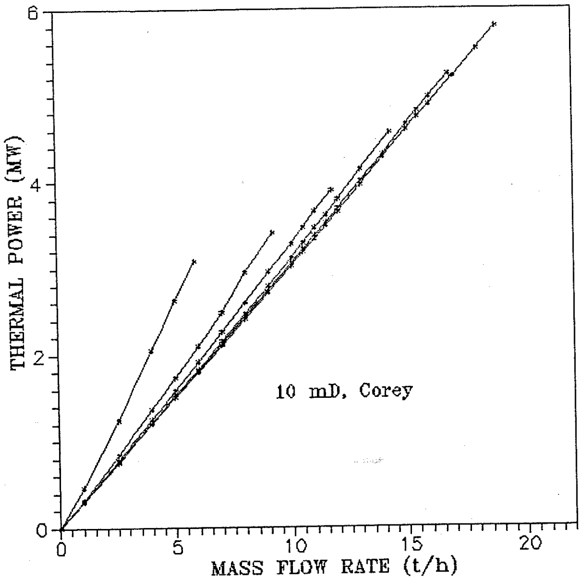

Fig. 5 Characteristics curves of thermal productivity for T_0=250°C, P_0=50 bar, and 0.5 CO_2 initial mass

Adimensional model of thermal productivity.

On normalizing each GIPR curve with the corresponding maximum values of thermal power and mass flow, we obtained the reference curve shown in Figure 6. The notable self-similarity of the dimensionless data reflects that heat deliverability in closed reservoirs is insensitive to undisturbed reservoir initial conditions, fluid and formation properties and history of reservoir production. This is due to the fact of that geothermal heat reserves residing overwhelmingly in the rock formation and not in the fluid.

Effect of CO_2 on mass and thermal productivities

In order to determinate the effect that the presence itself of CO_2 have on the productivities, the preceding study was conformed also for a pure water system. By comparation of the IPR and GIPR curves corresponding to binary system, with that corresponding to pure water system (no shown here),

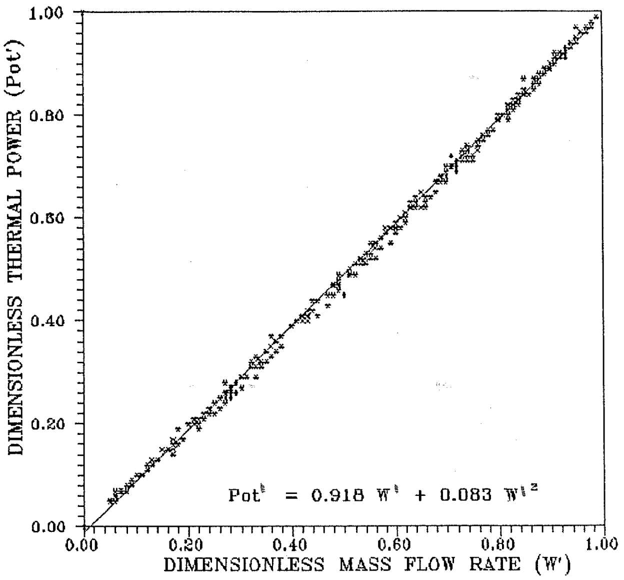

Fig. 6 Thermal productivity reference curve proposed for geothermal reservoir with CO_2.

it is conclude that the mass flows, and therefore the thermal powers, are higher for the binary system (up to 2 times more). This principally for the 250°C initial temperatura cases, at begining of the production, when the partial pressures of CO_2 are more important.

The Figure 4 includes the reference IPR curve obtained in this work for the pure water system. It is also compared with the one previously obtained (Iglesias y Moya, 1990) by means of another less adequate numerical methodology. By comparation of both curves for pure water with the obtained for the binary system, it is evident that the presence of CO_2 influences notoriously in the behaviour of the productivities, even though the initial concentration of CO_2 considered was scarcely of 0.5% in mass.

CONCLUSIONS

The numerical results presented under IPR and GIPR curves denote, respectively, the behaviour of mass and energy productivities of geothermal wells. This behaviour is a reflect of the properties of rock formation and of fluid, of the initial conditions and the history of the reservoir production.

The IPR and GIPR curves normalized with the corresponding maximum values of pressure, mass flow and thermal power, dimensionless curves, trend to collapse in relatively narrow zones, in spite of the wide ranges of properties of the rock-fluid media, of initial conditions and of the percentage of accumulated produced mass. Taking advantage of this self-similarity, two dimensionaless reference curves are proposed for the binary system H_2O-CO_2, one for mass productivity (figure 4) and another one for thermal productivity (figure 6). These curves, in conjunction with a few ground measurements (mass flow and discharge enthalpy, plus a determination of downhole pressure) allow to estimate the mass and energy productivities of geothermal wells for short, medium and long terms.

Nevertheless the presence of CO_2 in geothermal reservoirs affects negatively to the enthalpy content of the produced fluid, it helps to obtain higher mass flows and consequently, thermal powers also higher.

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