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Dual-porosity and Dual-fracture Model for Fractured Geothermal Reservoir Simulations

Didier Yu DING
IFP Energies Nouvelles, Rueil-Malmaison, France
e-mail : didier-yu.ding@ifpen.fr

Introduction

The dual-porosity model has been widely adopted in fractured reservoirs. This kind of model is useful to describe the flow behavior in fractured system, where the fracture supplies the fluid flow while the matrix provides most of the pore volume for storage. Barenblatt et al. (1960) and Warren and Root (1963) introduced the dual-porosity model which treats a naturally fractured reservoir with irregular matrix and fractures as an equivalent, homogeneous model. The dual-porosity model is greatly used in petroleum fractured reservoirs with success (see, for example, Lemonnier and Bourbiaux 2010). One of the key issues discussed in the dual-porosity model is the determination of a suitable factor for the matrix to fracture transfer term. Among other authors, Kazemi et al. (1976), Thomas et al. (1983), Coats (1989), Zimmerman et al. (1993), Lim and Aziz (1995), Bourbiaux et al. (1999) proposed expressions of the shape factor that differ from one another by the value of the involved multiplying factor applied to the sum of the inverse of squared block dimensions. Whereas Kazemi et al.'s shape factor is approximated by an equivalent flow transmissibility between matrix block centre and limits. Different authors (see, for example, Zimmerman et al. 1993, Lim and Aziz 1995) successively proposed a more rigorous expression of the shape factor, that is valid under pseudo-steady-state assumption. Discussions of the evolution of a constant shape-factor definition adopted in dual-porosity simulators for simulating diffusive transfers can be found in Landereau et al. (2001), Van Heel et al. (2008), Bourbiaux and Ding (2016).

The dual-porosity approach is also widely used in fractured geothermal reservoirs. Austria and Sullivan (2015) performed a sensitivity study to determine when to employ a dual-porosity model instead of a single-porosity approach in geothermal system. The application to Mt. Apo geothermal reservoir showed that a dual-porosity model is preferred. The dual-porosity model was also applied to Leyte geothermal production field (Omagbon et al. 2016). Aliyu et al. (2017) applied the dual-porosity model together with faults modeling to the Soultz geothermal reservoir. Fujii et al. (2018) performed simulations with dual-porosity and MINC approach. They observed that the recharge water sometimes reached producing wells much earlier than predicted by simulation models. They believed one of the reasons for this mis-prediction is related to the non-equilibrium effects and proposed a technique for non-equilibrium modeling. The dual-porosity model is particularly useful for tracer test simulation in geothermal reservoirs (Ratouis et al. 2019).

The concept of dual-porosity model is particularly suitable for convective flow, where the convective flow is much faster in fractures than in the porous matrix. But it does not always adapt to geothermal reservoirs, because the thermal conduction plays an important role and the temperature variation is a major concern in geothermal simulations. In a dual-porosity

approach, two media are considered, one matrix medium and one fracture medium. The convective transfer between these two media is proportional to the pressure difference in these media, and the conductive transfer is proportional to the temperature difference. As the fracture permeability is very high, the pressure diffusion in the fractures is very fast. So the pressure is almost locally a constant in the connected fractures, while it is not the case for the temperature because the thermal conductivity in fractures is as low as that in the matrix. In particular, the fracture pressure around a matrix block can be considered as a constant, but the fracture temperature is not. In other words, we can define a correct fracture pressure to compute the matrix-fracture exchange, but we don't have a suitable fracture temperature for this exchange calculation. So we cannot always correctly simulate the conductive heat matrix-fracture transfer, while the thermal conduction is an important transfer mechanism in geothermal reservoirs.

The MINC (Multiple INteracting Continua) method is usually considered to improve the matrix-fracture transfer computation in geothermal reservoir (Pruess and Narasimhan 1985; Wu and Pruess 2000; Fujii et al. 2018), in order to take into account the slow temperature diffusion inside the matrix medium due to low thermal conductivity. However, this concept can only improve the description for the pressures and temperatures gradients inside the matrix by further subdividing individual matrix blocks, the temperature modeling inside the fractures cannot be improved by MINC approach.

The discrete fracture model is also used for geothermal reservoir simulations (see, for example, Mezon et al. 2018). This kind of models usually involves much more unknowns than a dual-porosity one.

In this work, we propose a dual-porosity and dual-fracture approach by using two sets of fractures, one set for the modeling of fracture flow in the x-direction, and the other set for the fracture flow modeling in the y-direction. These two sets of fractures are hydraulically connected without any barrier, while they are thermally poorly connected through low thermal conductivities. In other words, these two sets of fractures have locally the same pressure, but have different temperatures. This approach can improve the temperature modeling in the fractures, hence the matrix-fracture exchange simulation for both the convective and the conductive transfers.

Governing Equations

To simplify, we consider one phase water transport problem. The mass and energy balance equations are respectively given by:

$$\frac{\partial(\phi\rho_w)}{\partial t} + \text{div}(\rho_w \vec{v}_w) - q_w = 0 \quad (1)$$

and

$$\frac{\partial}{\partial t}((1-\phi)\rho_r U_r + \phi\rho_w U_w) + \text{div}(\rho_w H_w \vec{v}_w) - \text{div}(\overline{\overline{\lambda \text{grad} \Theta}}) - q_E = 0 \quad (2)$$

where ϕ is the porosity, ρ_w is the water density, ρ_r is the rock density, $\vec{v}_w$ is the water velocity, U_r and U_w are the internal energies of rock and water respectively, H_w is the water enthalpy, Θ is the temperature, $\bar{\bar{\Lambda}}$ is the effective conductivity tensor of water and rock, q_w is the source/sink term of water, and q_E is the source/sink term of energy. The velocity $\vec{v}_w$ is calculated by Darcy's law:

$$\vec{v}_w = -\frac{\bar{\bar{K}}}{\mu_w}(\overrightarrow{\text{grad}P} - \rho_w \vec{g}) \quad (3)$$

where $\bar{\bar{K}}$ is the permeability tensor, μ_w is the water viscosity, P is the pressure, $\vec{g}$ is the acceleration of gravity.

In the above system, the primary unknowns are the pressure P and the temperature Θ . Other variables, such as the density and enthalpy, are functions of the pressure and/or the temperature.

Standard Dual-porosity Model

In a standard dual-porosity approach, two media are considered. The fracture medium transports the fluid flow from one zone to another due to its high permeability, while the matrix medium supplies the storage volume to the fractures. The fractures are homogenized. The considered mass balance equations are written in both the fracture and the matrix media:

$$\frac{\partial(\phi^f \rho_w^f)}{\partial t} + \text{div}(\rho_w^f \vec{v}_w^f) - Q_w^{mf} - q_w^f = 0 \quad (4)$$

and

$$\frac{\partial(\phi^m \rho_w^m)}{\partial t} + \text{div}(\rho_w^m \vec{v}_w^m) + Q_w^{mf} - q_w^m = 0 \quad (5)$$

where the superscript f represents the fracture medium, the superscript m represents the matrix medium, Q_w^{mf} is the mass exchange term between the matrix and the fractures. The energy balance equations in these two media are:

$$\frac{\partial}{\partial t}((1-\phi^f)\rho_r^f U_r^f + \phi^f \rho_w^f U_w^f) + \text{div}(\rho_w^f H_w^f \vec{v}_w^f) - \text{div}(\bar{\bar{\Lambda}}^f \overrightarrow{\text{grad}\Theta}^f) - Q_E^{mf} - q_E^f = 0 \quad (6)$$

and

$$\frac{\partial}{\partial t}((1-\phi^m)\rho_r^m U_r^m + \phi^m \rho_w^m U_w^m) + \text{div}(\rho_w^m H_w^m \vec{v}_w^m) - \text{div}(\overset{=m}{\Lambda} \text{grad} \Theta^m) + Q_E^{mf} - q_E^m = 0 \quad (7)$$

where the matrix-fracture energy exchange is composed of two terms:

$$Q_E^{mf} = Q_H^{mf} + Q_D^{mf} \quad (8)$$

with Q_H^{mf} the convective exchange, and Q_D^{mf} the conductive or diffusive exchange.

The above system (Eqs. (4)-(7)) is usually discretized in space using a control-volume method, and the time discretization is carried out using a backward, first order, finite difference scheme. The control-volume method is very flexible for handling the interactions between various kinds of media. For example, considering a 2D problem in the xy plane, the space discretization of the divergence term on a control volume i in the mass flow equation in the fracture medium is given by (Fig. 1 shows the space discretization for a Cartesian grid):

$$\text{div}(\rho_w^f \vec{v}_w^f)_i = \sum_{j \in \Omega_i} F_{w,ij}^f \quad (9)$$

with

$$F_{w,ij}^f = \lambda_{w,ij}^f T_{ij}^f (P_j^f - P_i^f) \quad (10)$$

where $\lambda_w^f = \frac{\rho_w^f}{\mu_w^f}$ is the water mobility in the fracture medium, Ω_i is the set of direct neighbors

of the cell i , F_{ij} is the flux between the grid cell i and its neighbor j , $T_{ij} = K_{ij} \frac{S_{ij}}{d_{ij}}$ (with S_{ij} the

interface area, d_{ij} the distance between the cell centers, and K_{ij} the weighted harmonic average permeability in the direction between i and j) is the (convective) transmissibility between Cells i and j , an upstream scheme is used for the mobility term λ_w^f in the transport equation. The mass exchange term between a matrix cell i and the corresponding fracture cell is calculated by:

$$Q_{w,i}^{mf} = \lambda_{w,i}^m K^m V_{Gi} \sigma (P_i^m - P_i^f) \quad (11)$$

with K^m the matrix permeability (for simplicity, we assume the permeability is isotropic in the matrix medium), V_{Gi} is the bulk volume of Cell i , σ the shape factor. This exchange is proportional to the pressure difference between the matrix and the fracture cells. One of the key issues in the dual-porosity model is the determination of the shape factor for an accurate matrix-fracture exchange modeling.

We have similar discretization for the mass balance equation in the matrix medium, as well as for the energy balance equations in both the fracture and the matrix media. In particular, the convective flux between two neighboring fracture cells i and j in the energy equation is calculated by:

$$F_{H,ij}^f = \lambda_{H,ij}^f T_{ij}^f (P_j^f - P_i^f) \quad (12)$$

with

$$\lambda_H^f = \frac{\rho_w^f H_w^f}{\mu_w^f} \quad (13),$$

and the conductive or diffusive flux between the fracture cells i and j is discretized by:

$$F_{D,ij}^f = G_{ij}^f (\theta_j^f - \theta_i^f) \quad (14)$$

with

$$G_{ij}^f = \Lambda_{ij}^f \frac{s_{ij}}{d_{ij}} \quad (15),$$

where G_{ij}^f is the conductive transmissibility, Λ_{ij}^f is the effective thermal conductivity between Cells i and j . As the fracture aperture is usually small and the thermal conductivity in the fracture is of the same order as that in the matrix medium, the equivalent fracture thermal conductivity is much smaller than the conductivity of the matrix media and can be neglected in many cases.

The energy exchange between matrix and fractures on a grid cell i due to convection is calculated by:

$$Q_{H,i}^{mf} = \lambda_{H,i} K^m V_{Gi} \sigma (P_i^m - P_i^f) \quad (16)$$

and the heat exchange due to conduction is given by

$$Q_{D,i}^{mf} = \Lambda_i^m V_{Gi} \sigma (\theta_i^m - \theta_i^f) \quad (17)$$

where Λ^m is the effective matrix thermal conductivity (we assume it is isotropic), and σ is the shape factor. The energy exchange due to conduction is proportional to the temperature difference between the matrix and the fracture cells.

Problem of Dual-porosity Approach in Geothermal Simulations

In a geothermal reservoir, the thermal conduction plays an important role for energy transport. The matrix-fracture heat exchange depends mainly on the conduction/diffusion instead of convection. It is therefore very important to handle accurately matrix-fracture energy exchange due to the conduction.

In a dual-porosity model, the fracture network is homogenized. We assume that the main flow directions are oriented to the x and y directions with equivalent fracture permeabilities K_x^f and K_y^f . We also assume the fracture pressure is almost a constant inside a simulation cell and around a matrix block. This assumption is reasonable, because the pressure diffusion is very fast among the connected fractures due to high fracture permeability. So the convective exchange between matrix and fractures can be computed with Eq.(11) and Eq.(16), using the cell fracture pressure P^f . However, it is not always suitable to consider that the temperature is a constant inside a fracture cell or around a matrix block. The temperature diffusion inside the fracture is very slow, because of the low fracture thermal conductivity. The high fracture permeability cannot help the temperature diffusion inside the connected fractures. If the fracture temperature varies a lot around a matrix block, it is not convenient to use an unique fracture temperature θ^f to compute the matrix-fracture energy exchange with Eq.(17). We may encounter this kind of problems in some geothermal reservoirs.

Take an example of a square matrix block as shown in Fig. 2. Considering the main flow is in the x-direction, that is $F_x^f \gg F_y^f$ (Fig. 2a), whatever the flow direction, the pressure around the matrix block is always almost a constant due to high fracture permeability (Fig. 2b)

$$P_1^f \approx P_2^f \approx P_3^f \approx P_4^f \quad (18)$$

so the convective flux exchange is uniform around the matrix block for both the mass flux and the heat flux:

$$Q_{w1}^{mf} \approx Q_{w2}^{mf} \approx Q_{w3}^{mf} \approx Q_{w4}^{mf} \quad (19)$$

and

$$Q_{H1}^{mf} \approx Q_{H2}^{mf} \approx Q_{H3}^{mf} \approx Q_{H4}^{mf} \quad (20).$$

But it is not always the case for the temperature and the conductive exchange. When the injected cold water flows by, the temperature in the fractures parallel to the x-direction decreases first and the temperature in the fractures parallel to the y-direction does not change much (Fig. 2c):

$$\theta_1^f \approx \theta_2^f \ll \theta_3^f \approx \theta_4^f \quad (21).$$

The heat exchanges occur mainly between the matrix block and the fractures parallel to the x-direction due to its lower fracture temperature, while the exchanges with the fractures parallel to the y-direction is limited by the higher fracture temperature. So, the matrix-fracture heat exchange is not uniform:

$$Q_{D1}^{mf} \approx Q_{D2}^{mf} \gg Q_{D3}^{mf} \approx Q_{D4}^{mf} \quad (22).$$

The temperature in a fracture depends on the volume of cold water flowing through the fracture as well as the matrix-fracture exchange. In a standard dual-porosity model, we don't have a representative fracture temperature for the computation of matrix-fracture conductive thermal exchange with Eq.(17). So the simulations might be inaccurate.

Dual-fracture Approach

In this section, a dual-fracture approach is proposed to improve the conduction/diffusion matrix-fracture exchange modeling in a dual-porosity model. This approach can be considered as an improvement of the dual-porosity model for non-isothermal reservoir simulations.

Consider a 2-Dimensional matrix-fracture exchange problem. In a standard dual-porosity model, the fracture networks are idealized by two sets of fractures, one oriented in the x-direction with fracture spacing L_y and the other oriented in the y-direction with fracture spacing L_x (Fig. 3). The fracture properties are homogenized, and in particular we get the equivalent fracture permeability K_x^f in the x-direction and K_y^f in the y-direction. These two sets of fractures intersect. In a standard dual-porosity model, both the pressure and the temperature are considered locally as constants in the connected fractures in a fracture cell. As discussed above, this assumption is suitable for isothermal flow simulation, but it can be inaccurate for non-isothermal problems. To improve the accuracy for non-isothermal simulations, we propose a new approach based on the concept of the dual-fracture approach.

In the dual-fracture approach, the fracture medium of a dual-porosity model is split into two homogenized fracture networks, one oriented in the x-direction and the other oriented in the y-direction (Fig. 4). Therefore, we have two fracture media, a X-fracture medium and a Y-fracture medium. In the X-fracture medium, flow is only allowed in the x-direction and there is no flow

in the y-direction, while in the Y-fracture medium, the flow is only allowed in the y-direction and there is no flow in the x-direction. In this modeling, each grid cell in the mesh is composed of three superposed cells (Fig. 4): one matrix cell and two fracture cells (one X-fracture cell and one Y-fracture cell). These two fracture cells are hydraulically connected without barrier, while they are poorly thermally connected through low fracture thermal conductivity. The connections between different media are described in the following.

We denote T_x^f and T_y^f the fracture (convective) transmissibility in the x- and y-directions respectively in a standard dual-porosity model, G_x^f and G_y^f the fracture conductive transmissibility in the x- and y-directions respectively, V^f the fracture cell porous volume in the standard dual-porosity model, and σ the shape factor in the standard dual-porosity approach.

X-fracture medium

In the X-fracture medium, the convective and conductive transmissibilities between two neighboring cells i and j in the x-direction are given by

$$T_{x,ij}^{fX} = T_{x,ij}^f \quad (23)$$

$$G_{x,ij}^{fX} = G_{x,ij}^f \quad (24)$$

where $T_{x,ij}^f$ and $G_{x,ij}^f$ are respectively the fracture convective and conductive transmissibilities between Cells i and j in a standard dual-porosity model. Two neighboring cells in the y-direction are disconnected:

$$T_{y,ij}^{fX} = 0 \quad (25)$$

$$G_{y,ij}^{fX} = 0 \quad (26)$$

In a standard dual-porosity model, the porous volume of a fracture cell i is the sum of the porous volumes of the fractures oriented in the x-direction and the fractures oriented in the y-direction.

The porous volume of the X-fracture medium V_i^{fX} corresponds to those oriented to the x-direction. Let w_{fx} and w_{fy} be the apertures of the fractures in the x- and y-directions, the porous volume of Cell i in the X-fracture medium is given by:

$$V_i^{fX} = \frac{w_{fx}/L_y}{w_{fx}/L_y + w_{fy}/L_x} V_i^f \quad (27)$$

Y-fracture medium

The connection in the Y-fracture medium is a complement to the connection in the X-fracture medium, with respect to a standard dual-porosity model. Two neighboring Cells i and j in the x-direction are disconnected in Y-fracture medium:

$$T_{x,ij}^{fY} = 0 \quad (28)$$

$$G_{x,ij}^{fY} = 0 \quad (29)$$

The convective and conductive transmissibilities between two neighboring cells in the y-direction are given by

$$T_{y,ij}^{fY} = T_{y,ij}^f \quad (30)$$

$$G_{y,ij}^{fY} = G_{y,ij}^f \quad (31)$$

where $T_{y,ij}^f$ and $G_{y,ij}^f$ are the fracture convective transmissibility and conductive transmissibility between i and j in a standard dual-porosity model.

The porous volume of the Y-fracture medium V^{fY} corresponds to the volume of the fractures oriented to the y-direction in a standard dual-porosity model:

$$V_i^{fY} = \frac{w_{fy}/L_x}{w_{fx}/L_y + w_{fy}/L_x} V_i^f \quad (32)$$

Connection between X-fracture and Y-fracture media

The superposed cells between X-fracture and Y-fracture media are also connected. The convective flux between these two cells may be very large due to high permeability, but the conductive flux is small because of low thermal conductivity. The convective flux between these two media is modeled using a very high transmissibility:

$$F_{w,i}^{ff} = \lambda_{w,i}^f T_i^{ff} (P_i^{fX} - P_i^{fY}) \quad (33)$$

and

$$F_{H,i}^{ff} = \lambda_{H,i}^f T_i^{ff} (P_i^{fX} - P_i^{fY}) \quad (34)$$

where the convective transmissibility T_i^{ff} between these two fracture media has a large value. When this value is very large, we have $P_i^{fX} \approx P_i^{fY}$. In the following simulations, we use a transmissibility value 1000 times larger than that in X- or Y-fracture medium.

The conductive flux is calculated by:

$$F_{D,i}^{ff} = \Lambda_i^f C_i^{ff} (\theta_i^{fX} - \theta_i^{fY}) \quad (35),$$

where the coefficient C_i^{ff} is a geometric transmissibility coefficient between the X-fracture and Y-fracture media, Λ_i^f is the fracture conductivity. We present here a simple approach to compute this geometric coefficient. Let C_{bx} and C_{by} be the half block geometric transmissibility coefficient along x- and y-directions around a matrix block, given by (Fig. 5):

$$C_{bx} = \frac{w_{fx}/2}{L_x/4} \quad (36)$$

and

$$C_{by} = \frac{w_{fy}/2}{L_y/4} \quad (37).$$

Here, we consider half fracture aperture around a matrix block, and a quarter of the block size to get an effective distance towards each corner. The transmissibility coefficient C_b around a matrix block between the x- and y-fractures is calculated through the sum of the resistivity:

$$\frac{4}{C_b} = \frac{1}{C_{bx}} + \frac{1}{C_{by}} \quad (38)$$

We have a factor of 4 in the above formula, because this exchange occurs through the 4 corners. So the final geometric coefficient for conductive exchange between the two fracture media is given by:

$$C_i^{ff} = \frac{V_{Gi}}{V_b} C_b \quad (39)$$

with V_b the matrix block volume.

The above formula is just a simple approximation to compute the connections between the two fracture media. It is possible to improve it. As the conductive flow between the two fracture media is generally very low, compared to the possible convective flow between these two media and to the conductive flow between matrix and fractures, a small geometrical transmissibility coefficient allows us to distinguish the temperature between different fracture media.

Connection between matrix and fracture media

The shape factor in a standard dual-porosity model is also split into two parts, one for the exchange with the X-fracture medium and the other for the exchange with the Y-fracture medium.

Several shape factors are available in the literature for the matrix-fracture exchange computation in a dual-porosity model. In general, the shape factor of a cell i can be written in the following form (for a 2-Dimensional matrix-fracture exchange):

$$\sigma = \alpha \left(\frac{1}{L_x^2} + \frac{1}{L_y^2} \right) = \frac{\alpha}{V_b^2} (L_y^2 + L_x^2) \quad (40)$$

where the coefficient α depends on the hypothesis used by the authors. For example, $\alpha = 4$ corresponds to the shape factor of Kazemi *et al.* (1976), and $\alpha = \pi^2$ corresponds to that of Lim & Aziz (1995). The first term of Eq.(40) corresponds to the exchange with fractures parallel to the y-direction, and the second term corresponds to the transfer with fractures parallel to the x-direction. This form implies that the exchange between a matrix block and a fracture is proportional to the square of the contact areas. It is not our objective to discuss the shape factor computation in this work. We will only show how to split the shape factor for matrix-fracture exchange computation in a dual-fracture model.

For the X-fracture medium, the matrix-fracture interaction occurs only on the matrix block boundary parallel to the x-direction (Fig. 6). Similarly, for the Y-fracture medium, the exchange occurs only on the matrix block boundary parallel to the y-direction. Assuming the matrix-fracture exchange is proportional to the squared exchange area in a block, the shape factor associated to the X-fracture medium is therefore given by:

$$\sigma_X = \frac{L_x^2}{L_x^2 + L_y^2} \sigma \quad (41)$$

and the shape factor associated to the Y-fracture medium is:

$$\sigma_Y = \frac{L_y^2}{L_x^2 + L_y^2} \sigma \quad (42).$$

So, the convective exchanges between matrix and X-fracture medium are computed by:

$$Q_{w,i}^{mfX} = \lambda_{w,i} K^m V_{Gi} \sigma_X (P_i^m - P_i^{fX}) \quad (43),$$

and

$$Q_{H,i}^{mfX} = \lambda_{H,i} K^m V_{Gi} \sigma_X (P_i^m - P_i^{fX}) \quad (44)$$

and the conductive exchange is:

$$Q_{D,i}^{mfX} = \lambda_i^m V_{Gi} \sigma_X (\Theta_i^m - \Theta_i^{fX}) \quad (45).$$

Similarly, the exchanges between the matrix and the Y-fracture medium are given by:

$$Q_{w,i}^{mfY} = \lambda_{w,i} K^m V_{Gi} \sigma_Y (P_i^m - P_i^{fY}) \quad (46),$$

$$Q_{H,i}^{mfY} = \lambda_{H,i} K^m V_{Gi} \sigma_Y (P_i^m - P_i^{fY}) \quad (47),$$

and

$$Q_{D,i}^{mfY} = \lambda_i^m V_{Gi} \sigma_Y (\Theta_i^m - \Theta_i^{fY}) \quad (48).$$

In summary, the discretization coefficients between the dual-fracture approach and the standard dual-porosity model have the following relationships:

- For flux in x-direction:

$$T_{x,ij}^{fX} + T_{x,ij}^{fY} = T_{x,ij}^f \quad (T_{x,ij}^{fY} = 0) \quad (49)$$

$$G_{x,ij}^{fX} + G_{x,ij}^{fY} = G_{x,ij}^f \quad (G_{x,ij}^{fY} = 0) \quad (50)$$

- For flux in y-direction:

$$T_{y,ij}^{fX} + T_{y,ij}^{fY} = T_{y,ij}^f \quad (T_{y,ij}^{fX} = 0) \quad (51)$$

$$G_{y,ij}^{fX} + G_{y,ij}^{fY} = G_{y,ij}^f \quad (G_{y,ij}^{fX} = 0) \quad (52)$$

- Porous volume:

$$V_i^{fX} + V_i^{fY} = V_i^f \quad (53)$$

- Shape factor:

$$\sigma_X + \sigma_Y = \sigma \quad (54).$$

As we take a high transmissibility T^f for convective flow simulation between the two fractured media, the fracture pressures on these media are very close ($P_i^{fX} \approx P_i^{fY}$). In case of isothermal simulations ($\Theta^m = \Theta^{fX} = \Theta^{fY}$), the proposed dual-fracture approach is equivalent to the standard dual-porosity model.

Examples

Considering a geothermal domain of $500 \times 500 \times 10$ m. This reservoir is fractured, and the matrix block size is 100 m in the x-direction, and 25 m in the y-direction as shown in Fig. 7. The hydraulic conductivity for fractures in the x-direction is 40 mD·m, and the hydraulic conductivity for fractures in the y-direction is 60 mD·m. The fracture aperture is 1 cm and the fracture permeability is 4 D. The matrix permeability is 0.0001 mD. The initial reservoir temperature is 200 °C, and the initial reservoir pressure is 255 bar. Two configurations are considered: one with a pair of horizontal wells and the other with a pair of vertical wells.

Before performing the flow simulation, we first need to find a convenient shape factor for the matrix-fracture exchange calculation for a matrix block size of 100×25 m. Determining a suitable shape factor allows us to compare between the dual-porosity / dual-fracture model and the standard dual-porosity without bias.

Shape factor determination

Many shape factors are proposed in the literature, and each one has its application range. Here, we perform several numerical simulations to compare the impact of different shape factors on a matrix block with a size of 100x25 m.

The accuracy of a shape factor depends mainly on the size of the matrix block, and is independent of other parameters. So we can perform a comparison of the shape factor accuracy with different parameter values and simulation conditions. Here, we consider an impermeable matrix block. The initial matrix temperature is of 150 °C. A temperature of 100 °C is imposed on the fractures surrounding the matrix block. The reference solution is obtained with a very fine grid discretization and a single-porosity model simulation. Figure 8 shows the average matrix temperature against time using a standard dual-porosity approach with several different shape factors. Comparing with the reference solution, both Kazemi et al.'s (1976) and Lim & Aziz's (1995) shape factors underestimate the exchange on a 100x25 m matrix block. A higher shape factor is required. According to the simulations illustrated in Fig. 8, it seems that using $\alpha = 14.5$ is a compromised suitable choice for this matrix-fracture exchange computation. This shape factor is used in the standard dual-porosity model in the following simulations.

Doublet of horizontal wells

A pair of horizontal wells (one injector and one producer) with a length of 300 m is considered (Fig. 9). A water of 80°C and with a flow rate of 50000 kg/day is injected through the injection well, and a water with a flow rate of 50000 kg/day is produced at the production well. The minimum bottom-hole pressure at the production well is of 50 bar.

The reference solution is obtained using a very fine grid simulation with a single-porosity model. The fractures are explicitly discretized, and small cells are used for the discretization of matrix media in the near-fracture zones (Fig. 9). The dual-porosity model has 20 cells in the x-direction and 20 cells in the y-direction with a cell size of 25x25x10 m. The dual-fracture approach has the same discretization as the standard dual-porosity model.

Figure 10 compares produced water temperature at the production well for the standard dual-porosity model, the dual-porosity / dual-fracture model and the reference solution. The reference solution shows that thermal breakthrough is quite early due to the high hydraulic conductivity in the fractures along the y-direction. However, the standard dual-porosity model (curve "DP" in the figure) shows a very late thermal breakthrough because of the overestimated thermal exchange between matrix and fractures due to the low fracture cell temperature in the standard dual-porosity simulation. At the end of 10000 days, the dual-porosity model still produces hot water with the initial reservoir temperature of 200°C, while produced water temperature of the reference solution drops to 180°C. In fact, with the standard dual-porosity model, the cold water is assumed to move through all the fractures in a fractured cell, and the temperature is dropped to the same value in these fractures. Thus the thermal exchange between

matrix and fractures is overestimated because of a lower fracture temperature. So, the cold water is more heated by the overestimated transfer, and the thermal breakthrough is delayed. We observed that the dual-porosity / dual-fracture model (curve “DP dual-fracture” in the figure) gives a result very similar to the reference solution, because this model can calculate different fracture temperatures according to the fracture orientation to get a more accurate matrix-fracture thermal exchange.

Figure 11 presents the temperature map of the fine grid reference solution at 1000 days, and Figure 12 is the pressure map of the reference solution. The cold water moves forward along the y-fractures quickly, because the exchange areas between a matrix block and y-fractures are relatively small. The temperature in the x-fractures varies very slowly, because of the large exchange area with the matrix block and poor thermal connections between x- and y-fractures. The fracture temperature around a matrix block is very different according to the fracture orientation. However, the pressure front moves quite uniform and the fracture pressure is also uniform around a matrix block, whatever the fracture orientation.

Figure 13 shows the temperature in the fracture cells simulated with the standard dual-porosity model at 1000 days. The temperature front moves slowly towards the production well. In fact, in the fine grid simulation, the matrix-fracture heat exchange with the fractures in the y-direction is small, due to small contact area with a matrix block. The matrix cannot supply sufficient energy to heat the moving cold water. While in the standard dual-porosity model, the matrix-fracture exchange occurs uniformly through all the fractures surrounding the matrix block. The exchange with x-fractures is more important than that with y-fractures, because the contact area is larger with x-fractures. In other words, the dual-porosity model highly overestimated the matrix-fracture heat exchange in this example. So the cold water front cannot move forward very quickly.

Figure 14 presents the fracture temperature maps simulated with the dual-fracture model at 1000 days. Figure 14a is the temperature in the X-fracture medium, and Figure 14b is the temperature in the Y-fracture medium. The temperatures in these two media are quite different. In the X-fracture medium, which represents the fractures oriented in the x-direction, the temperature front moves slowly towards the producer. This result is similar to the temperature in x-fractures in the reference solution. In the Y-fracture medium, which represents the fractures oriented in the y-direction, the temperature front moves quickly, which is also similar the temperature in the y-fractures in the reference solution. This is because we consider separately the matrix exchange with x-fractures and y-fractures in the dual-fracture model. So the produced water temperature can be more accurately predicted. Figure 15 is the fracture pressure maps of the dual-fracture model at 1000 days. As expected, the pressures in these two fracture media are almost identical.

Figure 16 compares the average temperature in four matrix zones of 100x100x10 m located near the corner (Fig. 16a). In all the zones, the simulation results with the dual-porosity / dual-fracture model are very similar to the reference solution, and are much better than those from the standard dual-porosity model. In Zone 1, which is very close to the injection well, cold water enters into this zone very quickly. The standard dual-porosity model gives an

overestimated matrix-fracture thermal exchange, and this overestimated heat exchange makes the temperature in this matrix zone drops quickly. A similar analysis can be applied to Zone 2, which is also close to the injection well. For Zone 3, which is very close to the production well, the cold water arrives late with the standard dual-porosity model, because the water is overheated on its way by the overestimated matrix-fracture thermal transfer. So the temperature drop is delayed in the matrix Zone 3 by the standard dual-porosity simulation. This analysis is also suitable for Zone 4, which is far from the injector. The dual-porosity and dual-fracture model can handle conveniently the fracture temperature simulation and the matrix-fracture thermal exchange computation.

Now we perform a dual-porosity simulation using a coarser grid with 5 cells in the x-direction and 5 cells in the y-direction. The cell size is of 100x100x10 m. Figure 17 compares the produced water temperature simulated by 5x5 cells with the reference solution as well as with the dual-porosity simulation of 20x20 cells. Again, the dual-porosity and dual-fracture model using a coarser grid with 5x5 cells improves the standard dual-porosity simulation. As the wells are modeled as sink/source on the grid cells, the distance between the doublet in the numerical model is shortened by using the coarser grid with 5x5 cells. This reduces globally the thermal breakthrough time. So the produced water temperature simulated by the standard dual-porosity model with 5x5 cells seems better than that of the standard dual-porosity model with 20x20 wells. But for the dual-porosity and dual-fracture simulations, using 20x20 cells is still better than using 5x5 cells.

Doublet of vertical wells

Now we consider a pair of vertical wells located at the diagonal corners. Figure 18 shows the temperature map of the reference simulation at 1000 days. The fracture temperature around a matrix block is again not uniformly distributed. We found two directions in which the cold water moves, one along x-fractures and one along y-fractures. The cold water moves faster along y-fractures than along x-fractures, because the exchange area of a matrix block with y-fractures is smaller than that with x-fractures and less heat is supplied to the y-fractures. Figure 19 presents the fracture temperature map with the standard dual-porosity model simulation. The cold water is concentrated near the injection well, and the temperature front moves very slowly in the y-direction. The standard dual-porosity model cannot simulate correctly the global temperature distribution along the fractures. Figure 20 presents the fracture temperature obtained with the dual-porosity / dual-fracture model. The temperatures in both x- and y-fractures seem correctly simulated with the dual-fracture model, and the cold water moves rapidly in the Y-fracture medium.

Figure 21 compares the produced water temperature for these three simulations. The dual-porosity / dual-fracture model gives better result than the standard dual-porosity model. The temperature decrease with the dual-fracture simulation at early time might relate to the inaccuracy of the matrix-fracture exchange in a single matrix block as illustrated in Fig. 8. We cannot find a perfect shape factor for matrix-fracture exchange simulation, even if the fracture temperature is uniformly distributed around the matrix block. The shape factor used in this

simulation underestimates the matrix-fracture exchange in early time (Fig. 8). To improve further the accuracy of matrix-fracture transfer computation, application of MINC method can be useful.

Figure 22 presents the average temperature variation at the four zones near the corner. In all the zones, the dual-porosity / dual-fracture model improves the standard dual-porosity model simulations.

Conclusion

A dual-porosity and dual-fracture approach is proposed for geothermal reservoir simulations. In this approach, the fracture medium of a dual-porosity model is split into two sets of fractures: one for the transport in the x-direction, and the other for the transport in the y-direction. These two sets of fractures are hydraulically connected without barrier using very high transmissibilities, but they are thermally poorly connected due to low thermal conductivity. In the discretization grid, each grid cell has three superposed cells: one matrix cell and two fracture cells. These two fracture cells have near-identical pressures, but may have very different temperature. This approach is suitable for the simulation of thermal problem in fractured reservoirs. A commonly-used dual-porosity may overestimate the matrix-fracture heat exchange in the geothermal context. The proposed new approach can simulate much more accurately the heat exchange compared to a standard dual-porosity model. It can be considered as an extension of the dual-porosity model to non-isothermal modeling, and is particularly adapted to geothermal reservoir simulations.

The proposed dual-porosity and dual-fracture approach improves the matrix-fracture exchange modeling by considering more realistic fracture temperatures. The heat flow inside a matrix block is still based on shape factors using a pseudo-steady-state approach. It is expected that the transient flow behavior inside the matrix block can further be improved by using the MINC approach. Combining the dual-fracture model and the MINC method is our ongoing work.

Nomenclature

C	= <i>geometric transmissibility coefficient</i>
d	= <i>distance, L</i>
F	= <i>flux, MT^{-1}</i>
G	= <i>conductive transmissibility, $ML^2T^{-3}\Theta^{-1}$</i>
g	= <i>gravitational acceleration, LT^{-2}</i>
H	= <i>enthalpy, ML^2T^{-2}</i>
K	= <i>permeability, L^2</i>
L_x	= <i>matrix block dimension in x-direction, L</i>

L_y	= matrix block dimension in y-direction, L
P	= pressure, $ML^{-1}T^{-2}$
q_w	= source/sink term of water, MT^{-1}
q_E	= source/sink term of energy, ML^2T^{-3}
Q	= matrix-fracture exchange, MT^{-1}
S	= surface area, L^2
t	= time, T
T	= convective transmissibility, L^3
U	= internal energy, ML^2T^{-2}
$\vec{v}$	= velocity, LT^{-1}
V	= volume, L^3
V_G	= bulk volume, L^3
w	= fracture aperture, L
α	= shape factor coefficient (Eq.(39))
ϕ	= porosity
ρ	= density, ML^{-3}
μ	= viscosity, $ML^{-1}T^{-1}$
λ	= water mobility, $L^{-2}T$
λ_E	= defined by Eq.(13), MT^{-1}
σ	= shape factor, L^{-2}
Θ	= temperature, Θ
Λ	= thermal conductivity, $MLT^{-3}\Theta^{-1}$
Ω	= set of direct neighbours

Superscript

D	= diffusive or conductive exchange
f	= fracture
ff	= exchange between X-fracture and Y-fracture media
fX	= X-fracture
fY	= Y-fracture
H	= convective exchange
m	= matrix
mf	= matrix-fracture exchange

Subscript

b	= matrix block
E	= energy
i	= cell index
j	= cell index
r	= rock
w	= water
x	= x direction
y	= y direction
z	= z direction
X	= X-fracture medium
Y	= Y-fracture medium

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