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Scaling of two-phase water-steam relative permeability and thermal fluxes in porous media



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ARTICLE INFO

Article history: Received 30 October 2019 Revised 16 February 2020 Accepted 29 February 2020 Available online 23 March 2020

Keywords: Two-phase flow Porous media Relative permeability Water and steam Geothermal Mass and energy fluxes

ABSTRACT

Two-phase water-steam flow conditions are frequently encountered in many engineering applications, including geothermal reservoirs. Although routine calculations are based on the multiphase Darcy's law, the role of the topology of the flowing phases at the pore-scale is usually neglected in the estimation of relative permeabilities. Instead, the latter are frequently computed using empirical models like the Corey correlation. In this work, we first apply the model for relative permeabilities based on pore-scale flow regimes developed by Picchi and Battiato (2019), Relative permeability scaling from pore-scale flow regimes, Water Resour. Res. 55, 3215-3233, to scenarios typical of geothermal reservoirs and then extend it by deriving the scaling laws for the transmissibilities and the thermal properties as a function of temperature. First, we discuss the scaling behavior of normalized relative permeabilities in terms of viscosity ratio and capillary number of water-steam systems and, then, we provide a validation of the model against experimental data available in the literature. The model captures well the data trends collected in real 3D porous media. These results suggest that water-steam relative permeabilities follow the same scaling behavior of gas-liquid systems where the non-wetting phase is much less viscous than the wetting phase. Finally, we investigate the impact that relative permeabilities have on heat transfer rates at twophase flow conditions and the scaling of mass and energy transmissibility and thermal properties of the mixture. An estimation of the exergy carried by the two-phase water-steam mixture is also included.

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1. Introduction

A geothermal reservoir is a large-scale convective system where hot water migrates through permeable rocks from a deep and high-temperature zone to a cooler region near the earth surface. The natural recirculation of water is sustained by buoyancy effects that are generated by gradients in temperature and pressure. In this context, water may experience phase-change and lead to two-phase flow conditions (see e.g., Woods, 1999; Grant and Bixley, 2011; Horne, 2016). For example, boiling can occur when the colder and denser water is heated up in proximity of a magma intrusion. Alternatively, steam can form near production wells as a result of flashing due to the local drop in pressure when hot fluid is extracted from the reservoir. The onset of biphasic flow conditions can affect the production of hot steam, and, consequently, reliable forecasting tools should be able to model these processes across scales.

https://doi.org/10.1016/j.ijmultiphaseflow.2020.103257 0301-9322/© 2020 Elsevier Ltd. All rights reserved.

Due to their reduced computational burden, upscaled models are routinely used to describe the transport of mass, momentum, and energy in geothermal reservoirs both in single and twophase flow conditions (see e.g., Brownell Jr. et al., 1977; Faust and Mercer, 1979; Sorey et al., 1980; Tsypkin and Woods, 2004). In such models, the momentum fluxes at the continuum scale are estimated with Darcy's law (Leverett, 1941; Bear, 1972; Auriault, 1987; Whitaker, 1986) and the pore-scale physics is taken into account through the concept of relative permeability. Although thermal effective properties are strongly affected by relative permeability estimates (Bodvarsson et al., 1980; O'Sullivan, 1981), the latter are still evaluated with empirical models like the Corey (1954), the Brooks and Corey (1964), and the Chierici (1984) correlations. Such correlations require experimental data to fit the model exponents, i.e. to empirically identify the scaling relations between relative permeability and saturation. Despite the considerable amount of relative permeability data available in the literature (see e.g., Arihara et al., 1976; Counsil and Ramey, 1979; Verma, 1986; Sanchez and Schechter, 1990; Closmann and Vinegar, 1993; Piquemal, 1994; Ambusso et al., 1996; Satik, 1998; Mahiya, 1999; Gudjonsdottir et al., 2015b), currently there is

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Fig. 1. Sketch of flow regimes in a realistic geometry and their idealization in the framework of the capillary tube analogy. Water (wetting phase depicted in light blue) and steam (the non-wetting phase depicted in white) are referred in the text with the subscript *w* and *s*, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

no physics-based scaling generally applicable to water-steam systems.

Recent advances in X-ray microtomography and highperformance computing have led to the direct visualization of the distribution of the flowing phases at the pore-scale and revealed that the non-wetting phase can become disconnected or even remain immobilized (trapped) in the porous matrix (see e.g., Prodanovic et al., 2007; Blunt et al., 2013; Berg et al., 2013; Armstrong et al., 2012; 2014; Reynolds et al., 2017; Gao et al., 2017; Garing et al., 2017; Tahmasebi et al., 2017; Gao et al., 2020; Liu et al., 2019). Four possible pore-scale flow regimes have been identified by Avraam and Payatakes (1995): largeganglion dynamics, small-ganglion dynamics, drop-traffic flow and connected-pathway flow. In large and small ganglion dynamics, the non-wetting phase flows intermittently in the form of individual ganglia. Instead, in the connected pathway regime, both phases flow through separate and uninterrupted pathways. The classification of the flow regimes is usually based on the order of magnitude of the capillary number, $Ca = \mu_{\ell} U / \sigma$, defined as the ratio of viscous forces (μ_{ℓ}) is the dynamic viscosity of the wetting phase and *U* is a characteristic scale for the velocity) and surface tension, σ . Following the classification proposed by Armstrong et al. (2016) and Picchi and Battiato (2019), when the capillary number is lower than $\mathcal{O}(Ca) \approx 10^{-6}$, the flow is dominated by capillary phenomena and the dominant flow regime is the quasi-static connected pathway. In this regime, each phase advances mainly through preferential paths and wets the solid walls. At intermediate capillary numbers, a progressive mobilization of the non-wetting phase occurs through the onset of small and large ganglia, i.e., disconnected domains of non-wetting phase that are surrounded by a film of the wetting phase and flow intermittently. At capillary numbers of order $O(Ca) \approx 1$, viscous forces stabilize topological characteristics of the flowing phases leading to coalescence phenomena and the formation of very long ganglia. A sketch of the transition is given in Fig. 1(left). It is widely accepted that neglecting such topological features in the calculation of effective parameters (e.g., the relative permeability) is one of the

main deficiencies of macroscale models (Avraam and Payatakes, 1995; Datta et al., 2014; Rucker et al., 2015; Armstrong et al., 2016; Schluter et al., 2016). Yet, to the best of our knowledge, a theoretical framework that includes the impact of the topology of the flowing phases on effective properties of water-steam systems is still not available.

A number of models have been proposed throughout the years to account for fluid-fluid interface evolution in porous media (Hassanizadeh and Gray, 1990; Niessner and Hassanizadeh, 2008; Gray et al., 2015; Rybak et al., 2015; McClure et al., 2016; Schluter et al., 2016; Kjelstrup et al., 2018). Yet, the majority of such approaches, based on upscaling of the Navier-Stokes equations in multiphase fluid-fluid systems, have introduced additional complexity in the definition of state variables and in the formulation of macroscale evolution equations. Alternatively, more practical and *ad hoc* formulations of relative permeabilities have been proposed by Dehghanpour et al. (2011), Clavier et al. (2017) and Pasquier et al. (2017). Standnes et al. (2017) developed a relative permeability model based on mixture theory that embeds the role of the viscosity ratio between the fluids and is applicable also to counter-current flows. More recently, Picchi and Battiato (2018, 2019) have developed a new homogenization framework that allows one to derive upscaled equations that are regime-specific, yet practical, i.e. they still have the form of a multiphase Darcy's law. The main idea is to reduce the problem complexity by proposing an analogy between flow regimes in real porous media and in a capillary tube, while allowing for the coexistence of different flow regimes at intermediate capillary numbers. A visual schematization of the proposed analogy is shown in Fig. 1. By means of onedimensional closures (Ullmann and Brauner, 2004; Picchi et al., 2018), effective parameters in the macroscopic equations are determined for different pore-scale flow regimes. In the Darcy's limit, i.e., when inertial effects are negligible and the average velocity of the two fluids is linear with respect to the pressure gradient, expressions of the relative permeability have been obtained analytically together with the permeability scaling in terms of the mobile saturation, the viscosity ratio, and the capillary number. Although such a model has been validated with published data ranging from, e.g., brine- CO_2 to oil-water systems, the question of whether it can be applied to geothermal flows remains still open.

In this paper, we test the model proposed by Picchi and Battiato (2019) to two-phase water-steam flow in porous media and provide new insights on the modeling of relative permeabilities in the context of geothermal reservoirs. Differently from empirical correlation models, e.g. Brooks and Corey expressions, the model proposed by Picchi and Battiato (2019) rigorously derives from upscaling and physical arguments the scaling relationship (i.e. the scaling exponent) between nondimensional permeabilities and saturation for different capillary numbers and viscosity ratios. First, we classify water-steam systems based on their viscosity and density ratios which depend on the working temperature and pressure. Then, we identify a scaling law between relative permeabilities and saturation and provide a validation against experimental measurements available in the literature. We also discuss the impact that relative permeabilities have on transport rates at two-phase flow conditions: the interpretation of field data (Gudjonsdottir et al., 2015a), geothermal reservoir simulations (Ijeje et al., 2019) and the analysis of performance of geothermal fields (Koroneos et al., 2017) rely on the calculation of mass and energy fluxes in the reservoir. We include the estimation of the exergy carried by the geothermal fluid (i.e., the maximal theoretical work obtainable from the flow) which, to the best of our knowledge, has been computed just for the case of pure geothermal fluids (Phuoc et al., 2018) and has not been generalized to the case of water flowing in a biphasic state through a porous medium. An accurate computation of the exergy fluxes has also direct implications in the identification of inefficiencies in the utilization level of geothermal reservoirs. We conclude by summarizing the main results of our study.

2. Theoretical considerations

In this Section, we first discuss the applicability of the relative permeability model of Picchi and Battiato (2019) to biphasic watersteam systems (Section 2.1), and, then, we compute both mass and energy fluxes (Sections 2.2 and 2.3) as well as the system exergy (Section 2.4).

2.1. Relative permeability model based on pore-scale flow regimes

The momentum transfer between (liquid) water and steam (vapor) flowing in a porous medium can be described by the macroscale equations

$$\left\langle \hat{\mathbf{u}}_{\ell} \right\rangle = -\frac{\hat{\kappa}k_{\ell}}{\mu_{\ell}} \nabla \hat{p}_{l}, \qquad \left\langle \hat{\mathbf{u}}_{\nu} \right\rangle = -\frac{\hat{\kappa}k_{\nu}}{\mu_{\nu}} \nabla \hat{p}_{\nu}, \tag{1}$$

when the following conditions are satisfied:

- water is in a biphasic state, i.e., liquid and vapor exist as separate phases;
- at a prescribed boiling temperature (and pressure) and a fixed saturation (i.e., steam quality), water and steam are conceptualized as two immiscible and incompressible phases;
- liquid water is the wetting phase and steam is the non-wetting phase;
- the Bond and Reynolds numbers are small at the pore scale enough to neglect inertial and gravitational effects. These conditions are often satisfied in real rocks where the characteristic length scale of the pores is sufficiently small to consider Stoke's flow at microgravity conditions.
- both phases are subjected to the same driving force and the average velocity is linear with the pressure gradient (this assumption is known as Darcy's limit and the conditions for which this simplification holds are discussed in detail Picchi and Battiato (2018)).

In Eq. (1), $\langle \hat{\mathbf{u}}_{\ell} \rangle [m/s]$, $\langle \hat{\mathbf{u}}_{\nu} \rangle [m/s]$, \hat{p}_{ℓ} [*Pa*], \hat{p}_{ν} [*Pa*], k_{ℓ} [-] and k_{ν} [-] are the average velocity, pressure, and relative permeabilities of water and steam, respectively; $\hat{\kappa}$ [m^2] is the absolute permeability of the medium. The viscosities μ_{ℓ} and μ_{ν} are the dynamic viscosity of water in the saturated liquid and vapor states, respectively, while the hats denote dimensional variables. The operator $\langle \cdot \rangle$ is the average over a representative elementary volume and time interval. Such representative volume, also called unit cell, is a spatial domain that is sufficiently large to contain a great number of pores so that we can define a mean global property but sufficiently small that the parameter variations from one domain to the next may be approximated by continuous functions (De Ghislain, 1986).

Equation (1) is a continuum representation of the flow at the macroscale that is representative of pore-scale physics. The underlying assumption is that one can define two distinct spatial scales l and L at the pore- and macroscale, respectively, such that $l \ll L$. Specifically, the pore-scale refers to millimeter and sub-millimeter spatial scales while the macro-scale, also defined as Darcy's scale, refers to spatial scales in the order of centimeters. Let U be a representative velocity at the macroscale scale. We introduce the dimensionless variables

$$\langle \mathbf{u}_{\ell} \rangle = \frac{\langle \widehat{\mathbf{u}}_{\ell} \rangle}{U}, \quad \langle \mathbf{u}_{\nu} \rangle = \frac{\langle \widehat{\mathbf{u}}_{\nu} \rangle}{U}, \quad p_{\ell} = \frac{\hat{p}_{\ell} l^2}{\mu_{\ell} U L}, \quad p_{\nu} = \frac{\hat{p}_{\nu} l^2}{\mu_{\ell} U L}, \quad (2)$$

and recast Eq. (1) in dimensionless form as

$$\langle \mathbf{u}_{\ell} \rangle = -\kappa k_{\ell} \nabla p_{\ell}, \qquad \langle \mathbf{u}_{\nu} \rangle = -\frac{\kappa k_{\nu}}{M} \nabla p_{\nu},$$
(3)

where $\kappa = \hat{\kappa}/L^2$ is the normalized absolute permeability (i.e., $\kappa = 1/32$ for a capillary tube (Picchi and Battiato, 2018), and *M* is the viscosity ratio defined as

$$M = \frac{\mu_{\nu}}{\mu_{\ell}}.$$
 (4)

The relative permeabilities, k_{ℓ} and k_{ν} , depend on the spatial distribution of the flowing phases at the pore-scale, the wetting phase saturation, S_{ℓ} , and, as outlined by Picchi and Battiato (2019), they should capture the transition between the flow regimes depending on the order of magnitude of the capillary number. In fact, as shown in Fig. 1(left), in the capillary limit, the flow is dominated by quasi-static connected pathway flow (i.e., phases flow through separated and uninterrupted pathways) while, in the viscous limit, coalescence phenomena lead to the formation of very long ganglia. To embed these features into the model, Picchi and Battiato (2019) proposed an analogy between flow in complex geometries, Fig. 1(left), to flow in the capillary tube setting, Fig. 1(right). The analogy is based on the assumption that the most relevant features of the momentum transfer between phases can be captured at the leading order by their interactions in a simplified setting (i.e., the capillary bundle for the capillary limit and core-annular flow for the viscous limit). For example, the analogy with core-annular flow mimics the key role of the wetting film in the viscous limit. We then define the normalized relative permeabilities as follows

$$k_{\ell}^* = \frac{k_{\ell}}{\beta_{\ell}}, \qquad k_{\nu}^* = \frac{k_{\nu}}{\beta_{\nu}}, \tag{5}$$

where, β_{ℓ} and β_{ν} are the endpoint relative permeabilities of the liquid (wetting phase) and vapor (non-wetting phase). Specifically, β_{ℓ} is the relative permeability of the liquid evaluated at the saturation $S_{\ell} = 1 - S_{or}$, with S_{or} the residual saturation of the non-wetting phase; β_{ν} is the relative permeability of the vapor evaluated at the saturation $S_{\ell} = S_{ir}$, with S_{ir} the irreducible saturation of the wetting phase. The permeability-saturation relationships have the following form (Picchi and Battiato, 2019)

$$k_{\ell}^* = S_*^2, \tag{6a}$$

$$k_{\nu}^{*} = (1 - S_{*})^{2} \left(1 + \frac{2S_{*}}{1 - S_{*}} M \alpha \right),$$
(6b)

where *S*^{*} is the mobile liquid saturation,

$$S_* = \frac{S_{\ell} - S_{ir}}{1 - S_{or} - S_{ir}}.$$
(7)

and $S_* \in [0, 1]$. Following this normalization, $k_{\ell}^*(1) = 1$ and $k_{\nu}^*(0) = 1$ 1.Equation (6b) accounts for pore-scale flow regimes through the flow-regime parameter α , which controls the transition from the capillary (when $\alpha = 0$) to the viscous (when $\alpha = 1$) limit at the Darcy scale, with $0 \le \alpha \le 1$. The only three fitting parameters of the model are $(\beta_{\ell}, \beta_{\nu}, \alpha)$. It is worth emphasizing that the validation with experimental data in Picchi and Battiato (2019) suggests that α depends linearly with the logarithm of the capillary number. Specifically, a universal relation of the type

$$\alpha = C_1 \log Ca + C_2, \qquad 10^{-b} < Ca < 1, \tag{8}$$

can be identified for a specific type of rock; Eq. 8 with $C_1 = 0.13$ and $C_2 = 0.91$ holds for the set-up of Armstrong et al. (2016).

Based on Eq. (6), three classes can be identified:

• Class I: if $M \ll 1$, $\mu_{\nu} \ll \mu_{\ell}$, i.e., the non-wetting phase is much less viscous than the wetting phase, the effect of the flowregime parameter α is negligible, and both the relative permeabilities scale with the square of the mobile saturation

$$k_{\ell}^* = S_*^2 \qquad k_{\nu}^* = (1 - S_*)^2;$$
 (9)

- Class II: if $\mathcal{O}(M) = 1$ and the flow is in the capillary regime (i.e. $\alpha = 0$), both the relative permeabilities scale with the square of the mobile saturation as in Eq. (9);
- Class III: if $\mathcal{O}(M) = 1$ at intermediate and high capillary number, the effect of pore-scale flow regimes cannot be neglected and Eq. (6b) holds.

The normalized relative permeability ratio, k_{ν}^*/k_{ℓ}^* , is therefore dependent on the Class the flow belongs to. Specifically,

$$\frac{k_{\nu}^{*}}{k_{\ell}^{*}} \sim \left(\frac{1-S_{*}}{S_{*}}\right)^{2} \quad \text{for Classes I and II}$$
(10)

$$\frac{k_{\nu}^*}{k_{\ell}^*} \sim \left(\frac{1-S_*}{S_*}\right)^2 \left(1 + \frac{2S_*}{1-S_*}M\alpha\right) \quad \text{for Class III.}$$
(11)

In Section 3, we will validate the aforementioned model against experimental measurements of relative permeabilities of watersteam systems in the geothermal context.

2.2. Mass transmissibility of the water-steam mixture

Numerical simulations in geothermal reservoirs are conducted solving conservation laws for the water-steam mixture. Such equations are in the form of partial differential equations that require a model for the mass and energy fluxes, see for example the formulation by O'Sullivan (1981). Here, we provide expressions for such fluxes as a function of the relative permeabilities and the thermal properties of water and steam. Furthermore, we show that the scaling behavior of both relative permeabilities and thermal properties has a large impact on mass and energy transport rates, and, therefore, it cannot be neglected in reservoir simulations.

The dimensional mass flux \hat{Q}_m of a two-phase mixture, (O'Sullivan, 1981), is

$$\hat{Q}_{m} = \hat{Q}_{\ell} + \hat{Q}_{\nu} = -\left[\rho_{\ell} \langle \hat{\mathbf{u}}_{\ell} \rangle + \rho_{\nu} \langle \hat{\mathbf{u}}_{\nu} \rangle\right],\tag{12}$$

where \hat{Q}_m is a flux per unit of area. If $\rho_\ell U$ is the scale of the mass flux, then Eq. (12) can be written in dimensionless form as

$$Q_m = -\langle \overline{\mathbf{u}}_\ell \rangle - R \langle \overline{\mathbf{u}}_\nu \rangle, \tag{13}$$

where Q_m is the dimensionless flux per unit area and R is the density ratio, defined as

$$R = \frac{\rho_v}{\rho_\ell},\tag{14}$$

with ρ_{ℓ} and ρ_{γ} the density of water in the saturated liquid and vapor states, respectively. Combining Eq. (13) with Eqs. (1) and (5), we obtain

$$Q_m = -\mathcal{T}_m \nabla p, \tag{15}$$
 with

$$\mathcal{T}_{m} = \kappa \beta_{\ell} k_{\ell}^{*} \left[1 + \beta^{*} \left(\frac{R}{M} \right) \left(\frac{k_{\nu}^{*}}{k_{\ell}^{*}} \right) \right]$$
(16)

the dimensionless mass transmissibility and

$$\beta^* = \frac{\beta_\nu}{\beta_\ell} \tag{17}$$

the ratio of the endpoint relative permeabilities. Mass transmissibility depends, a priori, on temperature through R and M, and on flow regimes through the dimensionless relative permeability ratio k_{ν}^{*}/k_{ℓ}^{*} , as shown in Eqs. (10) and (11).

2.3. Energy and entropy transmissibility of the water-steam mixture

The energy flux \hat{Q}_e of the mixture is given by

$$\hat{Q}_{e} = h_{\ell}\hat{Q}_{\ell} + h_{\nu}\hat{Q}_{\nu}, \tag{18}$$

where h_{ℓ} and h_{ν} are the enthalpy of water in the saturated liquid and vapor states, respectively. We define the dimensionless energy flux $Q_e = \hat{Q}_e / \rho_\ell U h_\ell$, and using Eq. (12), we obtain

$$Q_e = -\langle \mathbf{u}_\ell \rangle - HR \langle \mathbf{u}_\nu \rangle, \tag{19}$$

$$H = \frac{h_v}{h_\ell}.$$
 (20)

Combining (19) with (1), we obtain

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$$Q_e = -\mathcal{T}_e \nabla p, \tag{21}$$
 where

$$\mathcal{T}_{e} = \kappa \beta_{\ell} k_{\ell}^{*} \left[1 + H \beta^{*} \left(\frac{R}{M} \right) \left(\frac{k_{\nu}^{*}}{k_{\ell}^{*}} \right) \right]$$
(22)

is the energy transmissibility. The latter can also be expressed in terms of the flowing enthalpy of the mixture, h_m , as follows

$$\mathcal{T}_e = h_m \mathcal{T}_m,\tag{23}$$

with

where

$$h_{m} = \frac{1 + H\beta^{*} \frac{K}{M} \frac{k_{\nu}}{k_{\ell}^{*}}}{1 + \beta^{*} \frac{R}{M} \frac{k_{\nu}}{k_{\ell}^{*}}}.$$
(24)

An analogous expression can be derived for the entropy transmissibility T_s :

$$\mathcal{T}_s = s_m \mathcal{T}_m,\tag{25}$$

where

$$s_{m} = \frac{1 + S\beta^{*}\frac{K}{M}\frac{k_{\nu}^{*}}{k_{\ell}^{*}}}{1 + \beta^{*}\frac{R}{M}\frac{k_{\nu}^{*}}{k_{\ell}^{*}}},$$
(26)

is the flowing entropy of the mixture and

$$S = \frac{s_{\nu}}{s_{\ell}} \tag{27}$$

is the ratio of the entropy of water in the saturated liquid and vapor states, s_{ℓ} and s_{ν} , respectively. The energy and entropy transmissibilities depend on temperature through R, M, H, and S, and on flow regimes through the k_{ν}^*/k_{ℓ}^* ratio.



Fig. 2. Schematic of a porous medium A at a steady state with bulk flow interaction (injection of water and steam, \hat{Q}_m), heat interaction with the environmental reservoir and work interaction with a cyclic ideal machine X. The work produced by X is the exergy \dot{W}_{max} .

2.4. Exergy

To the best of our knowledge, a formulation for the exergy in terms of the effective properties of a permeable rock (e.g., the relative permeability) has not been proposed yet for water and steam. In the following, we compute the exergy associated with mass flux of water at two-phase flow conditions in a porous medium at steady-state.

We consider water and steam flows, \hat{Q}_{ℓ} and \hat{Q}_{ν} , through a porous system at steady state. The total mass flux at the inlet and outlet is \hat{Q}_m . The system exchanges heat with a reservoir *R* at temperature T_0 through an ideal cyclic machine *X*. The work produced by the ideal machine is \dot{W}_{max} . A schematics is provided in Fig. 2. Following the definition of Gyftopoulos and Beretta (2005), exergy is the maximum work that can be obtained by the system as a result of its interaction with the environment (reservoir) at temperature T_0 , i.e. exergy quantifies the maximum work that can be obtained from the flow of water at two-phase flow conditions in a porous medium. It is defined as

$$\dot{W}_{\max} = \hat{Q}_m A \Big[\hat{h}_m - \hat{h}_0 - T_0 \big(\hat{s}_m - \hat{s}_0 \big) \Big],$$
(28)

where \hat{Q}_m is the mass flux in dimensional form, \hat{h}_0 and \hat{s}_0 are the enthalpy and the entropy of the environmental reservoir, and

$$h_m = h_\ell h_m \quad \text{and} \quad \hat{s}_m = s_\ell s_m \tag{29}$$

are the dimensional flowing enthalpy and entropy with h_m and s_m defined by Eqs. (24) and (26), respectively.

3. Results and discussion

In this Section, we discuss the scaling of both relative permeability and thermal fluxes in two-phase water-steam systems. First, we classify the systems depending on the viscosity and density ratios (Section 3.1), and, then, we validate the model given by Eqs. (6a) and (6b) with water-steam relative permeability measurements collected from the literature (Section 3.2). Finally, we discuss the impact of relative permeabilities on both thermal fluxes (Sections 3.3 and 3.4) and the exergy carried by the flow (Section 3.5).

3.1. Remarks on two-phase flow conditions in a geothermal reservoir

Before proceeding with the model validation against experimental data, we briefly discuss which of the scaling described in Section 2.1 applies to geothermal systems. We restrict our analysis to biphasic states between the triple point (0.01 °C, 611.2 Pa) and the critical point (374 °C, 22.06 MPa). For any given temperature, water properties are known (Gyftopoulos and Beretta, 2005), and tabulated (Acree and Chickos, 2019). Using the Acree and Chickos (2019) database, we compute the viscosity and density ratios, Eqs. (4) and (14), for the whole range of boiling temperatures and pressures, see Figures 3(b).

Field data (Horne, 2016) indicate that temperatures in geothermal reservoirs are typically lower than the critical point, $T < 300^{\circ}$ C. In this range, both $M \ll 1$ and $R \ll 1$, i.e. a steamwater system behaves effectively like a gas-liquid system where the non-wetting phase is much lighter and less viscous than the wetting phase. As a consequence, the scaling behavior relevant to two-phase water-steam conditions is that of Class I. As such, we expect that the relative permeabilities, once normalized, will scale as the square of the mobile saturation and will not depend on the capillary number. Specifically, since $M \ll 1$, the effect of pore-scale flow regimes on Eq. (6) is negligible. Yet, one should expect a shift in the relative permeability scaling from Class I to Class III just in proximity of the critical point, where the density and viscosity ratios are of order one.

3.2. Validation with experimental data

Here, we compare model predictions from Equations (6a) and (6b) with water-steam relative permeability measurements collected at reservoir conditions by Verma (1986), Sanchez and Schechter (1990), Piquemal (1994), Satik (1998), and Mahiya (1999) following the procedure described in Appendix A. The overall dataset includes 140 experiments for which information about working temperature and experimental conditions are available, see Table 1. This knowledge is necessary to compute the viscosity and density ratio, and to determine the capillary number defined as

$$Ca = \frac{q_{\ell}\mu_{\ell}}{A\sigma},\tag{30}$$

where q_{ℓ} , A, and σ are the water flow rate, the cross-section area of the core sample, and the surface tension, respectively. It is worth emphasizing that surface tension depends on temperature (Vargaftik et al., 1983). Since the temperature of all the experiments mentioned above is considerably lower than the critical one, $M \ll 1$, as demonstrated in Fig. 4. Furthermore, all the experiments are in the capillary regime, i.e. the capillary number is very small with $\mathcal{O}(Ca) < \mathcal{O}(10^{-7})$ for the data of Verma (1986), Sanchez and Schechter (1990), Satik (1998) and Mahiya (1999), while $\mathcal{O}(Ca) \approx \mathcal{O}(10^{-5})$ for the data of Piquemal (1994). Following the classification given in Section 2.1, the experimental datasets belong to Class I.

Fig. 5 shows that the data collapse around the model predictions for the whole range of saturation both in linear and logarithmic scales and that Eq. (9) correctly captures the relative permeability trend at different temperatures. Importantly, once the relative permeabilities have been normalized, they scale as the square of the mobile saturation. Unlike the Brooks and Corey (1964) correlation where also the exponents are fitted to the data, the only fitting parameters in the proposed model are the endpoint relative permeabilities (see detailed procedure in Appendix A). Table 1 contains the full set of model parameters as well as the coefficient of determination for β_{ℓ} and β_{ν} .

The results in Fig. 5 suggest that steam-water relative permeabilities follow the same scaling of Class I and the effect of porescale flow regimes is negligible since $Ca \ll 1$ (see Fig. 4 and $\alpha = 0$) or $M \ll 1$. This behavior is typical of immiscible systems where the non-wetting phase is much less viscous than the wetting phase (see Picchi and Battiato (2019) where an extensive val-



Fig. 3. (a) The saturation dome of water in the temperature-entropy (T - s) plane. An isobar and the state of saturated liquid, s_{ℓ} , and saturated vapor, s_{ν} , are also plotted. (b) Viscosity ratio and density ratio as a function of the boiling temperature.

Table 1

Experiments and parameters in Equation (6) used for model validation. The coefficients of determination R^2 for the three fitting parameters (β_{ℓ} , β_{ν} , and α) are also computed.

	T (°C)	М	R.1000	Са	S _{ir}	Sor	eta_ℓ	β_{v}	$R^2_{eta_\ell}$	$R^2_{\beta_v}$	β^*
Piquemal (1994)	180	0.1	6	[4.3E-5, 4.3E-4]	0.22	0	0.55	0.76	0.95	1.00	1.4
Piquemal (1994)	150	0.08	3	[7.5E-5, 7.5E-4]	0.22	0	0.68	0.76	0.96	1.00	1.2
Mahiya (1999) ^a	100-130	0.04-0.06	0.6-1.6	[3.6E-9, 4.2E-7]	0.27	0.13	0.51	1.00	0.88	0.90	2.0
Mahiya (1999) ^b	100-130	0.04-0.06	0.6-1.6	[3.6E-9, 4.2E-7]	0.27	0.13	0.28	1.00	0.97	0.80	3.9
Sanchez and Schechter (1990)	104-107	0.05	0.6	[4.1E-8, 2.1E-7]	0.17	0.9	0.65	0.37	0.98	0.94	0.96
Satik (1998)	80-130	0.03-0.06	0.3 - 1.6	[3.4E-8, 2.1E-7]	0.17	0.90	0.65	0.37	0.98	0.94	2.3
Verma (1986)	104-110	0.04-0.05	0.7-0.9	[1.4E-8, 2.6E-7]	0.20	0	1.00	1.00	0.89	0.95	1.0
^a drainage, ^b imbibition											



Fig. 4. Capillary number, temperature, and viscosity ratio for the data set used for model validation.

3.3. Mass transmissibility

idation is proposed). This is confirmed by the experimental data of Piquemal (1994) where air and water were used as test fluids: although, the endpoint relative permeabilities may slightly vary in the case of water and steam, the rescaled data follow the same scaling.

The analysis of the experimental data supports the hypothesis that, as a first approximation, water and steam can be treated as two immiscible and incompressible phases with a very low viscosity ratio.

In this Section, we derive the scaling for mass and energy transmissibility. As described in the previous Sections, the scaling behavior of Class I, Eq. (9), is applicable to geothermal flow at twophase flow conditions when the temperature is sufficiently far from the critical point. If we combine Eqs. (16) and (10), we obtain

$$\mathcal{T}_m = \kappa \beta_\ell S_*^2 \left[1 + \beta^* \frac{R}{M} \left(\frac{1 - S_*}{S_*} \right)^2 \right]. \tag{31}$$



Fig. 5. Comparison between the predicted scaling (solid lines) of the normalized relative permeability of the liquid water - (a) and (c) - and the vapor - (b) and (d) - in terms of the mobile saturation and experimental measurements (symbols) from core-samples available in the literature. (a) and (b) are in linear scale, while (c) and (d) are in semi-log scale. Log-log plots are available in the insets.

In Figs. 6(a) and 6(b), we plot $\mathcal{T}_m/\kappa\beta_\ell$ in terms of the mobile saturation for different boiling temperatures with $\beta^* = 1$ and $\beta^* = 3$, respectively. When the endpoint relative permeability of steam is higher than that of liquid water, $\beta^* > 1$, the mass transmissibility increases in the low salutation range. This is the case for the experiments analyzed in the previous Section, see Tab. 1.

For low steam quality, i.e., at high saturations, the mass transmissibility scales with the square of the saturation as

$$\mathcal{T}_m \sim \kappa \beta_\ell S_*^2, \quad \text{for} \quad S_* \to 1.$$
 (32)

In this limit, T_m does not depend on thermal properties and the mass flux is controlled by liquid water saturation only. Instead, at low saturation (i.e., high steam quality)

$$\mathcal{T}_m \sim \kappa \beta_v \frac{R}{M}, \quad \text{for} \quad S_* \to 0,$$
(33)

the mass transmissibility is independent on water saturation and is a function of the thermal properties through the ratio R/M.

The effect of temperature on T_m can be made explicit by approximating the dependence of R/M on T through polynomial interpolation, i.e.

$$\frac{R}{M} \approx \delta_1 + \delta_2 \left(\frac{T}{T_c}\right)^{\delta_3}, \quad \text{for} \quad 30^\circ C < T < 300^\circ C, \quad (34)$$

where the fitting parameters are $\delta_1 = 4.32 \cdot 10^{-3}$, $\delta_2 = 3.235$, and $\delta_3 = 0.555$, T_c is the critical temperature and $T \ll T_c$. Fig. 7(a) shows the validity of the approximation against the exact solution. Combining Eqs. (34) and (31), we obtain

$$\mathcal{T}_m \approx \kappa \,\beta_\ell S_*^2 \left[1 + \beta^* \left(\frac{1 - S_*}{S_*^2} \right)^2 \left(\delta_1 + \delta_2 \left(\frac{T}{T_c} \right)^{\delta_3} \right) \right] \tag{35}$$

In the low saturation limit, transmissibility increases with temperature and

$$\frac{J_m}{\kappa \beta_v \left(\delta_1 + \delta_2 \left(\frac{T}{T_c}\right)^{\delta_3}\right)} \sim 1, \quad \text{for} \quad S_* \to 0,$$
(36)

i.e. a universal scaling law can be formulated in terms of the thermodynamic properties of the mixture (namely, temperature). Fig. 8(a) shows that, when properly rescaled, all the curves collapse on the same universal asymptote when $S_* \rightarrow 0$. In other words, the mass flux is enhanced for higher temperature of the mixture.

3.4. Energy transmissibility and thermal properties of the mixture

Combining Eqs. (22) and (10) leads to

$$\mathcal{T}_e = \kappa \beta_\ell S_*^2 \left[1 + \beta^* \frac{HR}{M} \left(\frac{1 - S_*}{S_*^2} \right)^2 \right],\tag{37}$$



Fig. 6. (a) and (b): Ratio of the mass transmissibility to the absolute permeability and the water endpoint relative permeability as a function of the mobile fluid saturation and temperature for different values of β^* .



Fig. 7. (a) The solid line is the ratio of the density and viscosity ratio, R/M, as a function of the normalized temperature, T/T_c . The dashed line is the proposed approximation. (b) The solid line are the ratios HR/M and SR/M as a function of the normalized temperature, T/T_c . The dashed line are the proposed approximation.



Fig. 8. Rescaled mass transmissibility, (a), and energy transmissibility, (b), as a function of the mobile saturation and the boiling temperature.



Fig. 9. (a) and (b): Ratio of the energy transmissibility to the absolute permeability and the water endpoint relative permeability as a function of the mobile fluid saturation and temperature for different values of β^* .

i.e.

$$\mathcal{T}_e \sim \kappa \beta_v \frac{HR}{M}, \quad \text{for} \quad S_* \to 0,$$
 (38)

and

$$\mathcal{T}_e \sim \kappa \beta_\ell S_*^2, \quad \text{for} \quad S_* \to 1.$$
 (39)

The functional dependence of HR/M on temperature can be approximated through a polynomial of the form

$$\frac{HR}{M} \approx \gamma_1 + \gamma_2 \left(\frac{T}{T_c}\right)^{\gamma_3}, \quad \text{for} \quad 30^{\circ}\text{C} < T < 300^{\circ}\text{C}, \quad (40)$$

where the fitting parameters are $\gamma_1 = 4.757 \cdot 10^{-2}$, $\gamma_2 = 0.871$, and $\gamma_3 = 2.290$. The approximation holds when $T \ll T_c$, as shown in Fig. 7(b). Combining Eqs. (40) and (37), we obtain

$$\mathcal{T}_{e} \approx \kappa \beta_{\ell} S_{*}^{2} \left[1 + \beta^{*} \left(\frac{1 - S_{*}}{S_{*}} \right)^{2} \left(\gamma_{1} + \gamma_{2} \left(\frac{T}{T_{c}} \right)^{\gamma_{3}} \right) \right]$$
(41)

Energy transmissibility \mathcal{T}_e is sensitive to temperature only in the low saturation limit, when the energy flux of the mixture increases with temperature. A universal scaling can be found by appropriately normalizing \mathcal{T}_e ,

$$\frac{\mathcal{T}_e}{\kappa \beta_\nu \left(\gamma_1 + \gamma_2 \left(\frac{T}{T_c}\right)^{\gamma_3}\right)} \sim 1, \quad \text{for} \quad S_* \to 0,$$
(42)

as showed in Fig. 8(b). It is worth emphasizing that although the trend for \mathcal{T}_e is qualitatively similar to that of \mathcal{T}_m , \mathcal{T}_e scales with the square of S_* just for a small range of saturations, as showed in Figs. 9 (a)-(b). Instead, the plateau extends for a significant range of saturations, i.e., $S_* < 0.1$. Also, higher values of β^* lead to higher energy transmissibility. As expected, mass and energy fluxes are smaller in lower permeability media.

Finally, we show how the scaling behavior of the relative permeability impacts the estimation of the thermal properties of the water-steam mixture. The flowing enthalpy and entropy are given by

$$h_{m} = \frac{1 + \beta^{*} \frac{HR}{M} \left(\frac{1 - S_{*}}{S_{*}^{2}}\right)^{2}}{1 + \beta^{*} \frac{R}{M} \left(\frac{1 - S_{*}}{S_{*}^{2}}\right)^{2}}, \quad s_{m} = \frac{1 + \beta^{*} \frac{SR}{M} \left(\frac{1 - S_{*}}{S_{*}^{2}}\right)^{2}}{1 + \beta^{*} \frac{R}{M} \left(\frac{1 - S_{*}}{S_{*}^{2}}\right)^{2}}, \tag{43}$$

respectively, and depend only on water saturation, viscosity and density ratios, and *H*, *S*, and β^* . Fig. 10 shows that both enthalpy and entropy scale nonlinearly with water saturation. Specifically,

both h_m and s_m reach a plateau at low saturations while they rapidly decrease as the steam quality decreases. Such a relationship between thermal properties and saturation (i.e., steam quality) in porous media differs significantly from the classical one for watersteam mixtures where enthalpy and entropy are usually estimated by a linear combination of properties of saturated water and saturated steam, respectively (Gyftopoulos and Beretta, 2005). These results provide (i) new insights on the computation of mass and energy fluxes of two-phase water-steam flow in permeable rocks and (ii) an expression for thermal properties in terms of the boiling temperature and the properties of the porous medium.

Fig. 10 also shows the dependence of the thermal properties of the mixture h_m and s_m on temperature. Such a dependence can be approximated by the following interpolation

$$\frac{RS}{M} \approx \theta_1 + \theta_2 \left(\frac{T}{T_c}\right)^{\theta_3}, \quad \text{for} \quad 30^{\circ}C < T < 300^{\circ}C, \quad (44)$$

where the fitting parameters are $\theta_1 = 4.678 \cdot 10^{-2}$, $\theta_2 = 0.7484$, and $\theta_3 = 2.385$, see Fig. 7(b).

3.5. Exergy of the two-phase mixture

We now investigate the scaling behavior of the exergy in terms of water saturation, boiling temperature, and properties of the porous medium.

We determine \dot{W}_{max} from Eq. (28) and we assume that the environment is at ambient temperature $T_0 = 20^{\circ}C$. In Fig. 11(a) we plot the exergy per unit of mass at four different temperatures: \dot{W}_{max} is constant in the limit of low saturations, $S_* \rightarrow 0$, while it varies nonlinearly with S_* for intermediate saturation values, i.e. more work can theoretically be extracted from the system when the flow is rich in steam. This can be explained as follows: exergy scales with the mixture enthalpy, see Eq. (28), and, when $T < 300^{\circ}$, the enthalpy of saturated steam is significantly higher than that of saturated water. As a result, exergy is maximum when steam quality in the pore space is high.

Fig. 11 (b) shows that \dot{W}_{max} increases with β^* at intermediate saturations. This is expected because, in that range, an increase in the endpoint relative permeability of steam, β_{ν} , leads to an enhancement of both mass and energy fluxes (see Figs. 6 and 9).



Fig. 10. (a): Flowing enthalpy as a function of the mobile fluid saturation and temperature for $\beta^* = 1$; the enthalpy is normalized with respect to the enthalpy of saturated water, h_{ℓ} . (b): Flowing entropy as a function of the mobile fluid saturation and temperature for $\beta^* = 1$; the entropy is normalized with respect to the entropy of saturated water, s_{ℓ} .



Fig. 11. (a) and (b): Exergy per unit of mass flux as a function of the mobile fluid saturation, the temperature, and different values of β^* .

4. Conclusions

This work extends the relative permeability model of Picchi and Battiato (2019) to water-steam systems. Two-phase mass and energy fluxes as well as thermal properties in the context of geothermal engineering applications have been determined. The analysis leads to the following main conclusions:

- 1. The steam and water relative permeabilities follow the same scaling behavior of gas-liquid two-phase systems where the non-wetting phase is much less viscous than the wetting phase, such as air-water, nitrogen-water, and *CO*₂-brine systems. This supports the hypothesis that, at a fixed temperature, as a first approximation, water and steam can be treated as two immiscible and incompressible phases, and are equivalent to a multiphase flow system with a very small viscosity ratio.
- 2. The normalized relative permeabilities for water and steam measured in cores samples in the $100 180^{\circ}C$ temperature range scale with the square of the mobile saturation.
- 3. The mass and energy transmissibility of the water-steam mixture exhibits a plateau at low water saturation (i.e., high steam quality), while scales with the square of the saturation when the system is dominated by liquid water. Temperature increases enhance both mass and energy fluxes.

- 4. The enthalpy and entropy of the mixture flowing in a porous medium scale non-linearly with the liquid water saturation.
- 5. The exergy associated to water-steam flow in a porous medium is maximal when the flow is rich in steam.

We believe the proposed framework is a promising starting point for the derivation of effective parameters, commonly used in geothermal reservoir simulations, from first principles, while accounting for the impact of operating temperature as well as porescale flow regimes. It is worth emphasizing that, although the analysis was conducted with a focus on Class I systems (i.e. small viscosity ratio flows), such a framework allows one to account for the impact of flow regimes when the operating temperature is closer to the critical temperature. Finally, the new formulation of exergy for water-steam systems in porous media provides the opportunity to systematically and quantitatively identify inefficiencies in the utilization level of geothermal reservoirs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Davide Picchi: Conceptualization, Methodology, Formal analysis, Validation, Writing - original draft, Writing - review & editing. Ilenia Battiato: Conceptualization, Methodology, Supervision, Writing - review & editing, Funding acquisition.

Aknowledgements

Full support by the Department of Energy under the Early Career Award DE-SC0014227 "Multiscale dynamics of reactive fronts in the subsurface" is gratefully acknowledged.

Appendix A. Data analysis Methodology

The water-steam relative permeability data have been analyzed as follows:

- Step 1. We identify whether the experimental data set belongs to Class I, ClassII, or Class III depending on the temperature and the viscosity ratio;
- Step 2. We identify whether the experiments exhibit residual and irreducible saturations, S_{ir} and S_{or};
- Step 3. We rescale the saturation of the wetting phase in terms of mobile saturation;
- Step 4. We determine the fitting parameters of the model, β_{ℓ} , β_{ν} , α.

The datasets that we used in the validation are listed in Table 1. We also list the working temperature, the estimated viscosity and density ratios, the model parameters, and the coefficient of determination computed for all the parameters.

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