Experimental Studies of a Steam Front in a Radial Porous Cell

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Abstract In many Geothermal reservoirs water is injected through porous media in order to obtain steam. This process is basically used to generate geothermal energy. It could be expected that the water or steam injected in the homogeneous porous media will have a stable motion. It has been found experimentally that this is not always true. In porous media with high permeability, steam migrates in a finger-shape form reported in literature as the Saffman-Taylor Instability. In this work, a couple of experiments based on steam injected through a radial porous cell are shown. The main objective of this study is to present the observed instabilities in the steam front.

1 Introduction

In this paper the experimental study of a steam front in a porous radial cell is studied. This kind of phenomenon is observed in Geothermal Reservoirs which are used for electrical production, therefore the importance of this research. It is assumed that the flow of the interface vapour–liquid through the porous radial cell is planar. The experiments here developed show the existence of some instabilities. This kind of disturbance in the flow of the interface through the porous medium is known as Saffman-Taylor Instability (1958).

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The flow of a liquid–steam interface in low permeability Geothermal Reservoirs remains stable, it means that the steam front does not advance in a finger-shaped form (a characteristic form in presence of this kind of instability but in the case of Geothermal Reservoirs considered of high permeability the movement of the vapor front occurs in a finger-shaped form, due to that the vapour-liquid interface in the liquid phase experiments minor opposition to the movement and advances quickly, reaching more exposition to the super-heated rock and rapidly vaporizing (Islam and Azaies 2010).

2 Problem Description

Many geothermal systems are characterized by a low permeability and by the fact that their internal flows have low Reynolds numbers, hence the flow can be described with the law of Darcy

$$\dot{m} = -\frac{K}{\mu}\frac{\nabla P}{L}. \tag{1}$$

where $\dot{m}$ is the mass flow rate, K is the permeability, μ is the viscosity, ∇P is the gradient of the pressure and L is the total radial length of the radial porous cell.
The problem of the motion of the steam front through a radial porous cell is described by using the Conservation of Mass (Continuity) and Darcy's Law, Eqs. (1) and (2)

$$\varphi\frac{\partial \rho_v}{\partial t} + \nabla\cdot(\boldsymbol{v}_v\rho_v) = 0. \tag{2}$$

where φ is the porosity and ρ_{v} is the steam density.
Moreover, if we want to study the heat transfer in this system, we need to add the Conservation of Energy (First Law of Thermodynamics) and the Perfect Gas Law to this system in every moment during the phenomena.

$$\frac{\partial(C_a T)}{\partial t} + \nabla\cdot(\boldsymbol{v}_v C_v T) = \kappa_a C_a \nabla^2 \mathrm{T}. \tag{3}$$

$$P = \rho_v R_v T. \tag{4}$$

where C is the specific heat referred to the unit volume, κ is the thermal diffusivity, subindexes are a for the average and v for the steam, R is the Universal Gas Constant and T is the temperature.

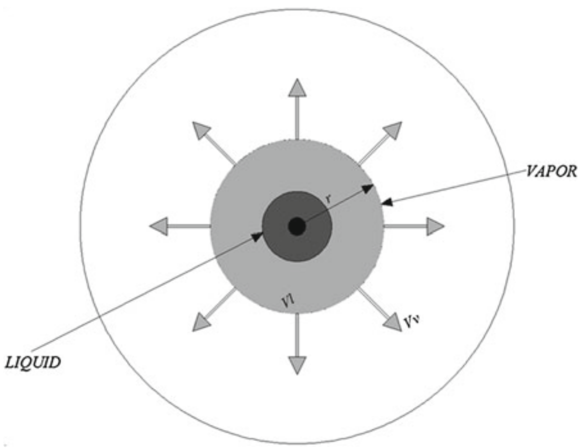

Fig. 1 Scheme showing the vaporization front phenomenon

If we observe Fig. 1, from the equality of the flow in the liquid–gas interface

$$\dot{m}_l - \dot{m}_v = (\rho_l - \rho_v)A\frac{dr}{dt} \tag{5}$$

where "r" is the radial coordinate, A is the area and is the massic flow.
Towards the steam front, part of the injected steam is condensed and we can see that (Fig. 1):

Hence, we can write the conservation of mass equation in this way:

$$\varphi(\rho_l - \rho_v)\frac{dr}{dt} = \rho_l v_l - \rho_v v_v \tag{6}$$

Darcy velocity for each phase can be expressed as:

$$v_v \sim \frac{k\Delta P_v}{\mu_v l_v} \tag{7}$$

and

$$v_l \sim \frac{k\Delta P_l}{\mu_l l_l} \tag{8}$$

If:

$$\rho_l \gg \rho_v$$

Table 1 Properties of different elements used in the experiment

Property	Value
Sand porosity	0.5
Atmospheric pressure	101 325 Pa
Water density	21 °C: 998 kg/m^3
Steam viscosity at 100 °C	1.37473×10^{-5} Pa*s
Sand permeability	1.8×10^{-6}
Water viscosity at 21 °C	2.30763×10^{-4} Pa*s
Steam pressure	392.26 kPa

Substituting (7) and (8) in (6) we have:

$$\frac{dr}{dt} = \frac{1}{\varphi}\frac{kP_T}{v_v L}\left(\frac{\Delta P_v L}{\Delta P_T l_v} - \frac{\Delta P_l L v_v}{\Delta P_T v_l}\right) \tag{9}$$

Finally, with this expression we can estimate the total advance of the liquid and the steam front:
The values used in the experiment are shown in Table 1. Hence, in order to estimate the velocity of the flow we use the next values (Table 1):
Also, an expression for the Conservation of Energy can be found as:

$$\varphi(h_l - h_v)\frac{dr}{dt} = \left[\kappa_a C_a \frac{\partial T}{\partial r}\right] + h_l v_l - h_v v_v \tag{10}$$

where $[r]$ denotes the change of the property r through the interface and denotes the specific enthalpy.
The problem is completely described with Eqs. (1)–(4), as it can be seen in (Fitzgerald and Woods 1995) and it can be solved numerically.

3 Experimental Procedure

A radial porous cell is manufactured with a circular plate of tempered glass with a 36 cm diameter. These dimensions allow us to see the complete behavior of the phenomenon. The glass plate is placed above a metallic container with the same diameter and a depth of 2 cm. One is filled with silica sand forming a nonconsolidated porous matrix. The injection port was drilled at the center of the glass plate in order to allow us to inject the steam (as can be seen in Fig. 2).

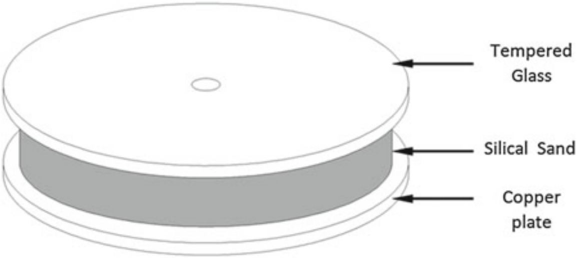

Fig. 2 Scheme showing the main conformation of the radial porous cell

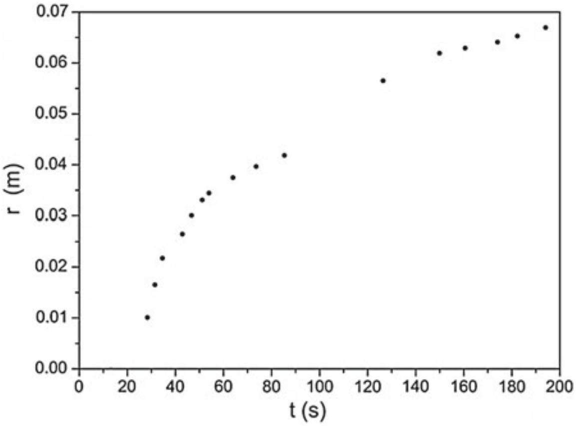

Fig. 3 Plot showing the steam front advance as a function of time

In the first experiment water is injected at ambient temperature (21 °C) through the center and it spreads through the matrix to a preheated porous matrix (about 100 °C). Part of the injected water boils almost instantly because of the heat exchanged with the porous matrix and the steam front moves through this system (Fig. 1). In Fig. 3, the advance of the steam front as a function of time can be observed.

In Fig. 4 water is injected and moving forward in a stable form, but due to the growth of the radial area, the rate area-injected water begins to decrease and the fluid begins to boil quickly, this steam front begins to move in a finger-shaped form, and we can say that the Saffman-Taylor instability is present.

In the second experiment, as in the previous one, water is injected constantly at an ambient temperature (21 °C) through the preheated porous matrix at about 120 °C over 20 °C more than in the first experiment. In this case, the steam front begins to destabilize in an asymmetric form at early stages of the phenomenon (Fig. 5). In Fig. 6 the advance of the vapor front as a function of time can be observed.

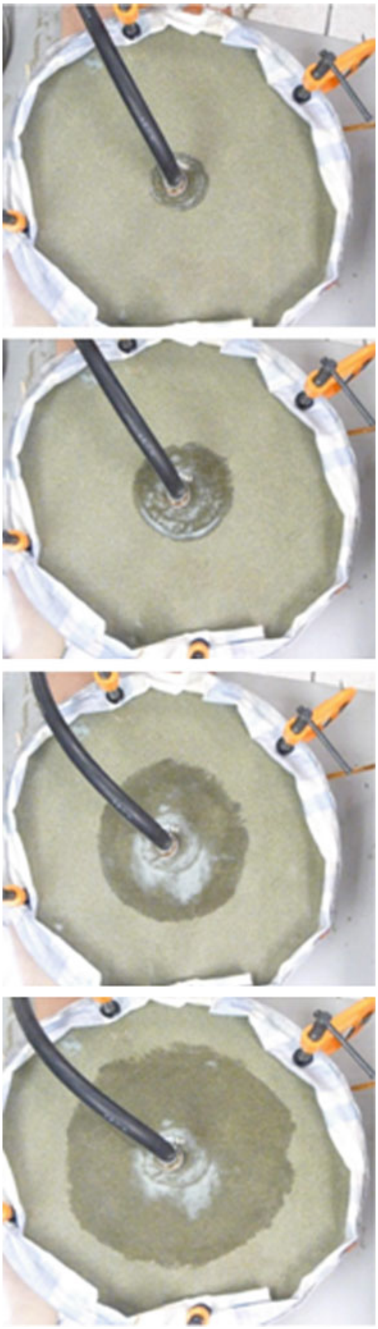

Fig. 4 Behavior of the vapor front moving through to the radial porous matrix in presence of a discrete Saffman-Taylor instability

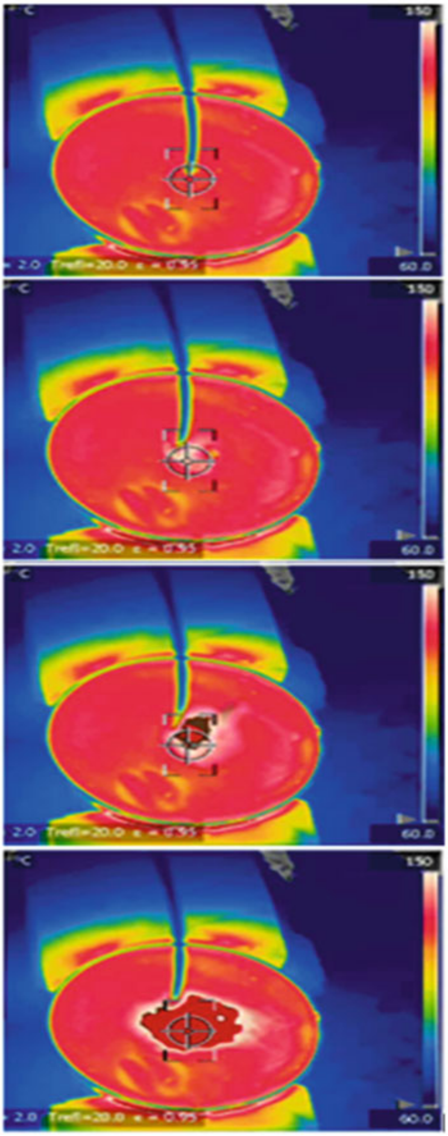

Fig. 5 Sequence showing a steam front moving through the radial porous matrix in presence of a strong "Saffman-Taylor" instability (Slide series was taken by using a thermal camera)

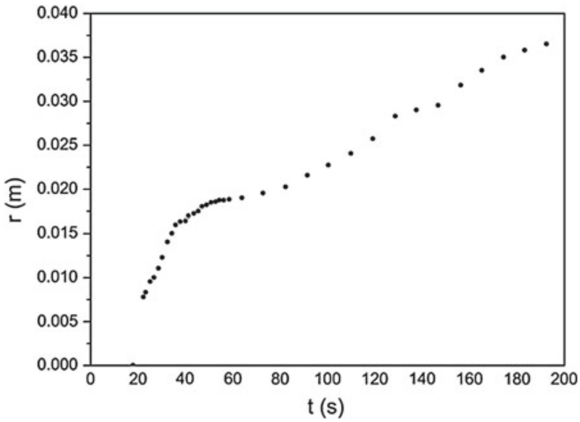

Fig. 6 Plot showing the steam front advance as a function of time

4 Conclusions

As it can be observed in this work, for both experiments the flow of the steam front through the porous cell showed the same behavior. This means that the steam front advanced in a finger-shaped form due to the Saffman-Taylor instability caused by the formation of zones of high and low pressure. The nonsymmetric finger-shaped behavior of the steam front observed in the second experiment (compared with the first one) can be attributed to the sudden change of state from water to steam due to the high temperature of the host core.

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