PROCEEDINGS, Twenty-Second Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 27-29, 1997
SGP-TR-155

# VAPORISING LIQUID CURRENTS DRIVEN BY GRAVITY THROUGH GEOTHERMAL RESERVOIRS

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## ABSTRACT

We present a series of solutions describing the propagation of injected water through a geothermal reservoir accounting for both the effects of gravity and also boiling at the advancing front. These new similarity solutions provide new insight into the complex coupled flow driven by gravity and can be readily extended to account for the effects of surface tension which may cause some residual liquid to remain in the pores once the main front has descended.

## INTRODUCTION

When liquid is injected into a superheated, vapour-saturated geothermal reservoir, the liquid descends under gravity towards the base of the reservoir. Once it has reached an impermeable boundary, the liquid begins to spread laterally under gravity. The leading front of the liquid partially boils as it invades the superheated rock, producing new vapour. Meanwhile, the trailing part of the liquid may descend through the reservoir. The temperature signal associated with the cold injectate advances more slowly than the liquid front, owing to the thermal inertia of the rock (figure 1). As a result, the main part of the liquid region has temperature close to the saturation temperature (see Woods and Fitzgerald, 1993). Thus, as the liquid near the source descends, the rock is left just at saturation conditions. In some cases, the effects of the surface tension will be to retain a fraction of the liquid in the pore spaces, although this may be a small effect.

## MODEL

Here we describe in outline the spreading of such currents along a horizontal impermeable boundary and for simplicity consider the case of a one-dimensional current. The model can be generalised to account for axisymmetric spreading, or spreading on an inclined surface and this will be reported subsequently. In the present case, the motion of the current can be specified by solving the equation of motion for the flow, based on a balance between the pressure gradient in the flow and the viscous resistance to motion in the porous layer, together with equations for the local and global conservation of mass and equations specifying the rate of vaporisation of liquid at the leading edge of the current and the rate of supply of new fluid at the rear of the flow.

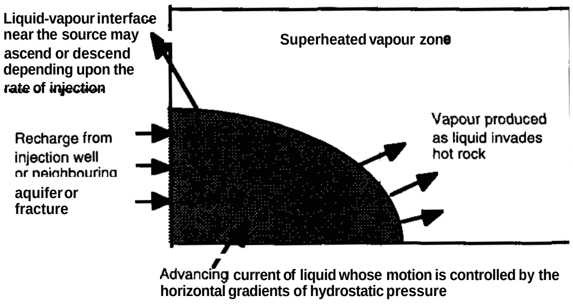

*Figure 1. Schematic of an advancing liquid gravity current showing the boiling at the nose and the descent of the rear of the current.*

As the current spreads out and thins, the motion of the flow becomes progressively more parallel to the x-axis and uniform with depth. The pressure at each point in the current is hydrostatic and so the velocity has value $u=(K\rho g\delta h/\delta x)/\mu$, where $K$ is the permeability, $\rho$ the density, $g$ the gravitational acceleration, $h$ the depth of the current, and $\mu$ the viscosity.

In regions where the current ascends into superheated rock, then a fraction $F$ of the current boils and the remainder of the liquid remains as liquid. Therefore, the depth of the liquid region evolves according to the equation for local conservation of mass

$$\frac{\partial h}{\partial t}=A(1-F)\frac{\partial^2 h}{\partial x^2} \tag{1}$$

where A is the effective diffusion or spreading rate of the current, given by $A=K\rho g/\mu$. The value of $F$ is given in terms of the superheat $S$ of the rock, $F=1/(1+L/C_pS)$.

In regions where the liquid descends, a fraction $R$ of the fluid may be left behind in the pore spaces of the rock, and so the depth of the current evolves according to

$$\frac{\partial h}{\partial t} = \frac{1}{1-R}\frac{\partial^2 h}{\partial x^2} \qquad (2)$$

The value of $R$ depends, amongst other things, on the surface tension and the pore size distribution, but in general is a complex property of the host.

Finally, the global conservation of mass has the form

$$Q_o t^{\gamma-1} =$$

$$(1+R)\phi \int_0^{L_1(t)} \frac{\partial h}{\partial t}dx + \frac{\phi}{1-F}\int_{L_1(t)}^{L_2(t)} \frac{\partial h}{\partial t}dx \qquad (3)$$

Here $L$, and $L_2$ denote the position of the interface and the leading edge of the current.

Equations (1), (2) and *(3)* may be solved in both the cases of maintained injection and also for a finite release of fluid at $t$=0. **A** special class of similarity solutions, which apply **for** a certain class of injection rates, allow for a relatively simple solution technique and have the form

$$h = h_0 t^{(2\gamma-1)/3} f\left(\frac{x}{bt^{(\gamma+1)/3}}\right) \qquad (4)$$

In the former case, the injection rate $Q=Q_0t^\gamma$ determines the rate of spread of the current, with the length of the current increasing at a rate $L \approx bt^{(\gamma+1)/3}$ where $b$ is a constant. Note that for $\gamma>0.5$, there is no descending region and the motion of the current is desribed by simpler versions of equation *(1)* and **(3)** together with appropriate boundary conditions.

## RESULTS

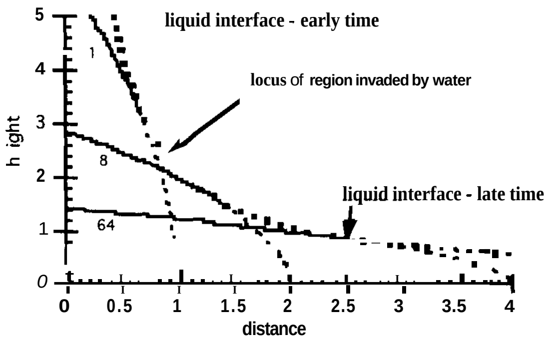

*Figure 2. Similarity solution for the shape of the regionfilled with liquid at times I, 8 and 64. The front of the current advances and partially boils, while the rear of the current descends. The solution corresponds to liquid injection at a rate Q/t.*

Figure *2* shows a typical solution, with $R$=0, with the depth of the current decreasing with time and the length of the current increasing with time. On successive time steps, the current evacuates some of the rock near the source, and invades hot rock further from the source. This continual redistribution **of** the current through the porous rock provides a continual source of heat to the liquid and hence enables a significant fraction of the injected liquid to boil. Indeed, for the special case $Q=Q_0/t$, the area of the current remains constant and the flux of injected liquid equals the flux of boiling liquid.

For the case of a fixed mass injected at $t$=0, **the** natural decay rate must be found as an eigenvalue of the global consevation of mass **(3).** Figure 3 shows how the decay rate, $\gamma<0$, of the mass **of** liquid, $Q=Q_0t^\gamma$, varies with the fraction $F$ which vaporises, again shown **for** the case $R$=0. It is seen that for very small mass fractions which vaporise, $F<<1$, the mass of the current remains nearly constant, whereas for large mass fractions which vaporise, $F \approx 1$, the mass of the current decays at a rate *llt*.

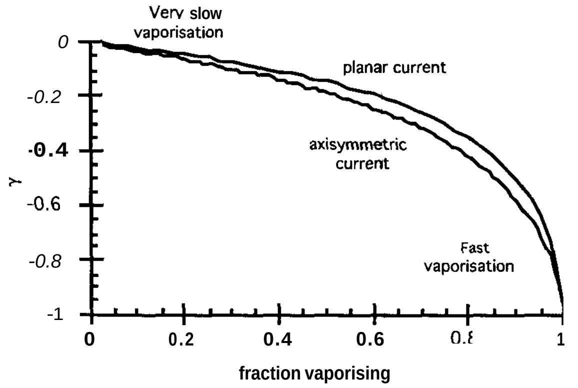

*Figure 3. The value of $\gamma$ as a function of the mass fraction which vaporises, F, where the volume of liquidfilled with water at time t is $Qt^g$.*

We deduce that in typical geothermal systems, the role **of** gravity in controlling the spreading of liquid through the reservoir is crucial in calculating the mass fraction of vapour which is produced. **As** liquid spreads under gravity, it may slump, leaving a cooled region of rock which is just saturated while invading rock which is superheated. In this way the liquid can access much more thermal energy than a planar interface.

This provides a much greater transfer **of** heat to the injected liquid, and allows the production of much more vapour. Indeed, for injection at a rate proportional to *llt*, we predict that the mass of liquid which vaporises in a spreading current, exactly equals the mass of liquid which is injected, and the volume of the liquid-filled region around the injection well is

## CONCLUSIONS

The present solution technique, which involves similarity solutions of the first and second kind (Barenblatt, 1996) provides key new insights into the vaporisation processes in geothermal systems. The solutions are valid as long as the effects of thermal conduction and vapour pressure are unimportant, and this range of validity may be shown to span most injection rates over times of interest of 1 week-10 years. A major strength of the solution is that it does not require numerical simulation, yet captures the main feature of the flow.

## ACKNOWLEDGEMENTS

This work is supported by UNOCAL and PG&E.

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