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THE STABILITY OF TWO-PHASE GEOTHERMAL RESERVOIRS

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ABSTRACT

n this paper we present a model of the stability of geothermal systems in which there are both boiling wo-phase zones and liquid saturated regions. We also present a series of preliminary laboratory experiments designed to examine the stability of liquid-two-phase boiling zones.

INTRODUCTION

In a number of geothermal systems, including the Geysers (Ca), Lardarello (Italy) and Tongonan (Philippines), well logs indicate that in some parts of he reservoir, a two-phase vapour- or liquid-dominated region is overlain by a colder liquid saturated zone. The stability of such systems is intriguing. Schubert and Straus (1980) have described how a liquid layer may overly a model superheated vapour zone if there is a sufficiently large conductive heat flux through the system. However, real geothermal systems involve a two-phase boiling zone below the liquid layer. This may be an important difference.

The effect of compressibility is to suppress the descent of liquid fingers into the two-phase zone. This is achieved because the compressibility allows the newly formed vapour to accumulate ahead of the interface, where it builds up the pressure, suppressing descent of the liquid finger (cf. Fitzgerald and Woods, 1994). If the two-phase zone has compressibility β, then the effective pressure diffusivity D of the two-phase zone is $K/\phi\mu\beta$ (Grant and Sorey 1979). In order for stability to result from this compression, the wavenumber, k, of any descending fingers must be smaller than $k<O(\sigma D)^{1/2}$ where σ is the growth rate of the perturbation. However, in addition to this stabilising mechanism, thermal diffusion can also act to stabilise the interface if the wavenumber is large, $k>O(\sigma\kappa)^{1/2}$. Hence, the interface will be absolutely stable if $\kappa>D$. For a two phase zone, the compressibility is large owing to the ease of phase change between the liquid and vapour phases, and we estimate that for permeabilities $K<10^{-17}$-10^{-16} m^2, $\kappa>D$. For such conditions it follows that liquid-two phase interfaces may be stable to fingering instabilities.

However, data from early experiments of Bau and Torrance (1982) and the experiments reported herein suggest that instabilities of such interfaces may develop in some conditions, although it is not clear that these instabilities are fingering instabilities. In order to understand such instabilities in more detail, we now examine the formation of 2-phase zones overlain by liquid experimentally.

EXPERIMENTAL OBSERVATIONS

We conducted a series of experiments in which a sand layer, saturated with water, was heated from below.

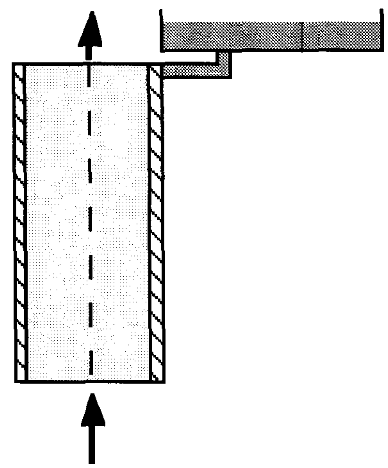

Figure 1 Schematic of the experimental apparatus. Heat was applied to the base of a water and sand-filled vessel, 3in diameter and 1m high. The top of the vessel was cooled at at 15°C, and the apparatus was connected to a constant pressure head water bath as shown. Insulation material was applied along the sides of the vessel to reduce the heat lost by conduction through the side walls. Thermocouples were placed along the centre of the vessel at 10cm spacings as indicated by the dashed line.

Figure 1 shows the apparatus in which the sand layer was open at the top surface to the atmosphere. A series of thermocouples measured the temperature as a function of depth in the vessel. At a critical heat flux of 850 W/m, a two-phase boiling zone developed at the base of the reservoir. Heat was then convected upwards through this zone by the heat pipe mechanism to an overlying layer of conducting liquid. **In** each experiment, the temperature gradient became weaker with height in the layer, as a result of the losses through the sides of the vessel. These were proportional to $A(T\text{-}T_0)$, where T_0 is the laboratory temperature. In steady state, the temperature profile in the liquid saturated region therefore satisfies the vertical conduction equation

$$\frac{\partial^2 T}{\partial z^2} = A\left(T - T_0\right) \qquad (1)$$

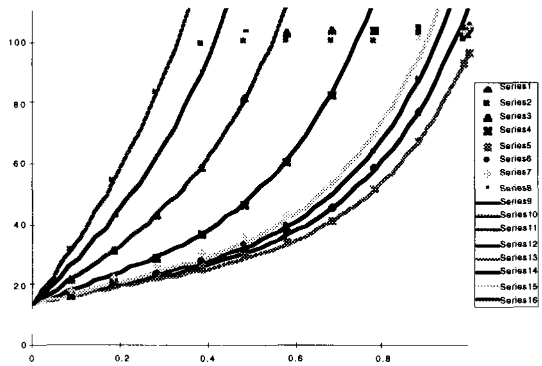

***Figure 2** Temperature **as** a function of depth. The symbols represent the experimental data for various heat fluxes. The solid lines indicate the theoretical prediction for the variation of temperature within the liquid-filled portion of the apparatus using the same empirical parameter for the thermal resistance of the insulating material A.*

As shown in figure 2, the solution to this equation, which is a sum of two exponential terms, fits all the experimental data with great accuracy. This allows us to estimate the heat flux at each height in the system. In figure **3,** the depth of the 2 phase zone is shown **as** a function of the heat flux at the liquid-two-phase interface. It is seen that a small increase in heat flux leads to a large increase in the depth of the two phase zone, with the zone extending to a depth of 50cm **as** the heat flux increases to 1000 W/m^2.

These experimental results suggest that the depth of the two phase zone is strongly controlled by the conductive heat flux above the two-phase zone, and ultimately by the heat flux which may be transferred convectively to the overlying ambient air from the liquid zone. By continually increasing the depth of the hot two phase zone, the amount of the heat flux supplied at the base of the reservoir which is lost through the walls of the vessel increases (figure **4),** since there is a greater depth in which the sand bed is at the boiling temperature (figure **4).** The results suggest that the heat pipe is not the rate limiting control on the heat transfer, and that the depth of the heat pipe is controlled by the overall heat flux through the system.

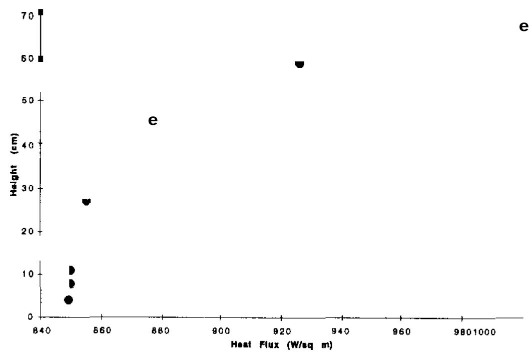

***Figure 3** Depth of the two-phase zone (cm) **as** a function of the heat flux (W/m^2) at the top of the two-phase layer. The heat flux is calculated using the temperature gradient at this point from figure I and assuming a conductivity of 2.6 W/mK (Bau and Torrance 1982)*

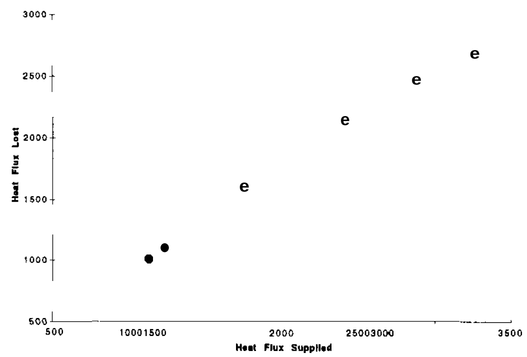

***Figure 4** Heat flux lost through the sidewalls of the apparatus as a function of the heat flux supplied at the base.*

Temperature profiles suggest that when the heat flux reaches values of order 1000 W/m^2, a bulk mode of instability sets in, with an oscillating temperature profile developing (figure 5). The magnitude of the oscillation increases with the applied heat flux. We suggest that even though the thermal balance requires the two-phase zone to continue deepening with the heat flux, eventually the depth of the two-phase zone exceeds a critical condition for stability, given that it is overlain by a relatively dense layer of liquid.

COMPRESSIONAL INSTABILITY OF TWO-PHASE ZONES

Our **data** suggest that this oscillation is consistent with a bulk compressional instability of the two-phase zone. Furthermore, given the magnitude of the temperature fluctuations, the instability does not appear to be a result of a small-scale local fingering instability. Essentially, the two-phase zone suffers a pressure change when compressed by the descending liquid. If this pressure change is smaller than the increase in gravitational head acting on the system, then one might expect instability, and the ensuing non-linear oscillation may be controlled by the readjustment of the heat budget. This simple criterion for a bulk compressional instability has the form $h>1/\Delta\rho\beta g$ where β is the compressibility and $\Delta\rho$ is the change in density between the liquid and two-phase zones.

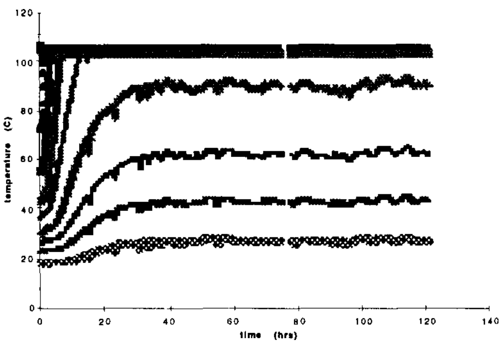

Figure 5 Temperature at various depths along the centreline of the apparatus as a function of time. The heat flux applied at the base of the system in this example was *2890W/m^2.*

The compressibility depends on the saturation of the layer. In this case, we estimate $\beta=10^{-3}$**Pa**, and $\Delta\rho=100$-500**kg/m^3** giving a critical depth for instability of 20-50 cm. Given the uncertainty in the data, and particularly the saturation of the two-phase zone, this prediction is consistent with the observations.

The long period of oscillation and the non-linear excursion of the temperature field, suggest that the restoring mechanism for this instability is thermal conduction across the layer. In the present system, where the conductive zone is of order 50-80 cm deep, this has a time scale of order $H^2/\kappa\approx10^5$-10^6s which is approximately 8-30 hours. Again this is broadly consistent with the data. In contrast, the oscillations noted by Bau and Torrance (1982) had a period of order 1 hour, but their system was a factor of 4 smaller than the present apparatus, which may also be consistent with a thermal conduction control on the time scale of the oscillation.

CONCLUSIONS

We deduce that in low permeability systems, $K<10^{-17}$ m^2 two-phase zones overlain by liquid may be stable to fingering type instabilities envisaged by Schubert and Straus (1980), owing to the high compressibility of the two-phase region. However, we have identified a bulk compressional instability which may develop when two-phase zones become overly deep. This is consistent with the laboratory data. Our results have important implications about the physical state of geothermal systems, and in particular as to whether steady states may be established when the two-phase zone is very deep.

ACKNOWLEDGEMENTS

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