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THE SUPPRESSION OF SONIC SHOCKS IN GEOTHERMAL WELLS

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ABSTRACT

The speed of sound in wet steam is only a small fraction of its value in either pure steam or water. As a result, sonic shocks form easily in wet steam.

Behaviour of wet steam under the action of gravity is of great importance in the operation of geothermal systems. Few systems create water with sufficient specific enthalpy to form dry steam and so the steam is of low quality. In a production well a balance point is reached at which the weight of wet steam provides precisely the correct pressure for boiling to commence. This point, "the depth of vaporization" is strongly dependent on the reservoir exit temperature. Thus small variations in reservoir exit temperature can cause large, rapid changes in the depth of vaporization. This can give rise to incompressible slugs of liquid water alternating with compressible slugs of wet steam in production well channels leading to complex, transient, resonating behaviour. This situation is analogous to a complex spring pendulum with a multiplicity of weights and springs. If a rapidly moving wet steam slug should locally exceed the speed of sound relative to the well-casing a sonic shock will form spontaneously even though there is no change in the diameter of the well. Extremely high pressures will then be manifested instantaneously in the fluid behind the shock, possibly causing damage to the well-casing. Such shocks would be recorded as earthquakes at the surface.

These phenomena can be suppressed as follows:

1. In a production well, by using a down-hole valve to maintain a high pressure in the production well in order to prevent the formation of wet steam.
2. Following stimulation, by releasing pressure very slowly, so as to avoid shock formation when wet steam forms.

INTRODUCTION

Wet steam (or any liquid in equilibrium with its own vapour) has an equation of state

$$f(p,V,q)=0 \qquad (1a)$$

and

$$g(p,T)=0 \qquad (1b)$$

which differs fundamentally from the equation of state for a single phase liquid or gas:

$$h(p,V,T)=0 \qquad (2)$$

For a perfect gas (2) becomes

$$pV-RT=0 \qquad (3)$$

In the above equations p is the pressure, V is the specific volume (the reciprocal of density), q , is the "quality" or mass fraction of the vapour phase and T is the absolute temperature.

The form of (1) leads to some strange behaviour. In wet steam, the specific heat at constant pressure and the bulk modulus at constant temperature are both zero so that the ratio of specific heats (and bulk moduli), γ , is also zero.

What concerns us here is the speed of sound. The speed of sound is very low in wet steam.

THE SPEED OF SOUND

The speed of sound in wet steam, v_{ws}, at various pressures was computed using the homogeneous model of Prandtl (Oertel, 2004), viz.:

$$v_{ws}^2 = \frac{u_v^2}{\varepsilon\{\varepsilon + \frac{\rho_v}{\rho_l}(1-\varepsilon)\}} \qquad (4)$$

where u_v is the velocity in pure vapour, ρ_v and ρ_l are the densities of the vapour and liquid phases and ε is the volume fraction of vapour given by

$$\varepsilon = \frac{1}{1 + \frac{1-q}{q} \cdot \frac{\rho_v}{\rho_l}}. \qquad (5)$$

Using numerical formulae for (1b) and for specific volumes of the vapour and liquid phases given by IAPWS (1997), the speed of sound was calculated for a range of values of pressure and quality, q. The results are shown in Figure 1.

The smallest value of sound speed calculated was 23.4 m/s which occurred at $p = 0.1$ MPa and $q = 0.000626$, i.e. at atmospheric pressure, when the vapour component comprised less than one part in a thousand of the total mass of the fluid. The speed of sound is lowest when the pressure is small and when superheated liquid first flashes to steam.

This formulation assumes the vapour phase is at rest and uniformly distributed with respect to the

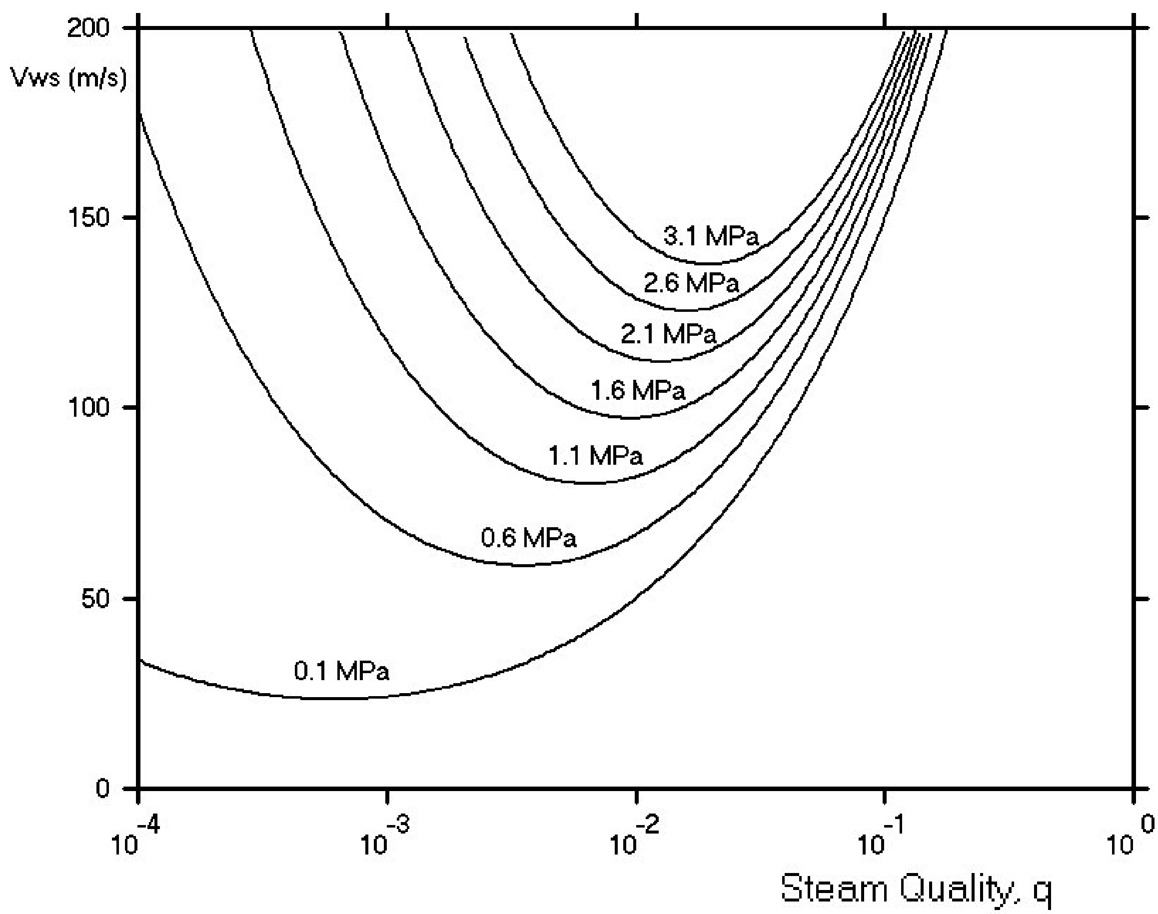

Figure 1. Speed of Sound, v_{ws}, as a function of pressure and quality, q.

liquid phase. It also assumes thermodynamic equilibrium. In practice neither of these assumptions may be true, particularly the latter. In any event the fact remains that the speed of sound in low quality wet steam is surprisingly small

DEPTH OF VAPORIZATION

When superheated liquid water (i.e. T >100°C) ascends a well or conduit, which is open to the atmosphere, a depth will be reached at which the pressure is sufficiently low for boiling to commence. The depth at which this occurs is termed, the Depth of Vaporization (DoV), z_v. Once boiling commences the density of the fluid above z_v will decrease so that boiling can commence at a lower depth. This feedback continues until, ideally, a steady state is reached in which the Depth of Vaporization is stable because the pressure exerted by the wet steam is precisely that needed for boiling to commence, i.e. there is a depth at which the pressure and temperature of the ascending fluid lie on the characteristic curve (1b). If heat losses are neglected, this depth depends solely on the temperature of the rising liquid.

The detailed modeling is described in Reid (2009). Some values of Depth of Vaporization are listed in Table 1 as a function of reservoir exit temperature.

It can be seen from Table 1 that the DoV is a strong function of reservoir exit temperature. At 200°C a temperature change of 10°C brings about a change in DoV of 500m. It is easy to envisage a situation where small temperature fluctuations generate a rising column of slugs of compressible wet steam alternating with slugs of incompressible liquid water.

Such a column will be unstable. It resembles a spring pendulum with a number of bobs and springs in a dynamic, turbulent environment.

This instability will extend to the reservoirs of Enhanced Geothermal Systems: Pressure fluctuations at the bottom of the column will feedback on the rate of Darcy flow through the reservoir and this, in turn, will affect the reservoir exit temperature.

Reservoir Exit Temperature	Steam Quality at Surface, q	Depth of Vaporization
170°C	0.120	1230 m
180°C	0.140	1560 m
190°C	0.157	1940 m
200°C	0.175	2360 m
210°C	0.196	2860 m
220°C	0.213	3400 m
230°C	0.234	4030 m
240°C	0.252	4740 m

Table 1. Steam quality at the surface and Depth of Vaporization as a function of Reservoir Exit Temperature.

As fluid rises in the well, pressure decreases so that more liquid is converted to vapour and existing vapour expands so that each parcel of fluid accelerates as it ascends. It is therefore possible for a slug of liquid, accelerated by expanding wet steam beneath it, to be traveling at high velocity relative to the walls of the well at the instant when it flashes to wet steam. As shown in Figure 1, this is precisely when the speed of sound is smallest. The quality, q, has a small value immediately following the onset of vaporization.

Thus the speed of sound can suddenly fall below the speed of the fluid in the well. When this happens a sonic shock must form spontaneously in the well, causing the vertical motion of the slug to be suddenly arrested, because the velocity of a fluid enclosed in a pipe cannot exceed the speed of sound.

Conservation of momentum requires that a very large force be exerted to so suddenly slow the motion of the ascending fluid. A very large pressure, manifested as an earthquake, thus suddenly develops behind the newly formed shock front.

PRESSURE RELEASE FOLLOWING STIMULATION

During stimulation, pressures in the injection well and reservoir are commonly too high for wet steam to form. However when pressure is released at the surface and water starts to flow out of the well boiling may occur within the well.

Consider the scenario depicted in Figure 2. As water rises in the well the temperature profile as a function of depth (Curve "a") can intersect the pressure-temperature characteristic of equation (1b) (Curve "b") resulting in some of the rising liquid being converted to wet steam in the overlapping region, the wet steam zone, "c". When this happens and the fluid continues to rise, this expanding wet steam causes the liquid above it to accelerate upward. As it does so the pressure drops further, forcing ever more liquid above the p-T curve, "b", so enhancing the expansion and acceleration until, finally, the liquid crossing into the wet steam zone is moving upward at greater than the speed of sound in low quality wet steam. When vaporization commences a sonic shock thus forms and the ascending fluid is rapidly decelerated by the large pressure behind the shock.

In our view this is the explanation for the occurrence "earthquakes" ranging from 2.9 to 3.7 on the Richter Scale associated with the stimulation phase of Enhanced Geothermal Systems. Indeed the event at Basel was described by one eye-witness as being "like a sonic boom".

A sonic boom is precisely what it was. The above description explains why these otherwise paradoxical events most often occur when pressure is released following stimulation instead of when the pressure is first applied.

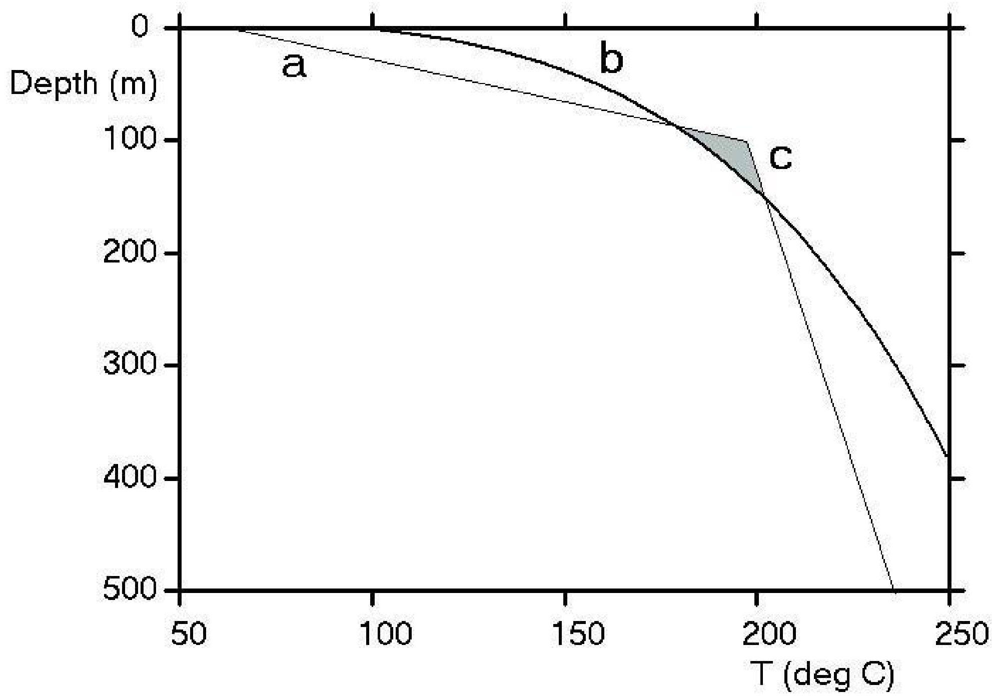

Figure 2. (a) Idealized profile of well temperature following stimulation. (b) The temperature-pressure characteristic of equation (1b). (c) Overlapping region in which wet steam is formed.

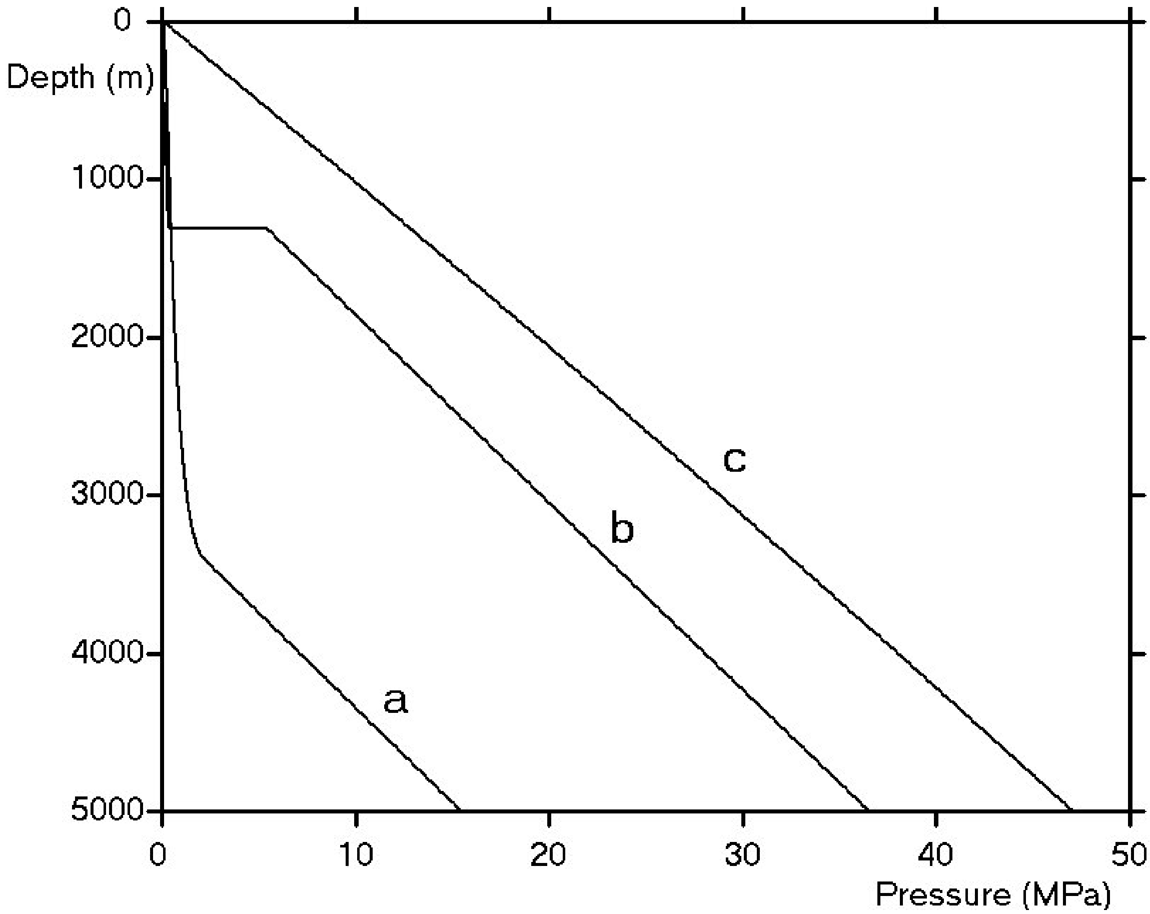

Figure 3. Pressure as function of depth. (a) Production well without valve. (b) Production well with pressure release valve. (c) Injection well.

PREVENTION

There is a very simple solution to these problems, viz.: *keep the fluid in the wells and in the reservoir in the liquid state to the greatest extent possible*.

This can be done following stimulation by releasing the pressure only slowly so that the temperature profile of the ascending column never crosses into the wet steam zone as depicted in Figure 2.

During routine Enhance Geothermal System operation what is needed is a down-hole pressure relief valve that maintains sufficiently high pressure to prevent the formation of wet steam lower down in the well.

A conceptual pressure profile of such a system is shown in Figure 3, in which the effect of introducing a pressure relief valve with a release pressure of 5 MPa at a depth of 1300m is shown as Curve "b". The pressure profile of the same production well without the valve can be seen in Curve "a". The reservoir exit temperature was assumed to be 220°C. The presence of wet steam is indicated by a steep profile because slope is inversely related to density. It can be seen that, without the valve, the Depth of Vaporization would be ~3400m.

The pressure difference across the reservoir at 5000m depth when there is no valve present is found by subtracting the x-axis intercepts of curves "a" and "c" and is about 31 MPa. When the down-hole pressure release valve is installed the pressure difference across the reservoir is reduced to only 10 MPa (Curve "c" minus curve "b".) so that well productivity is reduced disproportionately by the presence of the valve.

However, wet steam is no longer present in the production well below the level of the valve. Water flashes to wet steam as it passes the valve and both the valve and the upper part of the production well must be designed to accommodate this. Loss in well productivity will be more than compensated by operational stability.

The use of a pressurizing valve in Enhanced Geothermal Systems is thus analogous to established use, for operational stability, of resistive negative feedback in electronic circuit design.

CONCLUSION

Most, if not all, of the damaging earthquake-like events which bedevil Enhanced Geothermal Systems and reservoir stimulation can be eliminated by means of measures inhibiting the production of wet steam at depth.

LEGAL NOTICE

Some of the methods and apparatus described in this paper are the subject of a Provisional Patent Application

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