

SOME POSSIBLE CHARACTERISTICS OF GEOTHERMAL RESERVOIRS CONTAINING NEAR-CRITICAL PRESSURE FLUIDS

A. Watson. Geothermal Institute, University of Auckland

Abstract

It is argued that the long term future of geothermal electricity generation requires deep drilling for high temperature resources. The physical properties of water near the critical point are discussed and the peculiarities that they introduce into fluid and heat transfer behaviour in pipe flows is briefly discussed. Literature relevant to near-critical geothermal resources is reviewed. The possible nature of a near-critical reservoir is postulated

1.0 THE FUTURE FOR GEOTHERMAL ENERGY

If one examines the history of electricity generation, it can be seen that progress has not always been steady, but has sometimes required a backward step. The first large scale use of electricity was for **lighting**, about **1880**. In **1884**, Parsons patented the steam turbine and the turbo-generator. The major changes that have taken place since then are in steam conditions, which have increased from a few tens of bars to over 300 bars and superheat temperatures of 550 °C at present. The temperature controls the efficiency of conversion of the thermal energy to electricity, and a major development aim was to increase the temperature of steam at turbine inlet. For the larger sizes of turbo-generators that are economic, a steam temperature of about 550 °C was the optimum until the mid-1980's. The development history is set out in detail in a paper by Harris (1984).

In the course of this development, nuclear power appeared on the scene. As Harris says, using the first nuclear reactors to produce steam for turbines "put the clock back 60 years or more" since the steam conditions were so low. Present reactors still cannot match fossil fuelled steam generator conditions.

The significance of this to geothermal engineers is that the same has happened with the introduction of large scale geothermal power generation. The turbo-generators used are of conventional design but use very modest steam inlet conditions of typically only 6 or 7 bars with no superheat, steam conditions that were available for engines as early as 1712.

This apparently depressing review should not be taken as an indication that all our achievements in geothermal science and engineering, of which PNOG has taken a major role, have been a waste of time and effort. The generation in 1983 of up to 112MW of geothermal electricity on Leyte at a reasonable cost, where it was needed and from an indigenous resource was extremely valuable, no matter how modest the turbine inlet conditions. Steam conditions by themselves are not the main criterion. But if we can produce geothermal steam economically at better conditions, then the means of using it is available. The prospects for meeting the expected worldwide demand for electricity over the next 50 years seem to lie with coal, yet environmental concern about greenhouse gases and thermal pollution is growing. If geothermal energy is to make a larger contribution, then we must drill deeper and find resources other than those we are currently using. In this context, reservoirs at near-critical conditions might be very attractive, giving higher outputs per well and higher **steam** temperatures. The critical pressure for pure water is 221.2 bar abs. and the critical temperature is 374 °C. Pressures above the critical are often encountered in geothermal wells, but not with matching critical temperatures. Maximum temperatures in the critical region have been reported elsewhere, but not with matching critical pressures. With drilling to 4000m now being undertaken in Japan in a reservoir with high temperatures, it is appropriate to begin to examine the topic from a reservoir engineering point of view.

Quite separately, near- and supercritical fluid properties and behaviour have been studied by geoscientists in connection with ore deposits, notably the work by Norton and Knight (1977) on pluton cooling, and fluid inclusion interpretation.

2.0 FLUID PROPERTIES AND BEHAVIOUR NEAR THE CRITICAL POINT

The following shows the critical conditions for several pure fluids :-

	T _c (°C)	T _c (K)	P _c (bar abs)
CO ₂	31.0		73.85
H ₂ O	374.15		221.2
He		2.29	5.2 (He ⁴), [3.3 (He ³)]

Fluid behaviour in the region of the thermodynamic critical point has attracted interest for well over a century. Van der Waals proposed an equation of state for the region as early as 1873. By about 1960, several quite different advanced engineering applications of near-critical fluids were being studied, although this was not because of any special attractions of the properties of fluids in the near-critical region. It was simply that pressures and temperatures planned for the applications brought the working fluid conditions into the near-critical region. In improving the thermal efficiency of steam plant, the operating pressures of fossil fuelled boilers had increased to the near-critical region. Rocket motors for space flight and superconductors used hydrogen and helium respectively at near-critical conditions.

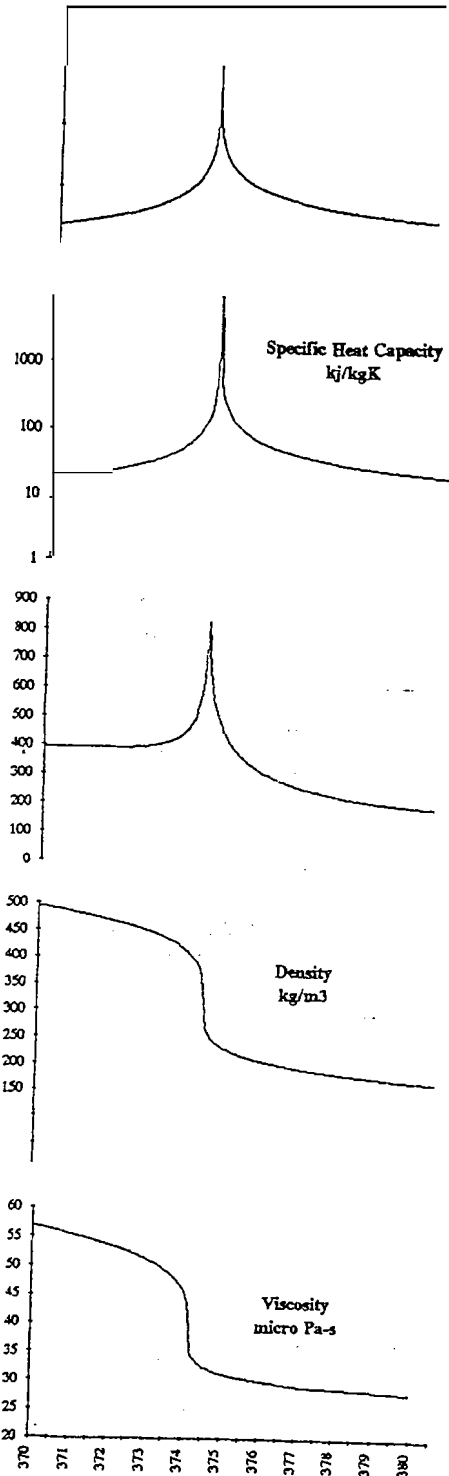
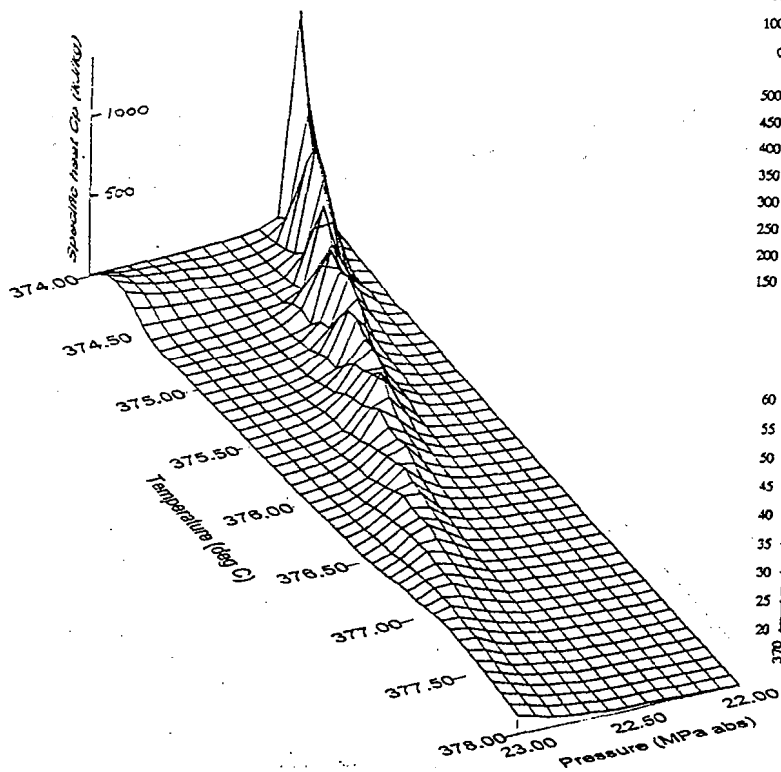
The range of critical points for different fluids is extreme, making laboratory experimentation difficult. Fortunately, according to the "Law of Corresponding States", isotherms of all fluids have the same shape when expressed as reduced parameters. $P^* = P/P_c$, $V^* = V/V_c$ and $T^* = T/T_c$. The law is unlikely to be precise, and there is no reason to suppose that it applies very well to the transport properties, however it provides a basis for easier laboratory experimentation. Thus CO₂ has been used for many laboratory experiments because of its modest T_c and P_c.

The best known feature of the critical pressure is that it is the pressure above which an interface between the liquid and vapour phases ceases to exist as the temperature rises through what would otherwise have been called the saturation temperature. This can be seen in fluid inclusions. Boiling continues to take place up to the critical point, although surface tension is reducing towards zero, so that bubble growth will differ from that at lower pressures.

Some properties of pure water at the critical pressure are shown in Fig. 1, calculated from the 1967 IFC Formulation for Industrial Use (currently available as the ASME Steam Tables). Specific heat at constant pressure, C_p, thermal conductivity, k, and volumetric expansion coefficient, β, all show large localised peaks at the critical temperature.

The thermal conductivity of rock, at typically 2 to 4 W/mK is larger than the peak value for water, so it may not be very significant. The variations in specific heat and expansion coefficient are likely to be the dominant factors in controlling fluid flow and heat transfer. Density and kinematic viscosity show reductions consistent with the idea that below the critical temperature the fluid is a liquid and above is a gas, with a localised steep but continuous variation between.

however the property functions are continuous above the critical point. The **high** Cp region is seen to form a ridge that decreases in amplitude, and the crest of the ridge is the locus of the pseudo-critical point. The values of specific heat are extremely **high** on this ridge, up to 1000 kJ/kg (for comparison Cp for pure water at atmospheric conditions is 4.2 kJ/kg) However the effect is very localised in temperature



3.0 LITERATURE REVIEW

The literature on heat transfer to fluids in the near-critical region flowing in ducts was reviewed by Hall (1971). Perhaps the most important physical effect discovered was the influence of buoyancy forces even in forced flows with high Reynolds Numbers. In experimental measurements of heat transfer in pipes at Reynolds Numbers in the region of 10⁵ the buoyancy effect was found to be significant. The effect of buoyancy is to reduce turbulence in upward flows when the buoyancy was aiding the flow, and to increase it when opposing the flow, as a result of the modification to the shear stress distributions. Thus the heat transfer was reduced when the buoyancy effects were aiding the flow, and vice-versa. Hall (1971) showed how the effects could be examined via the governing equations in dimensionless terms, and Harrison and Watson (1976) later examined the basis of correlations in the same manner.

These investigations provide a warning that similar unusual effects should be anticipated in flows of near-critical fluids through porous media.

Dunn and Hardee (1981) carried out laboratory experiments with water at pressures between 225 and 248 bar abs., within the high property value ridge of Fig 2, and measured the rate of heat transfer from a wire along the axis of a cylinder packed with silica sand - Fig 3.

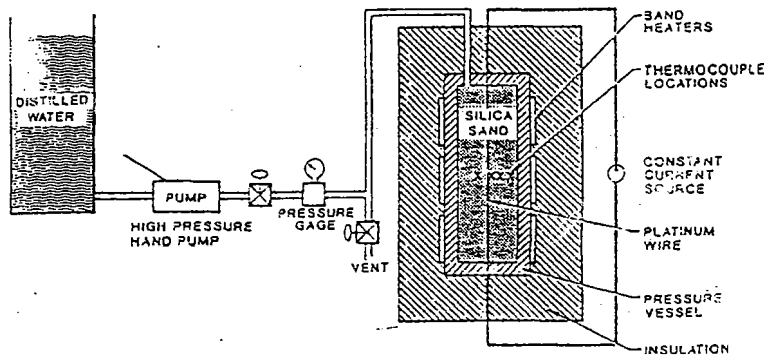


Fig 3 - Dunn and Hardee's experimental arrangement

The cylinder had closed ends and was able to be turned so that the wire was vertical, or horizontal. At the midpoint of the 0.387m long wire several thermocouples were placed at different radial positions in the sand. The vessel appears to have been about 0.028m in radius, giving a high length to diameter ratio. The measured heat transfer rate in the near-critical region peaked at about 70 times the rate at room temperature.

The experiment had no clearly defined thermal boundary conditions at the cylinder wall, so there was no steady state for the thermocouples to reach. There is no mention of the time after the start of heating that the temperature measurements were taken. With the wire vertical, it is probable that a radially symmetric cellular convection occupied the whole cylinder, whereas with the wire horizontal the convection would not have been radially symmetric, but is less likely to have been influenced by cylinder end conditions. Hence the agreement between a calculated Rayleigh number based on wire length and the measured heat transfer rate is rather empirical. The authors estimated the typical depth required to reach critical pressure in a typical reservoir and the rate of heat extraction that might be possible from a horizontal tubular heat exchanger situated in the critical region.

This experiment appears to be the only one carried out in near-critical conditions in porous media. It represents a significant laboratory effort, but the extension of the results to full scale geothermal reservoirs is doubtful. Firstly, there is the possibility of unexpected physical interactions, even in such a simple experimental arrangement. Additionally, the hydrostatic pressure variation in a small scale laboratory experiment would have been small enough to keep the entire cylinder in the high property region, whereas in a real reservoir hydrostatic variations impose a significant vertical property variation. This means that the

Rayleigh number alone, which they used to correlate their results, is not a sufficient parameter to characterise heat transfer.

Cos. Pruess and McKibben (1988) modelled **Dunn** and Hardee's (1981) experiment using the **MULKOM** reservoir simulator. They found that changes to the numerical procedures were required because of the extreme variation of properties with temperature and pressure. The simulations produced increases in heat transfer rate of a factor of **only 5** with reference to pure conduction as opposed to the factor of 70 measured by **Dunn** and Hardee. The authors called for more experimental measurements to allow the modelling to be validated.

There is currently a good deal of effort being put into modifying reservoir simulators, for example **Hanano** and **Seth** (1995) and **Kissling** (1995). It is my opinion that while there is no disadvantage in preparing the way for modelling, the message from non-porous media research into heat transfer near the critical point is that the physical processes involved need to be examined experimentally and will not immediately be demonstrated by solving the equations. More guidance is required for the solution process. Furthermore, given the very **high** expansion coefficients and hence buoyancy forces and natural convection, it does not seem reasonable to assume that **Darcy's** law will hold.

4.0 PRELIMINARY IDEAS OF THE BEHAVIOUR OF A RESERVOIR CONTAINING NEAR-CRITICAL WATER

In order to try and visualise how a reservoir containing near-critical water will exhibit itself, consider a reservoir of **uniform** porosity and permeability filled with pure water and infinite in lateral extent. It should be emphasised that the regime described is speculative. The pressure with depth is hydrostatic. Suppose level **A**, the bottom of the reservoir, has a pressure of 300 bar abs. and has a point heat source at a temperature of 600 °C. There will be some natural convection from the point **source**. Consider this as an effective conductivity. Taking into account the peak in expansion coefficient, promoting natural convection, and the **high** specific heat, reducing temperature rise, the vertical temperature distribution for a constant upwards heat flux from level **A** to level **B** at which the critical point is reached should have the general form shown in Fig 4.

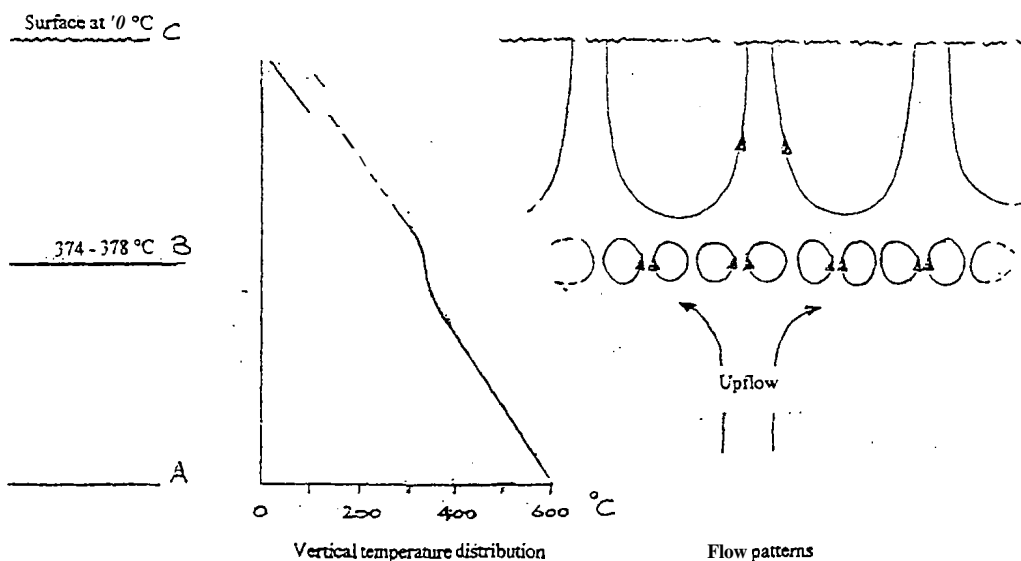


Fig 4 - Possible features of a reservoir containing near-critical fluid

The heat transfer **rate** through the ground surface at **C** is relatively low and dominated by conduction. If level **C** is assumed to be at 20 °C, then the upwards heat flux will be governed by the temperatures at

B (374 - 378 °C) and C. and not by the vertical heat flux below B. This will normally include sonic convection taking place between B and C. The peak in the buoyancy forces and the very high specific heat in the near-critical zone should effectively isolate the two parts of the reservoir; there is no effect of inertia, so the sharp and continued reduction in expansion coefficient and consequent decrease in the buoyancy forces above level B should localise the intense circulation in the near critical region. In fact, the natural convection within the high expansion coefficient region, the same ridge as shown in Fig 2, seems likely to extend only for the thickness of that region. There may be circulation in relatively "square" cells occupying the near critical region - Fig 4. The heat transfer coefficient in this zone (the effective conductivity) would be very high, and with the high specific heat would keep the zone at almost uniform temperature. Because the rate of heat transfer vertically is restricted a high vertical heat flux below B from the point source (a pluton) should cause the lateral spreading of the near-critical zone. Despite the very high values of specific heat, the enthalpy and hence heat storage in the near-critical zone are relatively normal, because the decreasing density smooths out the effect of Cp. The important effect should be on the fluid mechanics and heat transfer rates. With its high lateral heat transfer rate the zone would be potentially attractive for power development.

The above is speculative and idealised and some realities need to be addressed, as follows :-

4.1 Flow regime

It is not possible to arrive at the flow regimes with certainty by speculating as above, but neither in my view will the numerical solutions show them with certainty. Some experimental measurements are required.

4.2 The thickness of the near-critical zone

Because the variation of properties is so localised with temperature and pressure - Fig 1 - it is conceivable that the near-critical layer would be very thin. If this were the case, then it would be unreasonable to assume that it could effectively separate lower and upper reservoirs, and a laterally extensive near-critical reservoir would be less likely to exist, bearing in mind the randomness in geological formations.

Taking into account the density variations with pressure and temperature, the hydrostatic pressure distribution has been calculated. Fig 5 shows the pressure and temperature range over which Cp is greater than 100 kJ/kg,

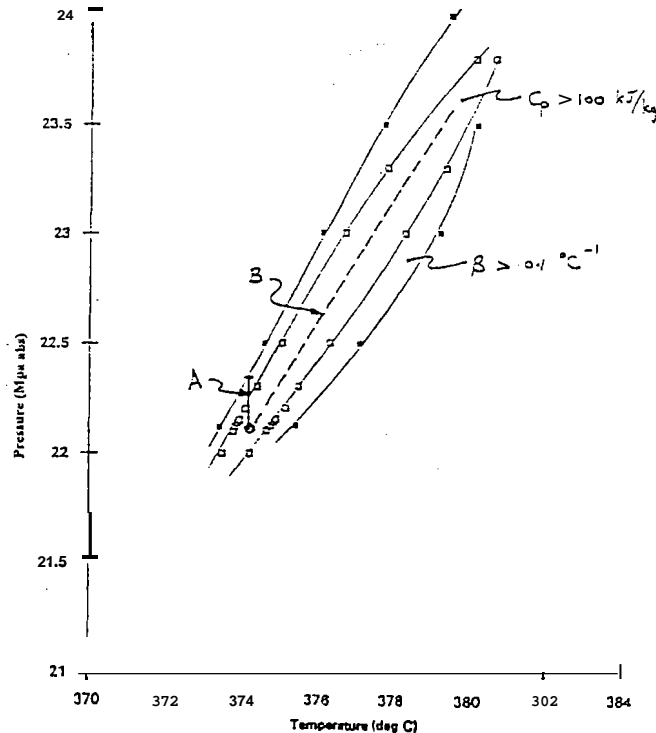


Fig 5 - Regions of high specific heat and expansion coefficient on the P-T plane

and β is greater than $0.1 \text{ } ^\circ\text{C}$. If the temperature of the near-critical zone **was** constant at T_c , the pressure variation through the region would be as shown in Fig 5 by the line marked A. In this case **the** zone would be of order 1-10m thick, and it would have insignificant effect. To achieve the maximum thickness, the temperature distribution would need to follow the ridge of Fig 2. With a modest vertical temperature gradient of about $0.1 \text{ } ^\circ\text{C/m}$ consistent with a high heat transfer rate, the zone could be **of** order 100m thick, which is thick enough to be significant.

4.3 Real fluid properties

Real geothermal fluids are weak solutions. The **critical** point increases with dissolved solids concentration - Fig 6 is taken from Sourirajan and Kennedy (1962). The effect of dissolved gas and other chemical species needs to be considered also.

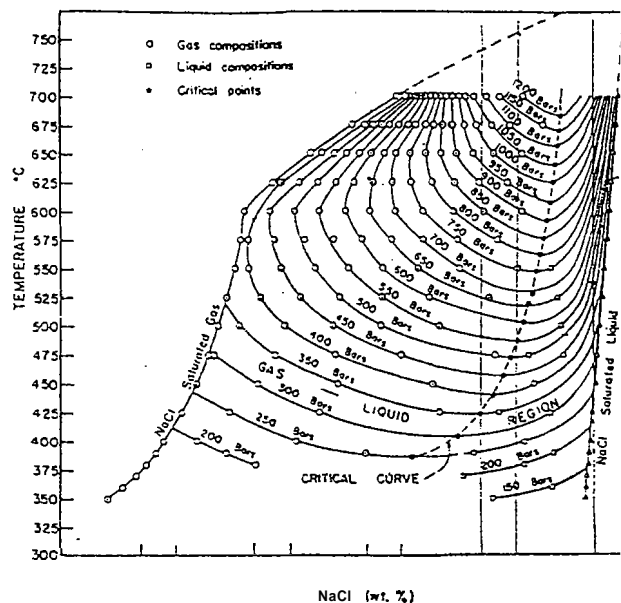


Fig 6 - locus of the critical point of NaCl solutions. from Sourirajan and Kennedy (1962)

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Nomenclature

P pressure

V specific volume

T temperature

Suffix c - critical point

C_p specific heat at constant pressure

β coefficient of cubical expansion

Superscript * - reduced values (eg $P^* = P/P_c$)