

A Review of Progress in Understanding Geysers

Xinli Lu and Arnold Watson

Geothermal Institute, University of Auckland, Private Bag 92019, Auckland, New Zealand

arnold.watson@auckland.ac.nz

Keywords: geysers, measurements, numerical models

ABSTRACT

There has been a longstanding and widespread interest in preserving geysers, which can best be achieved by understanding how they function. There is current interest in geysers on other planets. Recent measurements on a low temperature geysering well discharging an aqueous solution of carbon dioxide are presented, to demonstrate that the typical periodic flow that characterizes a geyser can occur in a single duct of uniform cross sectional area. Past research on geysers is reviewed in an attempt to determine whether there is clear evidence that other geysering mechanisms exist, for example through the interaction of connected chambers. Numerical models of geysers are discussed.

1. INTRODUCTION

Geothermal geysers attract a very great deal of interest from both the scientific community and the general public. In the latter case the interest is understandably due to the sudden appearance of a column of boiling water and steam where there was previously none, and the bigger the geyser the greater the interest. However the interest of the scientific community is less well defined and less understandable. Engineers are likely to regard geysers as simply a two-phase flow, but with a periodicity that clearly arises from a set of parameters that fall within a very narrow range, as evidenced by the rarity of such periodic flows. Many earth scientists, for reasons that we are not qualified to explore here, still regard them as possessing "mystique".

Nevertheless, preservation of those that are likely to be affected by human developments is well justified, in our view. Despite the priority given by the New Zealand Government to the preservation of its best known geyser, Pohutu at Rotorua, the authors were surprised to find that when its periodicity disappeared recently and it discharged as a continuous column for several months, no doubt impressive, this was hailed by local scientists as a major preservation success. Geysers by definition discharge periodically, and any that discharge otherwise are not geysers. The flow is potentially erosive, both mechanically and chemically; the rock may be altered and hence incompetent; silica deposition may take place to alter the passage dimensions; all of these factors cause geysers to have a limited life, even if other parameters such as aquifer conditions were to stay constant. Preservation would be assisted by better understanding.

The phenomenon of regular periodic discharge of two-phase flow (geysering) has been found in mechanically constructed equipment such as chemical processing plant, power station boilers, rocket motors and wells, both geothermal and petroleum. This provides the clues to the operation of natural geysers, because the flow passages are

regular in shape and hence are easy to make measurements in compared to a natural geyser flow path. The measurements reported here were made in a geysering well in Te Aroha, New Zealand. The well is 100mm in diameter and 70m deep, and is cased to within a few metres of the bottom. It discharges with a period of about 15 minutes. It will be demonstrated that the geysering action results from flow processes taking place entirely within the casing. This is of fundamental importance since historically geysers have been thought to require chambers that alternately empty and fill. It will be reasoned that geysers may have chambers, but that they are not the primary requirement for geysering flow. The primary requirement is the separation of steam or gas bubbles (vapour) from the liquid in the flow passage, their collection into slugs of vapour, and the differential flow rate of vapour and liquid.

2. LITERATURE REVIEW

Geyser studies have been carried out for about 190 years (Rinehart, 1980). The initial studies were mainly focused on Icelandic geysers; some of the papers are in Icelandic or are no longer available. There was some early New Zealand work that has received little attention, by Malfroy (1891) who was a French engineer appointed as engineer in charge of the Government Thermal Springs District of New Zealand immediately following the Tarawera eruption in 1886 (Just, 2000). According to Just, Malfroy was able to "engineer" a spring to perform as a geyser using earthenware pipes sunk to a depth of 6-10 feet, and he also made a laboratory model.

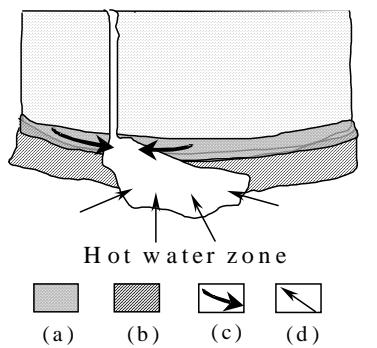
Allen and Day (1935) reviewed work up to that time. Bunsen and his colleagues measured the temperatures at different depths in the Great Geyser in Iceland and concluded that the boiling began approximately at the middle of the channel, where the temperature was closest to the boiling point curve. However, his theory was not accepted by some, such as Sherzer (1933), Lang, and Thorkelsson (in Allen and Day, 1935), on the grounds that Bunsen's theory did not satisfactorily explain the intermittent nature of the geysers and how the water was heated to boiling. The idea that the boiling did not take place in the geyser channel but at a lower place, where the temperature was higher, was supported by many researchers, including Allen and Day (1935). This idea led to the concept that there was an underground chamber at the bottom of the channel, where water was heated to boiling periodically.

Many researchers (Allan and Day, 1935; White, 1967; Anderson et al., 1978; Murty, 1979; Rinehart, 1980; Dowden et al., 1991) accepted the concept that it was the boiling of water that drives the eruption of most of the geysers, however, some considered that gases might play a role. Although Allen and Day's tests in the Yellowstone National Park gave no support for this, Rinehart (1980) suggested that CO₂ might play an important role. It was noticed that the behavior of geysers discharging gassy fluid

was markedly different to that of a steam-activated, hot water geyser.

Allan and Day (1935) concluded that there were three essential elements of a geyser: a heat source, a water source and a chamber with a very narrow or tortuous channel above. Based on temperature-depth curves of some geysers at Yellowstone National Park, they thought that the heat source was magmatic and was transported by steam. The water source was supposed to be supplied by the inflow of cold water from neighboring cavities. The inflow of cold water was considered not to be constant but greatest after eruption then decreasing. White (1967) recognised that direct magmatic involvement was not necessary. Anderson et al. (1978), Rinehart (1980), and Steinberg et al. (1981) all agreed the need for a flow channel that was narrow, with a number of sharp bends or constrictions along it, and perhaps more than one chamber.

Steinberg et al. (1981) developed a conceptual model as shown in Figure 1.



(a) cold water bearing horizon; (b) low permeability zone; (c) inflow of cold water; (d) inflow of hot water

Figure 1: Conceptual model of a geyser (Steinberg et al., 1981)

The chamber is connected to the surface by a narrow channel. Two feed points were assumed, one for the deep inflow of geothermal water, and the other for a shallow inflow of cold ground water. This conceptual model was used to develop numerical models. Saptadji (1995) reviewed the work of Lloyd (1975) on the three main New Zealand geysers at Rotorua, and went on to construct a laboratory model that included a chamber, and also a numerical model. Weir et al. (1992) developed a numerical model allowing interconnections between geysers, with each geyser consisting of a chamber and a channel fed by hot water from depth and cold water from a shallower source.

Turning now to geysering in engineered plant and equipment, geysering problems arose in the fuel feed systems of liquid fuelled rocket motors in missiles, which typically use long lines to connect the fuel tank to the engine. Since the propellants are cryogenic they are heated in the feed line by the atmosphere during missile fueling before launch. Geysering during this period was found to occur. Murphy (1965) carried out an experimental study using a vertical tube in the form of an open thermosyphon (i.e. a tube with a heated wall and closed lower end opening into a reservoir at the top), as shown in Figure 2. He developed an empirical correlation for the prediction of geysering, based on 114 tests using water, Freon 113, liquid nitrogen, and liquid hydrogen as working fluids. The

diameters of geyser tubes used in the tests were 4, 6, 8, and 13 inches, with the ratios of the tube length to the tube diameter (L/D) ranging from 1.5 to 30. The heat flux ranged between 50 and 1900 Btu/ft²·hr.

According to Murphy (1965), the liquid adjacent to the wall rises as it is heated and cool liquid from the reservoir descends down the center of the tube to take its place as shown in (A). A convection cell is created. The warm liquid rising adjacent to the wall forms a boundary layer, which grows in thickness from the bottom of the tube to the top. After a period of time, the thickness of the boundary layer blocks the downward flow of cool liquid, the temperature rises as convection decreases, and the liquid eventually boils at (B). Bubbles are first formed on the tube wall, and then detach and rise upward due to the buoyancy. They coalesce and form a large bubble (Taylor bubble) as shown in (C). The formation of the bubbles reduces the pressure below them where more bubbles form in the saturated liquid. This chain reaction causes the vapour to form so rapidly and violently that it expels the liquid upward from the tube in an eruption.

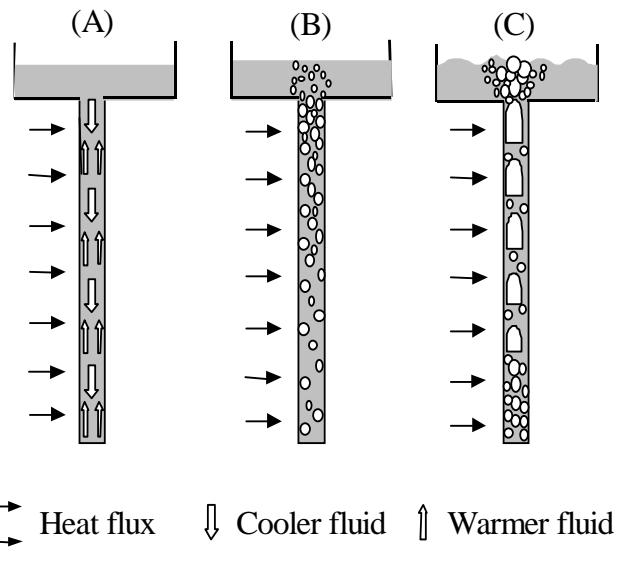


Figure 2: Murphy's (1965) open thermosyphon experiment

An empirical correlation for the prediction of geysering in terms of heating rate, system geometry, and fluid properties was obtained, based on which a geyser-nongeyser correlation map was generated. Murphy's results showed that the most significant parameters were the length of the tube L and the length-diameter ratio L/D . The heat flux appeared to have minor effect.

The loss of water from water cooled nuclear reactors is a major source of concern and related two-phase flow instability has been a topic of research since the 1950's. Geysering in coolant channels in the reactor core during startup has been examined by, for example, Aritomi et al. (1992, 1993), Jiang et al. (1995), and Paniagua et al. (1999). However the literature is not always clear about the distinction between geysering as a regular periodic event and irregular two-phase flow instability.

Both Jiang et al. (1995) and Paniagua et al. (1999) investigated the flow in a vertical tube with a length to diameter ratio of 50, with a smaller diameter heated section at the bottom through which liquid flowed upwards. They studied the growth and flow of bubbles in this tube.

The significance of all of this work to natural geysers is that the geysering action could be produced in a tube, without having a chamber. This leads immediately to a consideration of geysering wells. White (1967) discussed the behaviour of a geysering well in Steamboat Springs, Nevada. In his paper, some detailed data such as temperature-time curves and temperature-depth curves were shown and described. Rinehart (1980) listed many typical examples of geysering wells. Several geysering wells associated with the petroleum industry are found in the eastern USA. One such well was drilled to a depth of 600m. It was abandoned due to the small yield of oil but later became a gas-driven water geyser. It regularly projected a column of gas-saturated water to heights from 30 to 45 m at periods ranging from 10 to 15 min. The gas was found to be inflammable hydrocarbon and apparently it was often lit at night. Several other wells found in this region show similar behavior. The Crystal Geyser at Green River, Utah is a similar well that produces cool water and carbon dioxide (Rinehart, 1980). The water temperature in the pipe before eruption is only about 15 °C, but the geysering is reported to eject water to 50 m for about 5 to 10 min. The eruption continues at its maximum height for 4 to 5 seconds. Immediately after the eruption, the water in the well falls to approximate 8 m below wellhead, and about 3 hours after the eruption, it overflows with “foaming and hissing” in the pipe, and the process is repeated. Geysering wells producing water at less than 100°C have been reported in other countries, including France, Iceland and Russia.

At Te Aroha, North Island of New Zealand, there are three geysering wells, with water temperatures from 90 °C at the bottom to 70 °C at the top. Preliminary investigation by Michels et al. (1993) showed that the major dissolved component of the water in the well is bicarbonate, and hence CO₂ is the main reason for geysering.

Little detailed information with regard to the mechanism of gas-driven geysering wells has been reported, however Nurkamal (1999) carried out some downhole measurements of the type to be described below.

3. EXPERIMENTAL MEASUREMENTS IN A GAS DRIVEN GEYSERING WELL

The measurements are fully reported in the PhD thesis of Lu (2004). They were carried out in the well at Te Aroha, New Zealand, which as mentioned is continuously cased to a diameter of 100mm to a depth of 70m, with only a few metres of open hole below that. The bottom-hole temperature is of order 90°C and the discharge temperature is about 60°C. The well is artesian, and flows steadily until the wellhead valve is opened sufficiently, ie the wellhead pressure falls sufficiently. This causes the pressure at depth to fall below the pressure at which the gas comes out of solution. As reported by Nurkamal et al (2001) the well discharges every 15 minutes (approximately) and empties to a depth of approximately 5m. It refills at a steady rate. Pressure measurements at various depths were made using vibrating wire pressure transducers. These measurements have been extended by Lu (2004), who used two instruments, one hung at a reference depth and the other at various depths down to 60m. Each pair of measurements was made simultaneously over at least three geysering cycles, and the cycles were plotted as superimposed records, to compare the pressure variations throughout a geysering cycle.

The geysering cycle as seen at the surface is as follows. In every cycle there are usually several eruptions, increasing in magnitude (height), with slightly longer time between each. After the last one, the water level falls relatively quickly to about 5m below wellhead, and nothing more can be seen from the surface. After a time, water can be seen slowly rising towards the wellhead, it reaches the wellhead and begins to overflow. The water at this stage appears almost degassed, there are bubbles but they are relatively small and do not appear to make the flow non-uniform. After a period of overflowing the well begins to erupt. The pressure variations at a depth of 20m during a cycle are shown in Figure 3 below. The graph starts at the time at which the water just reaches the wellhead and begins to overflow, and the pressure at 20m declines as this overflow continues. This is interpreted to be the result of gas coming out of solution and reducing the fluid density between 20m and wellhead. After almost 200seconds, at B, the well begins to erupt, which shows as an increase in pressure at 20m depth. At point C the pressure is the lowest of any during a cycle, and the water level is also the lowest. After that the water level begins to rise due to the artesian pressure from the aquifer. From C to D the flow above 20m is clearing itself of gas bubbles, and at depth the generation of gas bubbles is decreasing. From D to E the water is refilling the well and above 20m the density is not affected by gas bubbles to any great extent.

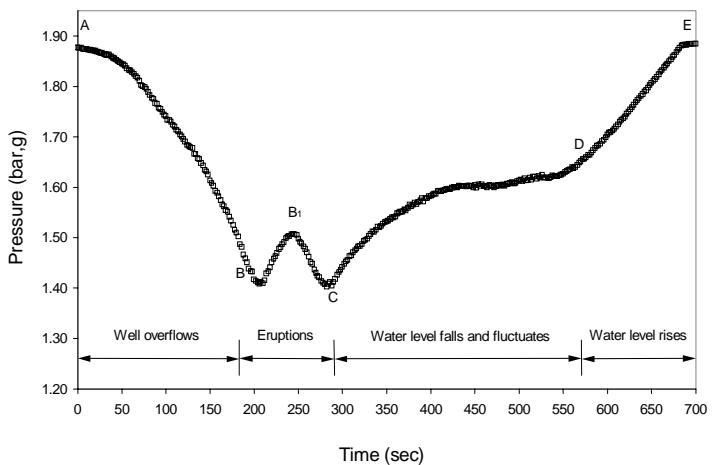


Figure 3: Pressure variations at a depth of 20m during a typical cycle

Whilst this is taking place the pressure variations at depth affect the depth (flash point) at which gas first comes out of solution; the flash point varies during a cycle as shown in Figure 4.

As explained above, Lu (2004) was able to measure the pressure variations at two depths simultaneously, and these demonstrate that the variation decreases with depth – this is consistent with the redistribution of gas taking place nearer to the surface. An example of his measurements is shown in Figure 5 for depths of 20m and 50m.

Finally it has been shown that the temperature variation during a cycle is not a major variable. The measured temperature distributions are shown in Figure 6.

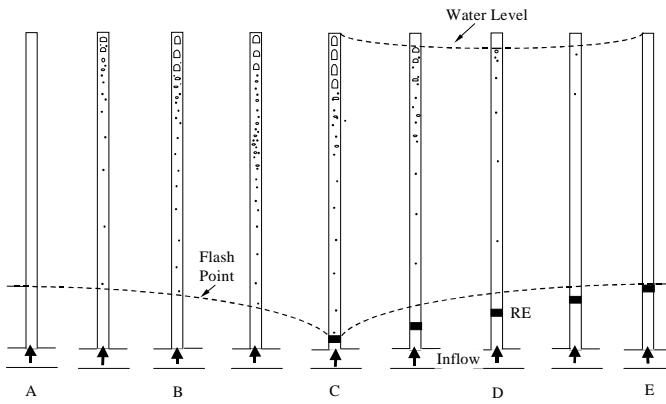


Figure 4: Showing the variation of flash point (gas dissolution point) during a cycle

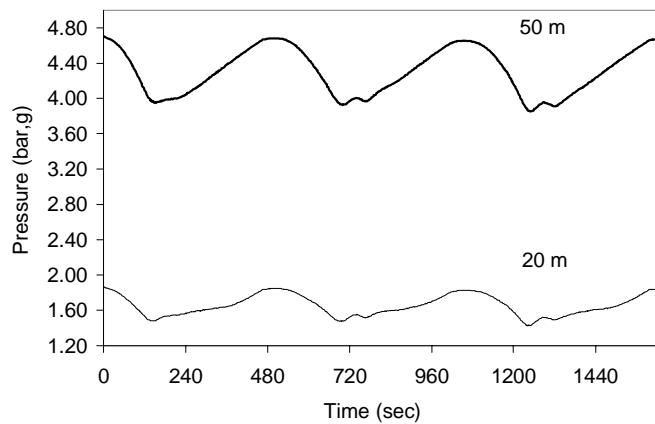


Figure 5: pressure variations at 20m and 50m below wellhead over several cycles

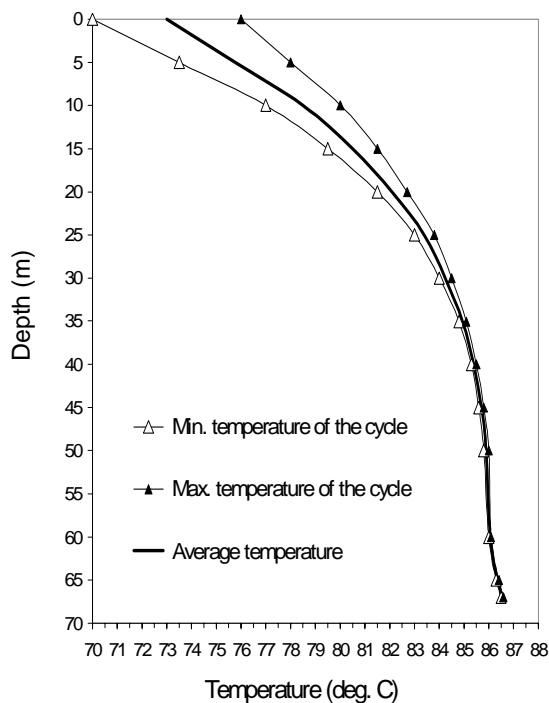


Figure 6: Temperature distribution in the well during geysering

4. NUMERICAL MODELLING

Numerical modeling is based on a one-dimensional representation of the flow. Because of the very small influence of the energy equation it has been found that the equations of continuity of mass and momentum flows are sufficient to obtain solutions that match the experimental measurements. Furthermore, acceleration and friction play only a very minor role in the flow, which is dominated by gravity. A feature of the equations is a source term to allow for carbon dioxide to come out of solution. The properties of aqueous solutions of carbon dioxide were variously described by Ellis and Golding (1963), Malinin (1974), Sutton (1976), and O'Sullivan et al. (1983). According to Michels et al. (1993), the mass fraction of CO_2 of the inflow at the bottom of the well (MF_{Cl}) is 3000 ± 500 mg/kg, so a value of 3000mg/kg was used. The mass flow rate entering the well was measured from the slope of the pressure rise at the end of the cycle, Figure 3, when the well was filled with water largely free of the influence of carbon dioxide bubbles. The solution procedure and results are described in detail by Lu (2004), who found good agreement with his experimental data. An example of the agreement is indicated by Figure 7. The pressure variation at a depth of 20m was measured many times, since it was the datum depth for each pair of measurements. The starting point of a cycle was defined as the time at which the water level just overflowed the wellhead, and this was easy to detect on pressure measurement graphs such as Figure 3. Thus many measured cycles at 20m depth were overlaid, and are shown in Figure 7, together with the numerical solutions for the assumed flow rate and gas concentration. The numerical solution is the heavy line. The solution procedure is not capable of identifying the chaotic processes of eruption near the low point of pressure during the cycle, but otherwise appears to be good.

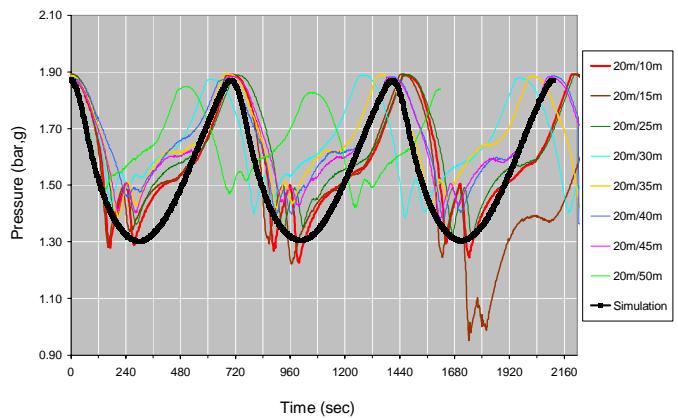


Figure 7: Comparison of model predictions (heavy line) with many measured cycles, which show some variation

5. DISCUSSION

The aim of this investigation is to understand how a gas driven geyser functions. The strategy of the investigation was first to make measurements in a single tube with the regular periodic two-phase flow driven by carbon dioxide coming out of solution, ie the Te Aroha well. This was chosen simply because it appeared to provide a clue and presented a difficult but feasible experimental opportunity. The next step was to represent the flow by appropriate one-dimensional equations. Both of these steps have been completed. The third step is to modify the equations to represent a flashing flow instead of a flow ex-solving gas. Carbon dioxide coming out of aqueous solution following

pressure reduction does so as a step change – almost all of the gas comes out of solution at once. In contrast, steam is continuously generated in a flashing flow as the pressure declines. The bubble source term in a gas driven geyser is very localized in depth while in a flashing flow it is distributed. Solutions for flashing flows are in progress. The final step would be to remove doubt about the validity of any numerical solutions by constructing a vertical heated tube laboratory experiment. No plans for this have been made.

CONCLUSIONS

It is postulated that the simplest flow channel arrangement that can produce geysering is a straight, constant cross section pipe such as a cased well. The work reviewed in this paper takes us part-way to verifying this postulate. The literature review shows that there are probably a very large number of variations in flow channel arrangements that can produce periodic two-phase flow, or geysering in flashing flows. Natural geysers might comprise a single channel or a more complicated arrangement – it is not possible to deduce this from measurements made at a geyser outlet (fluid, periodicity, etc). Laboratory measurements associated with natural geyser research have invariably used non-simple flow channels, with chambers, probably as a result of early ideas. In contrast unwanted geysering in engineering equipment has occurred mainly in simple tubular flow passages. Based on the work reported here on gas driven geysering, it is likely that the geysering discharge or eruption in natural geysers occurs as a result of large bubbles that fill almost the entire cross section of the final passage, no matter what the deeper arrangement is. Once these get to a level at which their pressure is greater than the hydrostatic pressure of the fluid column above, the resulting force imbalance accelerates the column in a discharge or eruption. Second order physical processes take place deeper in the flow channel arrangement, according to the geometry and fluid characteristics and also the supply of fluid into the flow channels, and these appear to dictate the period of the geyser.

REFERENCES

Allen, E. T. and Day, A. L.: Hot Springs of the Yellowstone National Park, *Carnegie Institution of Washington, Publication No.466*, (1935), 525 pp.

Anderson, L. W., Anderegg, J. W., and Lawler, J. E.: Model Geysers, *American Journal of Science*, **278**, (1978), 725-738.

Aritomi, M., Chaiang, J. H., Mori, M.: Fundamental Study on Thermo-hydraulics During Start-up in Natural Circulation Boiling Water Reactors, (I) Thermo-hydraulic Instabilities, *J. Nucl. Sci. Thechnol*, **29**(7), (1992), 631-641.

Aritomi, M., Chaiang, J. H., Mori, M.: Geysering in Parallel Boiling Channels. *Nuclear Engineering and Design*, **141**, (1993), 111-121.

Dowden, J., Kapadia, P., Brown, G. and Rymer, H.: Dynamics of a Geyser Eruption, *Journal of Geophysical Research*, **96**, (1991), No. B11, 18058-18071.

Ellis, A. J. and Golding, R. M.: The Solubility of Carbon Dioxide above 100°C in Water and in Sodium Chloride Solutions, *American Journal of Science*, **261**, (1963), 47-60.

Jiang, S. Y., Yao, M. S., Bo, J. H., and Wu, S. R.: Experimental Simulation Study on Start-up of the 5 MW Nuclear Heating Reactor, *Nuclear Engineering and Design*, **158**, (1995), 111-123.

Just, J. T.: Proposal to Restore the Malfroy Geyser Basin together with a Sustainable Working Geyser, *Report to Rotorua District Council*, (2000).

Lloyd, E. F.: Geology of Whakarewarewa Hot Springs, A. R. Shearer, *Government Printer*, Wellington, New Zealand, **23**, (1975).

Lu, X.: An Investigation of Transient Two-phase Flow in Vertical Pipes with Particular Reference to Geysering, *PhD Thesis*, Department of Mechanical Engineering, School of Engineering, The University of Auckland, New Zealand, (2004).

Malfroy, C.: On Geyser Action at Rotorua, *Trans. and Proc. New Zealand Institute*, **XXIV**, (1891).

Malinin, S. D.: Thermodynamics of the H₂O-CO₂ System, *Geochemistry International*, **II**, (1974), 1060-1085.

Michels, D. E., Jenkinson, D. and Hochstein, M. P.: Discharge of Thermal Fluids at Te Aroha (NZ), *Proceedings*, 15th New Zealand Geothermal Workshop, The University of Auckland, Auckland, New Zealand, (1993), 21-27.

Murphy, D. W.: An Experimental Investigation of Geysering in Vertical Tubes. *Advance Cryogenic Engineering*, **10**, (1965), 353-359.

Murty, T. S.: A Mathematical Model for Pre-boiling Convection in a Geyser Vent, *American Journal of Science*, **279**, (1979), 989-992.

Nurkamal, I.: The Fluid Mechanics of a Geysering Well in Ta Aroha, *Master's Thesis*, Department of Mechanical Engineering, School of Engineering, The University of Auckland, (1999).

Nurkamal, I., Lu, X., Watson, A and Gorine, A.V.: Flow Measurements in the Bore of a Carbon-dioxide Driven Geysering Well, *Proceedings*, 23rd NZ Geothermal Workshop, The University of Auckland, Auckland, New Zealand, (2001), 189-193.

O'Sullivan, M. J., Bbodvrsson, G. S., Karsten, P., and Blackley, M. R.: Fluid and Heat Flow in Gas-rich Geothermal Reservoirs, *SPE of AIME*, (1983), 12102.

Paniagua, J., Rohatgi, U. S. and Prasad, V.: Modelling of Thermal Hydraulic Instabilities in Single Heated Channel Loop During Start-up Transients, *Nuclear Engineering and Design*, **193**, (1999), 207-226.

Rinehart, J. S.: Geysers and Geothermal Energy, *Springer-Verlag*, New York, (1980).

Saptadji, N. M.: Modeling of Geysers, *PhD Thesis*, Department of Engineering Science, School of Engineering, The University of Auckland, (1995).

Sherzer, W. H.: An Interpretation of Bunsen's Geyser Theory, *Journal of Geology*, **41**, (1933), 501-512.

Steinberg, G. S., Merzhanov, A. G. and Steinberg, A. S.: Geyser Process: Its Theory, Modeling, and Field Experiment, Part 1, Theory of the Geyser Process, *Modern Geology*, **8**, (1981), 67-70.

Sutton, F. M.: Pressure-temperature Curves for a Two-phase Mixture of Water and Carbon Dioxide, *New Zealand Journal of Science*, **19**, (1976), 297-301.

Lu and Watson.

Weir, G. J., Young, R. M., McGavin, P. N.: A Simple Model for Geyser Flat, *Geothermics*, **21**, (1992), 281-304.

White, D. E.: Some Principles of Geyser Activity, Mainly from Steamboat Springs, Nevada, *American Journal of Science*, **265**, (1967), 641-648.