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Measurements in a low temperature CO_2-driven geysering well, viewed in relation to natural geysers

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Abstract

A literature review on natural geysers and geysering flows in engineering plants, such as nuclear reactors and rocket-engine fuel systems, is presented. Certain parallels are observed in the development of understanding in these different fields. The majority of references on natural geysers indicate that a chamber connected to the surface by a narrow channel or channels is essential to produce the intermittent discharge that is characteristic of geysers. A detailed set of measurements was obtained from a New Zealand well. These results demonstrate that a separate chamber is not essential to the production of a geysering discharge. The discharge is caused by the cyclic formation of Taylor bubbles from the devolved gas and it is these bubbles that produce the sudden eruptions that are characteristic of a natural geyser.

Keywords: Geyser; Geysering well measurements; Gas-driven flow; New Zealand

1. Introduction

Natural geothermal geysers have attracted considerable interest, but more from the general public than the scientific community. Large geysers that eject a plume many metres

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high rarely occur in easily accessible places, but when they can be easily viewed, they are major tourist attractions (e.g. Yellowstone National Park, USA). It should also be recognized that there are many small geysers that have plumes only a few centimetres high and that these geysers attract almost no attention. In New Zealand, the larger geysers in Rotorua are a significant national tourist attraction; they became a focus of scientific attention in the mid-1980s when they were considered to be in decline. This decline was caused by a supply pressure reduction within the geothermal aquifer that developed from the overuse of the aquifer to supply hot fluids for domestic heating, industrial purposes, and commercial-scale bathing. Preservation of these geysers effectively became a proxy for the preservation of the geothermal environment.

Although there have been scientific publications on geysers for about 200 years (Rinehart, 1980), there have been relatively few detailed scientific investigations of geysering as a phenomenon, mainly because of the difficulty in introducing instrumentation into the natural conduits through which geysers flow. A rare example that illustrates the difficulty of such work is that of Hutchinson et al. (1997), who introduced a video camera into the “Old Faithful” geyser conduit in Yellowstone.

The word ‘geyser’ is Icelandic, the Icelandic geysers were the first to attract attention in the scientific literature, and the name is used to describe the natural phenomena observed in geothermally active areas where hot water and steam are periodically ejected into the atmosphere. Flows with the same intermittent character are also found in some engineering equipment and the term “geysering” has been adopted but is not widely used. Perhaps as a result, there has been little cross-fertilization of ideas between earth scientists, who have traditionally studied natural geysers, and the process engineers, in whose equipment geysering has occurred as an unwanted flow regime. Examples are found in rocket-engine fuel-supply lines (Murphy, 1965), in nuclear reactor cooling channels (Aritomi et al., 1992; Jiang et al., 1995; and Paniagua et al., 1999), and in the petroleum industry (Taitel et al., 1990).

Although the term ‘geyser’ originally had a very specific meaning, the word is occasionally used to refer to less well-defined two-phase flows or ejections into the atmosphere. Recent studies have shown ejection plumes on the moons of other planets that have been described as geysers. The cameras on Voyager 2 observed dark plumes ascending into the thin nitrogen atmosphere on Neptune’s moon Triton (Soderblom et al., 1990), and geysering mechanisms were used to describe and interpret these interesting and spectacular events. It has also been suggested that an observed plume on Titan, the largest of Saturn’s moons, was due to a geyser (Lorenz, 2002).

The dominant feature of natural geysers is the sudden eruption of boiling water and steam; other gases may be present but this is not apparent to the casual observer. The traditional conceptual model for these geysers encompasses the following elements: an underground chamber, a channel connecting the chamber to the ground surface, and a heat source at the lower part of the chamber. The intermittent boiling within the chamber is considered to be the main driver of the periodic ejection or eruption. There are, however, a few examples of deep wells that erupt like geysers, with a clearly defined period, but where the discharge is at a temperature significantly less than 100 °C and contains a large amount of CO_2. An extensive catalogue of these wells has been produced by Glennon and Pfaff (2004), who conducted a worldwide survey. Examples of this type of geothermal well at Te Aroha in

New Zealand have also been described by Michels et al. (1993). The authors were fortunate enough to have access to one of the Te Aroha wells, known locally as the Wilson Street Well, to make the measurements presented here. This well does not have an underground chamber and thus does not fit the traditional conceptual model.

Firstly, the literature on natural geysers and geysering in engineering equipment is reviewed. The measurements found in the Te Aroha well are then presented and the flow processes responsible for the periodic eruption are described. It is concluded that an underground chamber is not a requirement for producing a periodic discharge from a single vertical duct containing an upward flowing two-phase fluid, and that such a chamber is probably not a requirement for the existence of a natural geyser.

2. Review of literature on natural geysers

All natural geysers by definition produce an intermittent discharge of liquid and vapour to the atmosphere. The height of eruption may range from less than a meter to a hundred meters (although this extreme height implies a large discharge so may result from buoyancy as well as the momentum of the discharge). Some geysers discharge in a single burst (eruption) while others produce several successive eruptions. The discharge period can range from minutes to months and it can also change with time. The activity of a geyser may vary over the years; the Rotorua geysers in New Zealand have gone through periods of inactivity during the last 100 years (Cody and Lumb, 1992).

A detailed review has recently been carried out by Lu (2004), on which this paper is based. A very early study was carried out by Malfroy (1891), a French engineer working in the Rotorua area on behalf of the New Zealand Government. Allen and Day (1935) reviewed much of the scientific work that had been conducted up to that time. They reported that Bunsen had deduced that it is the boiling of water that drives the geyser eruptions. Bunsen and his colleagues measured the temperatures at different depths in the “Great Geysir” in Iceland and concluded that the boiling began near the middle of the channel, where the temperature was closest to the local boiling point of the water. This was disputed by some researchers, such as Lang (1880), Torkelsson (1928), and Sherzer (1933) (all of these are given in Allen and Day, 1935). The critics pointed out that Bunsen’s theory did not satisfactorily explain the intermittent nature of the geysers nor the heating mechanism of the water. Allen and Day (1935) supported the suggestion by many researchers of the time, that the boiling did not take place in the geyser channel but in a lower region where the water temperature was higher. This approach led to the concept that there was an underground chamber at the bottom of the channel, where water was heated, and that geysering was due to the periodic release of pressurized steam. It was widely believed during this period that details of the subsurface channel arrangement (plumbing) could be used to explain the geysering process, especially the intermittent eruptions. Allen 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 considered that the heat source was magmatic and that the heat was transported by steam. They also deduced that the geyser’s water source was the inflow of cold water from neighbouring cavities and suggested that the inflow of water

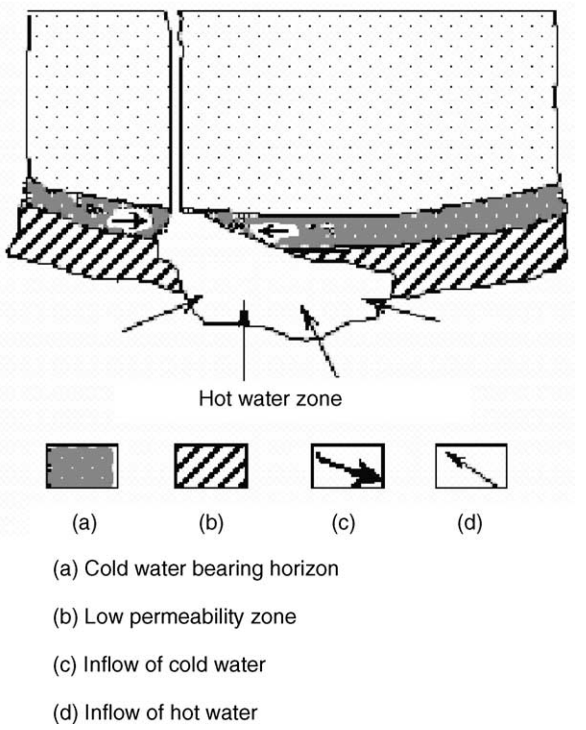


Fig. 1. Conceptual model of a geyser (from Steinberg et al., 1981a).

was not constant. The inflow was assumed to be relatively large after the eruption and that it would then decrease when the pressure at the base of the geyser increased.

White (1967) recognised that geysers were the near-surface expression of a large "*hot water driven*" convection system and produced a conceptual model to describe this system. His model, which was later supported by Anderson et al. (1978), was based on a study of geysers at Steamboat Springs, Nevada. A similar model was developed by Benseman (1965) to support the performance analysis of New Zealand geysers. In 1975, Lloyd (in Saptadji, 1995) proposed a possible model for the subsurface plumbing system using the underground chamber idea, to explain the eruptions at the Rotorua geysers. Anderson et al. (1978) thought that the essential subsurface plumbing system was located near the surface, most likely at depths between 1 and 25 m, but could in some circumstances be up to 70 m deep.

A typical conceptual model that was developed by Steinberg et al. (1981a) is shown in Fig. 1. In this model the chamber is connected to the surface by a narrow channel and two feed points are assumed. One is for the deep inflow of geothermal water, and another for the shallow inflow of cold ground water. This conceptual model was used to derive their theory of the geyser process, and their subsequent analytical models.

The study of the eruption initiation process has been aided by the construction of laboratory models that permit the main parameters, such as the chamber pressure, temperature, and cold water inflow rate to be measured and their influence assessed. A representative sample of these models would include those built by Sherzer (1933), Anderson et al. (1978), Steinberg et al. (1981b,c,d), and Saptadji (1995). Although each model has a different configuration and dimensions, most of the models (except that of Anderson et al. (1978)) contain the four elemental components:

- A chamber placed at the lowest level.
- A tube or tube-like channel open at the top and with its lower end connected to the top of the chamber.
- A heat source at the bottom or in the lower part of the chamber.
- An inflow of sub-cooled fluid into the heating area and the channel.

Sherzer (1933) was probably the first to recognize the importance of the ratio of the geyser tube diameter to its length in influencing the ability of a model geyser to generate the required periodic eruptions. In his paper, Sherzer pointed out that when the ratio of length to diameter was small (i.e. a short, wide tube), convection-induced circulation currents will develop within the liquid flowing up the tube, but when the ratio was large the currents were seriously impeded and geysering took place. Unfortunately no detailed information about experimental apparatus used by Sherzer was reported.

The model of Anderson et al. (1978) consisted of a chamber, a channel, a “catcher” attached on the top end of the channel to retain the discharged liquid, and one or two burners used as the heat source for the chamber. There was no continuous supply of water to the chamber, and the only inflow was the ejected water that fell into the catcher and was returned to the chamber. They observed that an eruption was initiated once boiling occurred in the chamber and caused vapour bubbles to rise into the channel without collapsing. It was also shown that intermittent overflow from the channel occurs prior to eruption, when boiling begins and the channel is nearly full. It will be seen below that this effect is noticeable in the measurements reported here.

Steinberg et al. (1981b,c,d) built several physical models. The experimental results from their first model, which used water as the working fluid, confirmed that the inflow rate of the cold water to the chamber rapidly increased after each eruption: the flow was enhanced by the condensation of the vapour when cold water re-entered. The cyclic nature of the process was confirmed by demonstrating that the pressure increased during channel filling and that there was a subsequent decrease in the cold-water inflow rate. In addition, the pressure and temperature in the chamber increased because of the continuous heating. When the water became saturated, further heating resulted in boiling and was followed by periodic eruptions. It is worth noting that, in this model, the ratio of channel length to the channel diameter was 2200 mm/20 mm = 110.

The second model of Steinberg et al. (1981c) was smaller, with length/diameter of 160 mm/4 mm = 40, and had Freon-113 as the working fluid. As a result of these experiments they suggested that liquid superheating was also a potential initiation mechanism for geysering. Their third model (Steinberg et al., 1981d) was used to investigate the influence of mechanical vibrations (pulses) on the geysering period. The data showed that high mechanical stressing reduced the degree of superheating and caused more frequent geyser eruptions.

The laboratory models built by Saptadji (1995) were similar in general pattern to those described above, with a channel above a chamber; they illustrated the flow regimes that evolved in the channel and how they changed during the eruption cycle. The experiments were initiated with the lower chamber full of water but with the channel only partly filled. When the chamber was heated at a constant rate its temperature increased and small bubbles started to form at the bottom of the channel. At higher bubble generation rates some of the bubbles separated from the wall and rose up the channel. In this situation the water level in the channel started to rise and eventually resulted in an overflow. After a slight delay, a large bubble appeared to enter the channel but collapsed at the bottom of the channel and only a few small bubbles continued to rise to the surface. This phase lasted for several minutes, with bubble collapse occurring at increasingly higher positions in the channel. Once vigorous boiling began in the chamber, a large vapour bubble rose through the channel without collapsing, followed quickly by other gas-filled slugs that filled almost the whole cross-sectional area of the channel. These bubbles, known in the two-phase flow literature as "Taylor" bubbles, forced the overlying water out of the channel. When this occurred, water and steam were discharged to the atmosphere, forming eruptions. The venting of the steam caused the inflow of cold water that re-initiated the cycle.

Most of the investigations into the actions of natural geysers assumed that their behaviour could be explained by the boiling of pure water, or a pure liquid, in the case of Steinberg et al. (1981b,c). However, a few investigators considered that the geothermal gases present in solution might play some role in the eruption process. In particular, Rinehart (1980) suggested that the role of CO_2 might be significant since behaviour of geysers discharging water with dissolved gas appeared markedly different from that of a steam-activated hot water geyser.

3. Review of engineering literature on geysering

Geysering is a two-phase flow phenomenon, and the engineering literature on this type of flow is extensive. Transient two-phase flows primarily occur when boilers, nuclear reactors and chemical process plants are started up or shut down, or under fault conditions. However, periodic two-phase flow, geysering, is only considered in a few studies. Most of these studies have been undertaken with the objective of devising methods or systems that will avoid the development of geysering flows; consequently these studies have circumvented the need to develop a deeper understanding of geysering flows.

3.1. Geysering in propellant feed systems

Geysering problems have arisen in the design of propellant feed systems for liquid-fuelled rocket motors in missiles (Murphy, 1965). In these systems, the fuel (propellant) is cryogenic and is delivered to the engine via a long fuel pipe. In passing through this pipe the fuel is heated. It was found that geysering during this period could temporarily empty the pipe of fuel and that the surge of liquid refill could seriously damage the integrity of the fuel circuit. Murphy (1965) carried out an experimental study to investigate geysering in vertical tubes in the form of thermosyphons (see Fig. 2) with length/diameter ratios ranging

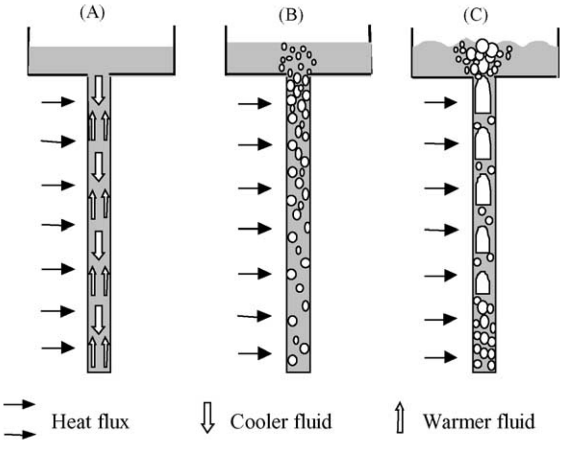


Fig. 2. Geysering in propellant feed systems (from Murphy, 1965). Small and large (Taylor) bubbles are shown in C.

from 1.5 to 30. The results showed that the length/diameter ratio of the fuel line, rather than the applied heat flux, is the most significant parameter controlling the occurrence of geysering.

The geysering mechanism proposed by Murphy (1965) is illustrated in Fig. 2 and described below. When the tube wall is heated, the density of the liquid adjacent to the tube wall decreases and the liquid rises upward as seen in (A). At the same time the cooler liquid from the liquid reservoir descends down the centre of the tube forming a convection cell. The thickness of the warm liquid film adjacent to the wall increases as it rises from the bottom of the tube to the top. After a period of time, the thickness of the boundary layer has increased such that it blocks the downward flow of the cooler liquid and eventually prevents the convective circulation. Continuous heating through the wall causes a further rise in temperature of the now static fluid until it reaches saturation temperature and begins to boil at (B). Bubbles are first formed on the tube wall, and then detach and rise upward. They coalesce and form a large bubble (a Taylor bubble) as shown in (C). The formation of the bubbles reduces the fluid 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.

3.2. Geysering in nuclear heating reactors

Some concern has been raised regarding the possible geysering of coolant flows during the start-up of water-cooled nuclear reactors. This problem has been extensively investigated by Aritomi et al. (1992, 1993), Jiang et al. (1995), and Paniagua et al. (1999). The geysering flows observed by Jiang et al. (1995) generated an energetic pressure pulse that produced significant vibrations in valves and other components in the system. The geysering flows described by both Jiang et al. (1995) and Paniagua et al. (1999) can be interpreted using Fig. 3, which shows a schematic diagram of a coolant channel through the core of a 5 MW

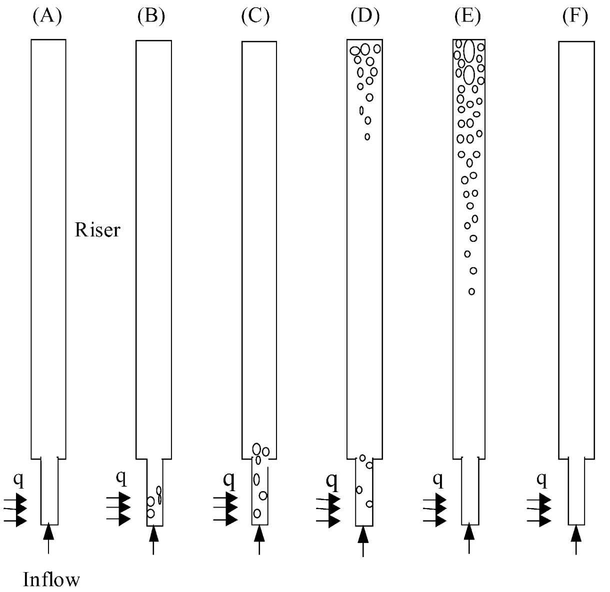


Fig. 3. Geysering in a nuclear reactor (from Paniagua et al., 1999).

reactor; the flow is upwards and the channel is referred to as a riser. This riser is in the form of a vertical tube with a smaller-diameter heated section, where the fluid enters at its base. For the tube section shown, the length/diameter ratio is 3000 mm/60 mm = 50.

The section shown in Fig. 3 is part of a liquid circuit and the sequence of events starts at condition (A), where there is a steady, upward-flowing liquid in the riser. The continuous heating at the bottom of the tube (B) initially generates localised sub-cooled boiling in the liquid and the vapour bubbles produced flow upward to condense in the sub-cooled water above (C). The fluid temperature in the riser gradually increases due to the continuous condensation and eventually the fluid at the top of the riser attains its saturation temperature. Flashing occurs at the top part of the riser as shown in (D) because the hydrostatic pressure decreases as the fluid flows upward. This results in a decrease of the hydrostatic pressure below the boiling point and causes the flashing to migrate downwards (E). The rapid bubble formation eventually leads to geysering. At the same time, the inlet mass flow rate increases significantly due to the increase of the system driving head. As this sub-cooled inflow enters the heated section, boiling stops and sub-cooled water enters the riser. Flashing gradually disappears and only single-liquid upward flow exists in the riser, as shown in (F), after which another similar cycle starts.

3.3. *Gas-driven geysering wells*

Petroleum and geothermal wells, like other engineering equipment, are designed to produce fluid at a steady rate. In both cases the fluids may begin their passage as single phase, but become two-phase on their way to the wellhead. There are examples of geothermal wells with cycling discharges, but the cause of this has often been ascribed to intermittent drawdown of the producing aquifers. Rinehart (1980) has, however, listed many examples of geysering wells and noted that geysering wells discharging a fluid below the boiling point of water were reported in many countries, including USA, Iceland, Russia, France, and Slovakia; in other words, the geysering was related to the presence of dissolved gas in the produced fluid. Glennon and Pfaff (2004) describe a typical example of a gas-driven geysering well known as the Crystal Geyser at Green River, Utah. They also provide an extensive list of similar features worldwide. Crystal Geyser is a gassy, cold water geysering well, activated by the evolution of carbon dioxide. The water temperature near the wellhead before eruption is only 15 °C, and it periodically ejects a 50 m high stream of water for about 5 to 10 min. Immediately after the eruption the water in the well falls to approximately 8 m below the surface, and about 3 h after the eruption, it overflows with “foaming and hissing” in the pipe. A few minutes later, the gas-laden water rises and falls two or three times, and the eruption reaches its maximum height for 4–5 s. The height of eruptions decrease and eventually the bubbles only cause splashing at the top of the wellhead, after which the water level retreats down the well out of sight. The well has a period of discharge of the order of 10 h.

At Te Aroha, a small town in the North Island of New Zealand, there are three geysering wells known locally as the Mokena Well, the Wilson Street Well and the Domain Trust Well. All of these wells produce water containing CO_2. The CO_2 is in solution while the water is at the aquifer pressure, but it comes out of solution during flow up the well, where the pressure declines towards atmospheric at the wellhead. Samples reported by Michels et al. (1993) showed that the major dissolved constituent of the water is bicarbonate. The water temperature in these wells is below its boiling point and ranges from 90 °C at the bottom to 70 °C at the top of the well. When fully opened, the wells have a “*geyser-like*” discharge, but each has a different period. Measurements on the Wilson Street Well are described below.

4. Discussion following the review

The literature reviewed establishes that geysering can occur not only in the boiling and flashing of pure liquids, but can also develop, for example, when gas comes out of solution as the fluid rises up a well. Boiling is a vaporizing process caused by heating, while flashing vapours are generated by the reduction in pressure of the saturated liquid and a heat source is not necessary. Flashing will occur in a vertical channel due to the hydrostatic pressure decrease in a saturated liquid as it flows upward, although the flashing front may migrate downwards; the flash-induced geysering in a nuclear reactor described by Jiang et al. (1995) is an example. The distinction between boiling and flashing in the acceleration of the upward flow in a vertical pipe was discussed by Karaalioglu and Watson (1999). There is an additional factor that distinguishes phase change by boiling or flashing and phase change as a result of gas coming out of solution. The solubility of CO_2 is dependent upon the pressure and temperature of the solution. Consequently, as a solution rises up the well, a level will be reached that permits the gas to be released from the solution and the majority of the gas will be released locally. In contrast, steam from flashing water in a well is continuously produced because the pressure continues to fall as the fluid ascends. In a geysering well the distribution of the released CO_2 will be different from that of the steam. Rinehart (1980) has noted that this difference will create changes in the geysering behaviour of the two well types.

There is considerable similarity between the natural geyser model (Fig. 1) and the nuclear reactor geysering model (Fig. 3). In both cases boiling is initiated in the lower heated portion of the channel and the bubbles that form will rise upwards to enter the tube-like channel, where they collapse in the sub-cooled liquid. When the bubbles condense, heat is transferred to the surrounding liquid in the channel and the liquid temperature in the channel increases. This increase is initiated at the bottom of the channel and slowly extends to the top, with the bubbles collapsing at higher and higher levels. This heat transfer process creates the temperature conditions suitable for flashing conditions to develop in the channel. Bubble rise and condensation are the most significant transport processes for transferring heat upwards in channels of high length/diameter ratio, since natural convection is inhibited and thermal conduction within the fluid is much too slow. Lu (2004) reviewed the studies by previous investigators and found that geysering developed when the length to diameter ratio was between 30 and 110. This high ratio is required to ensure that the intermittent boiling or flashing generates a slug flow regime in the fluid with the formation of Taylor bubbles: it is these bubbles that expel the overlying liquid out of the tube to create an eruption. Taylor bubbles were photographed by both Murphy (1965) and Saptadji (1995) in their experiments. Many other researchers, such as Kuncoro et al. (1995) and Aritomi et al. (1993), also noted that Taylor bubbles were observed in their investigations of geysering.

Historically, there have been two conceptual models for geyser action. According to Palmason (2002), Mackenzie in 1811 explained the action of the Icelandic Great Geysir by suggesting the presence of a chamber (a steam-filled cavity) outside the main geyser channel, but Palmason states that this was soon found to be unsatisfactory. Nevertheless, as noted above, a chamber was included in many of the experimental investigations of geysering, including the work of Steinberg et al. (1981b) and Saptadji (1995). The results described below reinforce the observation that geysering can be produced by the flow in a straight length of duct, and that a chamber is not required.

5. Experimental measurements

The experimental results described were carried out on the Wilson Street Well in Te Aroha and are part of a larger study by Lu (2004). The chemical constituents of the Te Aroha well water were established by Michels et al. (1993); the fluid is water with bicarbonate concentrations up to 7500 mg/kg, sodium concentration of approximately 3200 mg/kg, and chloride concentration of approximately 550 mg/kg; all other species have lower concentrations. Their investigations focused on the Mokena well, which has a geysering discharge period of approximately 50 min. This well is permanently open since it supplies hot water to commercial baths. This continuous operation has shown that the well bore becomes severely scaled with aragonite and must be reamed every 6 months.

The Wilson Street Well has been kept closed except to make the measurements and has no significant scale. A recent calliper survey has shown that it is a vertical well, 70 m deep and cased to within a few metres of the bottom with 100 mm bore casing. An earlier investigation by Nurkamal (1999) established that the well had a wellhead pressure, when shut-in, that varied according to recent rainfall but was of the order of a few bars (abs). Nurkamal (1999) also found, when opening the wellhead valve, that the initial flows were steady, but when the valve was opened further geysering flow would start. The opening of the wellhead valve also reduced the wellhead pressure to atmospheric values. For the experiments described below, the wellhead valve was removed and the well was fully open with the discharge clearly seen above the casing-head flange.

5.1. Experimental equipment

Geokon Model 4500 vibrating-wire piezometers (Geokon Inc., 1996) were used to measure the fluid pressures and temperatures in the well. The instrument uses a pressure-sensitive stainless-steel diaphragm to which a wire is connected, the other end being attached to a fixed position in the body of the instrument. Pressure variations in the fluid deflect the sensitive diaphragm, changing the tension in the wire. The wire is regularly "plucked" by an electromagnet and natural frequency of vibration recorded. This frequency is then interpreted in terms of diaphragm movement and hence pressure change. The sampling rate (sampling interval) was two seconds for all the measurements and the instrument has surface readout to a data logger. A thermistor within the instrument measured the fluid temperature. Two piezometers were used in all of the tests: one instrument was held at a reference depth of 20 m and the operational depth of the second was changed between tests. This procedure was adopted to minimise the measurement error created by the cycle variability. Measurements were also taken over a number of cycles in order to obtain representative values. The two instrument cables occupied some of the flow cross-sectional area of the well and would exert some influence on the test results. The test measurements were systematically taken to ensure that these effects could be detected, but none were found.

The arrangement of the equipment is shown in Fig. 4. The pressure and temperature variations at different depths with the instruments 2 m vertically apart allowed the mean density and void fraction of the two-phase mixture to be determined.

5.2. Typical geysering cycles

The measurement results of pressure and temperature variations over a typical geysering cycle period of approximately 700 s, at a depth of 20 m, are shown in Fig. 5.

Point A is defined as the start of the cycle when the water level reaches the wellhead, having risen slowly after the last cycle. The pressure measured at 20 m, corresponding to point A, is then at its maximum value (Fig. 5a). The fluid temperature at this point has its lowest value (Fig. 5b). It is worth noting that the temperature variation throughout the cycle is only a few degrees. In this initial phase, the well overflows smoothly, with very few bubbles observed (i.e. the fluid is almost pure liquid). As the overflow continues, more and more bubbles appear, resulting in a decrease of pressure at 20 m as the density of the fluid above falls. The temperature at 20 m also increases. After almost 3 min, the well discharges violently, accompanied by the surface eruption of large bubbles.

At point B, eruptions start to develop, with some small bubbles breaking the surface. These bubbles initiate a sequence that culminates with a few large eruptions that were

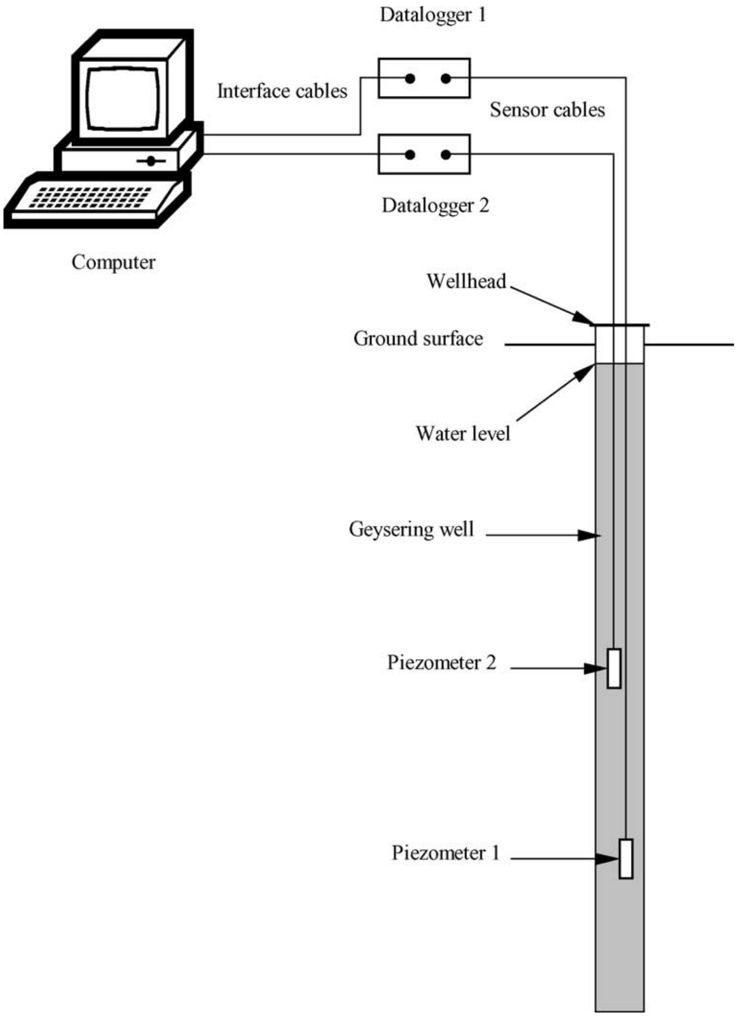
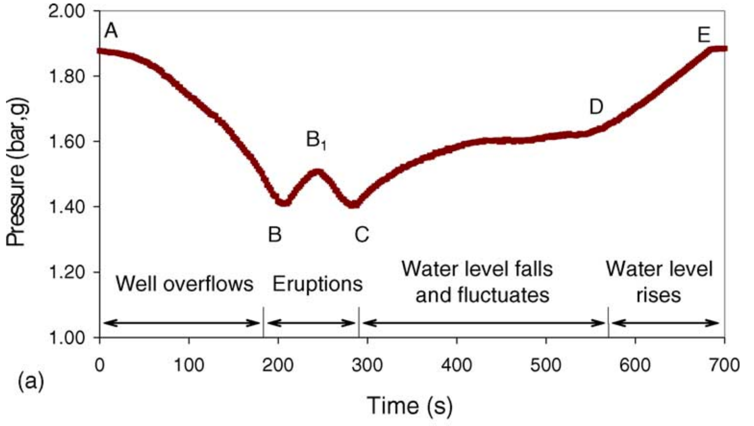


Fig. 4. The arrangement of piezometer measurement equipment.

observed to throw water to a height of 40 cm above wellhead. On some occasions, the cycle had an abnormally long period and in these cases the eruption heights were up to 1.5 m. The fluid pressure at B reaches its lowest value due to the very rapid increase of the bubble content in the upper part of the well. The temperature at B has risen by approximately half of the total temperature variation over a cycle, as shown in Fig. 5b, although, as already noted, this temperature variation is small, so is an indicator of the process taking place rather than an influential variable.

The eruptions last for nearly 2 min (between points B and C) and during this phase the pressure peaks at B_1. At C, the discharge has ceased and the water level is at a depth of between 2 and 5 m below wellhead. In this phase there is some local fluctuation in level and



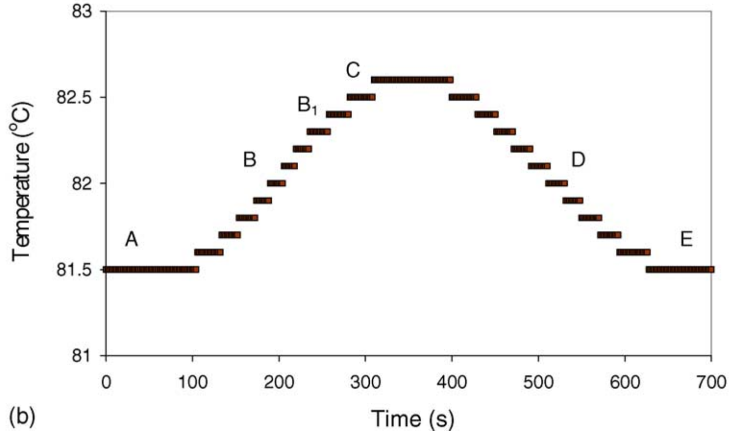


Fig. 5. Pressure and temperature variations of a typical geysering cycle. (a) Pressure variations at 20 m depth and (b) corresponding temperature variations at 20 m depth.

noise generation during C to D. The temperature at point C (see Fig. 5b) reaches its highest value and maintains it for about 100 s before it drops to D. At point D, the fallen water level starts to rise almost linearly until it reaches the wellhead at E. From D to E, the temperature continues to decrease, reaching the minimum value at E. After E, another cycle starts again.

5.3. Pressure and temperature measurements

The measurements of pressure and temperature variations, with time and at different depths over three cycles, are shown in Figs. 6 and 7, respectively, with one instrument always at a depth of 20 m. The cycles show similar pressure and temperature variations to those presented in Fig. 5. The cycle period is approximately 720 s. The main exceptions, illustrating the slight randomness of the cycles, are in the measurements at 15 and 50 m depth. These figures also demonstrate that the temperatures are well below boiling-point,

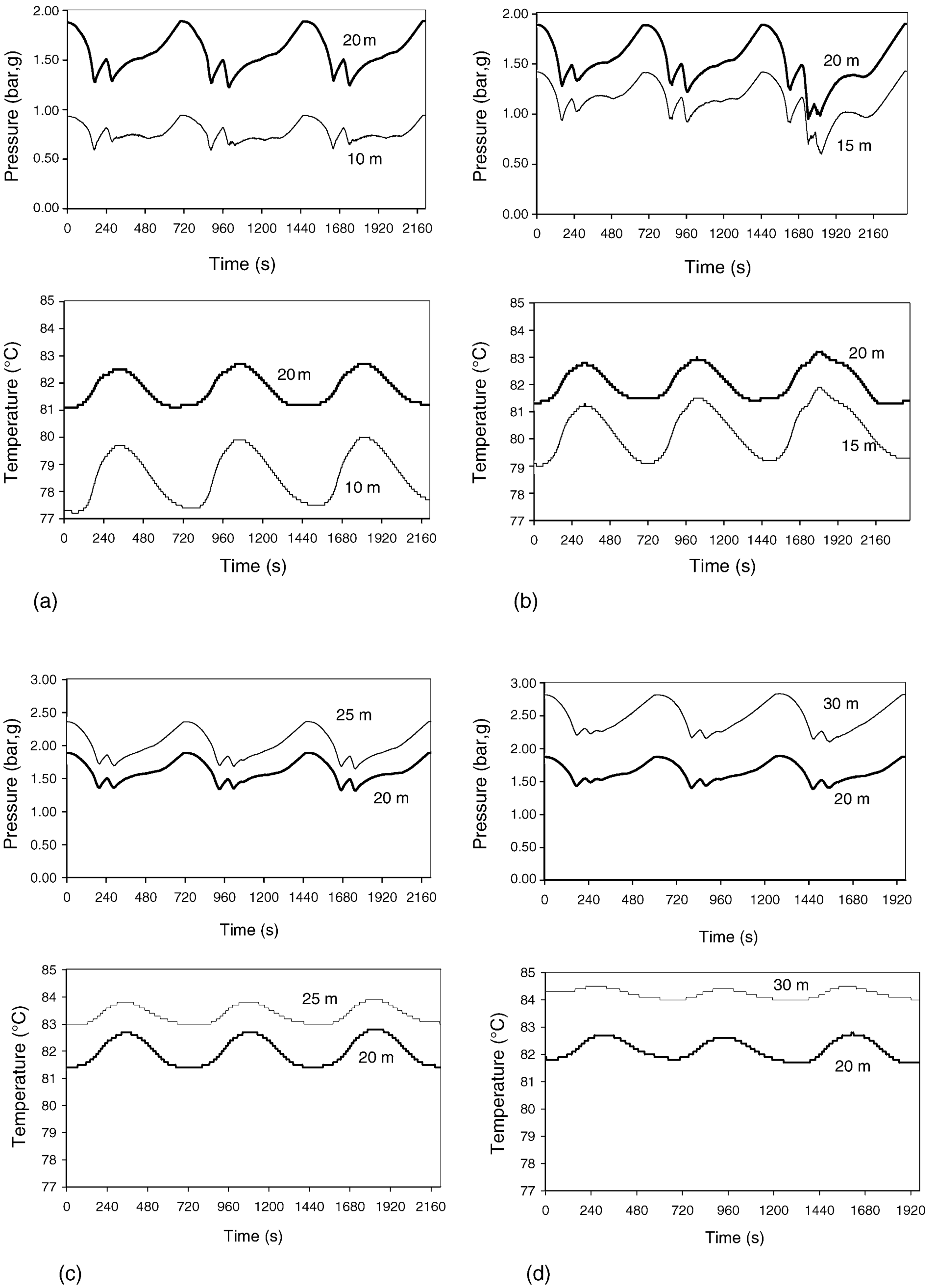


Fig. 6. Pressure and temperature variations at 10–30 m depth. (a) At depths of 10 and 20 m; (b) at depths of 15 and 20 m; (c) at depths of 25 and 20 m; and (d) at depths of 30 and 20 m.

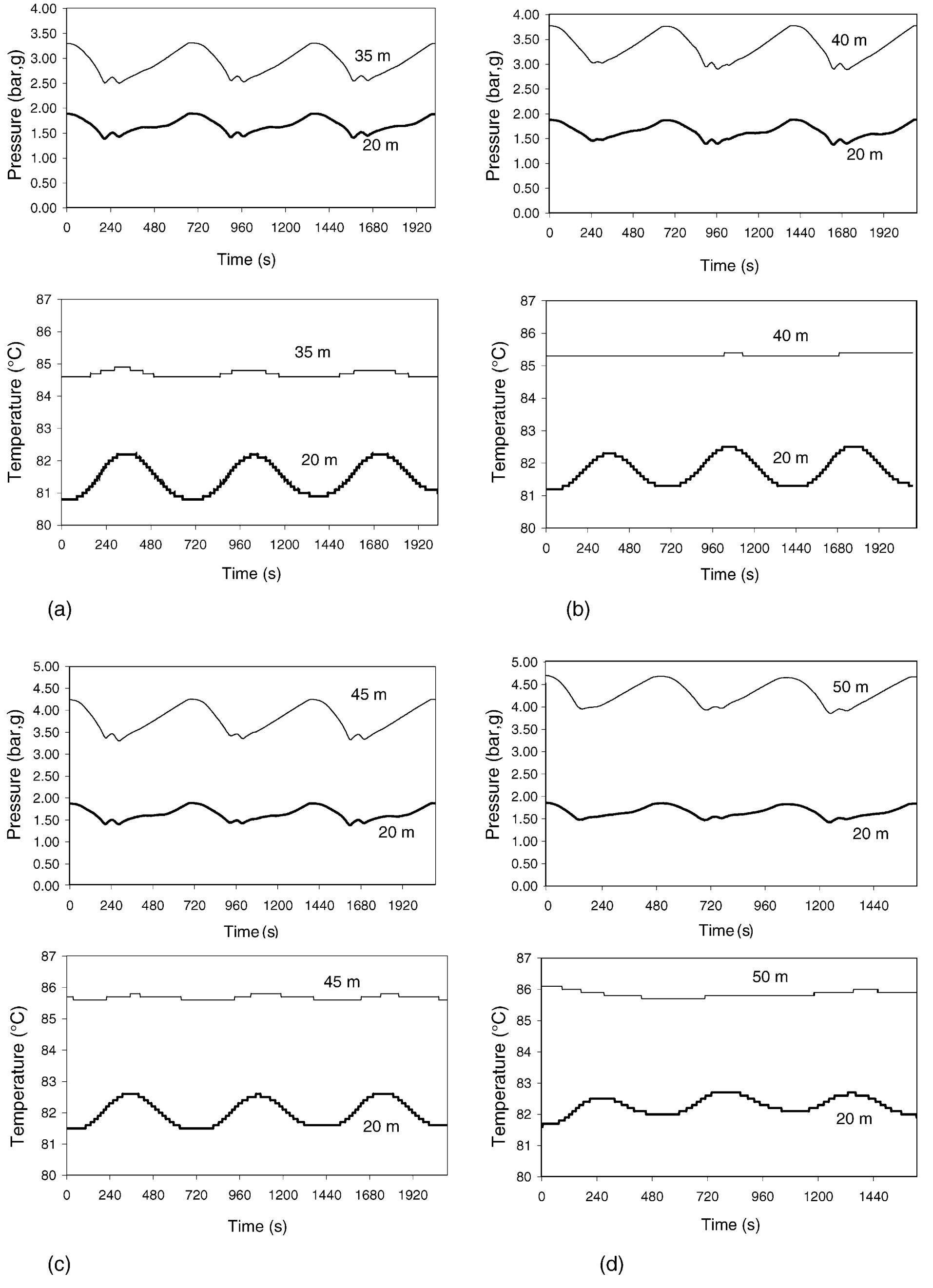


Fig. 7. Pressure and temperature variations at 35 to 50 m depth. (a) At depths of 35 and 20 m; (b) at depths of 40 and 20 m; (c) at depths of 45 and 20 m; and (d) at depths of 50 and 20 m.

and that temperature variations in the fluid become smaller with increasing depth; below 40 m the temperatures remain almost constant during the geysering cycle.

5.4. Measurements of mean density and void fraction

The local values of the mean density over a short part of the fluid column were determined by placing the two piezometers a known distance apart, generally 2 or 3 m. The pressure gradient in the flow up the well is made up of the three components, gravity, acceleration, and friction. In order to calculate density from pressure gradient it is necessary to assume that the pressure gradient is due entirely to gravity, i.e. it is hydrostatic. This is a reasonable assumption since the flow velocity is small. Thus, the mean mixture density (ρ_m) between these two points (h) can be expressed as:

$$\rho_m = \frac{P_1 - P_2}{gh} \tag{1}$$

where P_1 and P_2 are the pressures measured by the first and second piezometers, respectively.

If the density of the CO_2 in the bubbles can be neglected relative to water density, a reasonable assumption for pressures up to 7 bars, the maximum hydrostatic pressure in the well, the mean void fraction (α) in the fluid column between the measurement points can be determined as:

$$\alpha = 1 - \frac{\rho_m}{\rho_L} \tag{2}$$

where ρ_L is the liquid density.

The measured results of the density and void fraction at different depths in the well are presented in Figs. 8 and 9. Since the data in Fig. 8a and b have a high level of scatter, the trend lines shown were generated using a moving average value.

Fig. 8a shows the mean density and void fraction results corresponding to 11 m (the instruments were at 10 and 12 m depth), which follow well-defined trends in those time periods when the void fraction is less than 25%. When this fraction is greater than 25%, both the density and the void fraction become more scattered, especially during the periods when eruptions take place. This observation supports the suggestion of Taitel et al. (1980) that the bubble-slug flow transition occurs at a void fraction of about 25%. It is conjectured that, with further increase in void fraction, the bubbles coalesce and eventually form gas slugs in the upper part of the well, causing the local fluid column to become unstable and erupt. The test data obtained from the eruption periods show considerable scatter. The average value of void fraction during the complete period of eruption (from 120 to 420 s) is approximately 35%, with the measurements taken at 10 and 12 m. The corresponding average fluid density during the same period is about 650 kg/m^3. After eruption, the void fraction decreases and the density increases, and the plots become much less scattered; the void fraction is then less than 25%. This lower value of void fraction suggests that there are no gas slugs remaining in the channel and the flow regime has become bubbly again.

Fig. 8b shows the mean density and void fraction at a depth of 16 m (instruments at 15 and 17 m). The scatter in the measured values is less than in Fig. 8a and becomes smaller still with increasing depth, as can be seen in Fig. 8c and d. This suggests that two-phase flow

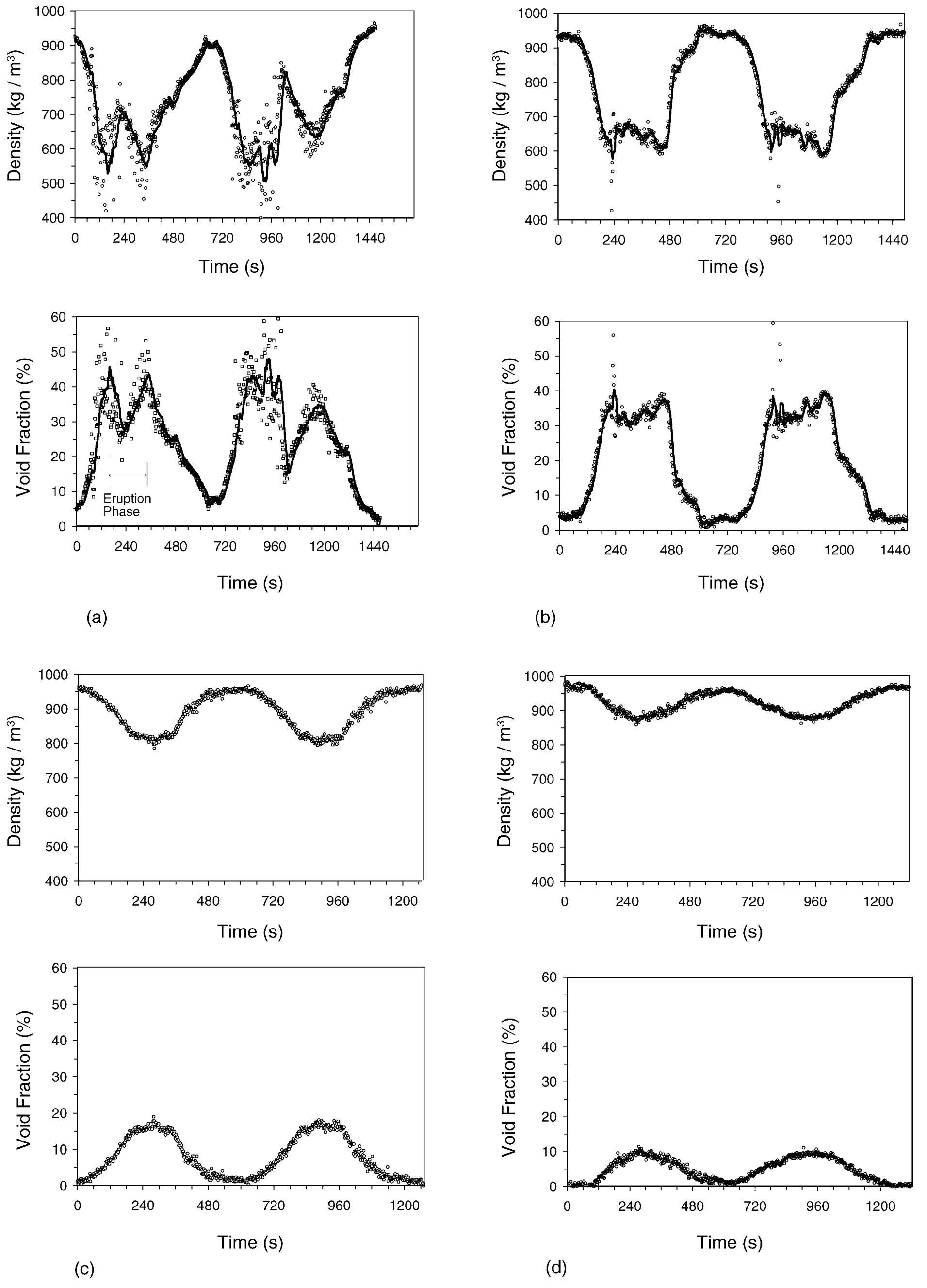


Fig. 8. Mean density and void fraction of the two-phase mixture at 10 to 43 m depth during two geysering cycles. (a) Between 10 and 12 m; (b) between 15 and 17 m; (c) between 30 and 33 m; and (d) between 40 and 43 m.

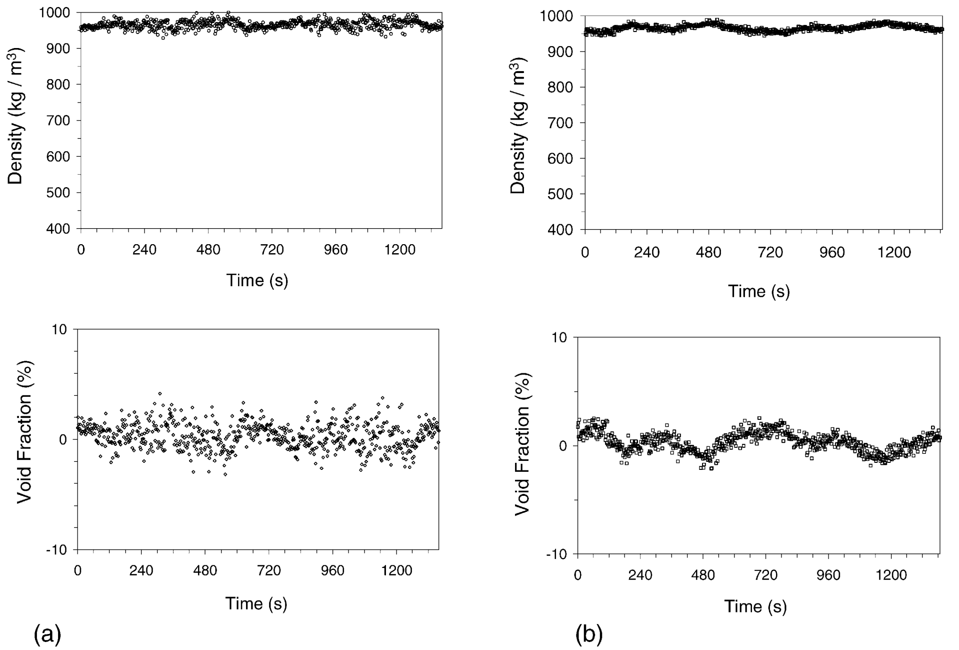


Fig. 9. Mean density and void fraction of the two-phase mixture at 55 to 67 m depth during two geysering cycles. (a) Between 55 and 57 m and (b) between 65 and 67 m.

is more stable at the greater depths where only bubble flow exists. Fig. 9a and b show the density and void fraction at depths of 56 and 66 m, respectively. At these depths there are no obvious cyclic variations; however, by examining the scatter in Fig. 9a and comparing it with the corresponding values in Fig. 9b, it can be deduced that the void fraction is zero at a depth of 66 m, i.e. no gas comes out from the solution between 65 and 67 m. The values obtained at a depth of 56 m, presented in Fig. 9a, show that the scatter in measured values varies throughout each cycle. There is negligible scatter at the beginning, middle and end of the complete cycle, which suggests that no gas is being released from the solution at these times. There is considerable increase in the scatter of the measured values for density and void fraction when the cycle times are between 60 and 660 s and 840 and 1260 s; this increase implies that gas is evolved during these parts of the cycle, at this depth. This analysis demonstrates that the flashing point lies between 55 and 65 m and that depth varies throughout the cycle.

6. Mechanism of CO_2-driven geysering in wells

The physical processes taking place in the cyclic discharges can now be interpreted using Fig. 10 along with Fig. 5a. For convenience, the complete cycle is broken into four stages and the reference markers used in the earlier figure are retained (A–E). Fig. 10 shows nine representations of the fluid column in the well; the time at which each occurs is indicated

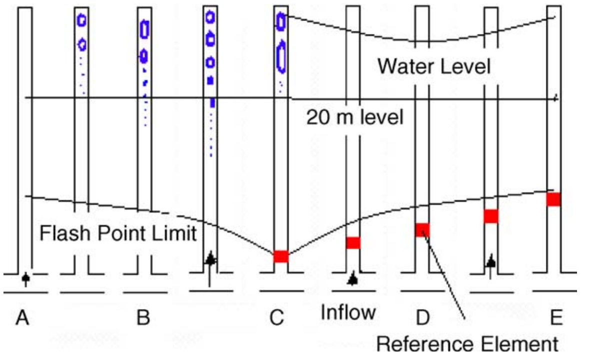


Fig. 10. Schematic diagram of the physical processes in the well leading to the geysering cycles.

by the markers in Fig. 5a, shown at the bottom of each column representation. In Fig. 10, the fluid state is shown approximately by the indications of bubbles, and the locus of the flash point is also shown.

6.1. Process A–B: from overflow to eruption

State A in Fig. 10 indicates the start of the geysering cycle, when the water reaches the top of the well and overflows. Just before overflow, the solution in the well contains bubbles, but they do not exert a major influence on the flow. The major influence is the refilling of the well at the bottom by the recharging aquifer, causing the water level to rise in the well. When the overflow starts, the few bubbles rising with the fluid begin to decrease the hydrostatic pressure at the top of the well. The water level is fixed at the wellhead, so any slight density change progresses down the well as gaseous CO_2 is released from solution and an increasing rate of bubble growth develops. From A to B, transition occurs from bubble flow to slug flow in the upper part of the well. After almost 3 min (at B), the upper 20 m of the well is filled by slug bubbles with void fraction >30%. The rising Taylor bubbles fill almost the entire cross-section of the well and accelerate the liquid ahead, producing eruptive discharges.

The position of the vapour flash point is also shown in Fig. 10; below this point the fluid is composed of liquid. From A to B, the flash point moves deeper in the well from the level marked as x in column A of Fig. 10; by the time of column C it reaches level y. Because of the decrease in hydrostatic pressure and the retreat of the flash point, more gas is liberated. The measurements shown in Fig. 9 suggest the height (x) is of the order of 16 m.

6.2. Process B–C: more vigorous eruptions

There are eruptions from the well between conditions B and C and they last for almost 2 min, as shown in Fig. 5a. After the eruption at B, the void fraction in the upper 20 m of the column decreases, causing the pressure measured at 20 m depth, for example, to increase, at B_1 (see also Fig. 6). After condition B_1, more large bubbles rise into the upper 20 m of the well. The bubbles coalesce to form slug flow, which creates larger eruptions, at condition

C. The pressures measured at 20 m depth, during this condition, were the lowest pressures recorded in the cycle and the flash point is at its lowest level (*y*) in the well. Based on the measurements given in Fig. 9, *y* is estimated to be within 4 m of the bottom of the well. This indicates that almost all the fluid in the well has contributed to releasing CO_2 gas in the well.

6.3. Process C–D: water level falls and fluctuates

At condition C, 280 s have elapsed since the cycle started and most of the gaseous CO_2 has been released from the liquid column. The inflow at the bottom of the well is relatively slow, with a measured inflow velocity of 0.02–0.03 m/s, estimated from the later rate of rise of pressure (water level) between D and E. The fresh supply of fluid entering the base of the well cannot provide the gas required to maintain the slug flow since the fluid pressure is too high for the gas to be devolved from the solution. This can be seen from Fig. 10, which follows a reference element RE that rises at uniform velocity, remaining below the flash point curve at all times. The decrease in gas supply and the release of the gas from the top of the well cause the decrease of the overall void fraction in the well. The water level in the well falls quite quickly, as could be seen at the wellhead (see the schematic location of the water level in Fig. 10). Although the CO_2-filled Taylor bubbles almost fill the well, it is apparent that a narrow annular liquid region forms between the bubble and the surrounding pipe wall and in this condition the degassed liquid surrounding the bubble effectively flows down the well. Meanwhile, the continuous inflow at the bottom of the well increases the hydrostatic pressure through the fluid columns. The increase in pressure between conditions C and D, seen in Fig. 5a, prevents the continued devolution of gas from the solution. The remaining gas in the well combines with the liquid to form an unsteady upward-flowing two-phase mixture that results in a fluctuating water level. The increase in fluid pressure also causes the flash-point curve to move upwards from C to D, as shown in Fig. 10. This transition takes almost 300 s and at its completion (condition D) most of the remaining gas in the well will have been discharged and the overall void fraction of the well will be very small.

6.4. Process D–E: water level rises to refill the well

At condition D, the fluid in the well is primarily liquid and the devolution of CO_2 cannot be maintained since the hydrostatic pressure within the well increases with time and depth. In the phase after condition D, the water level in the well rises at a steady rate until it reaches the wellhead at E. The rate of increase for this fluid obviously depends on the aquifer pressure and the nature of the channels connecting the aquifer to the well.

The eruption cycle is repeated when this condition E is reached.

7. Conclusions

A review of the literature on natural geysers reveals that the conceptual model of a separate chamber connected to the surface by a narrow channel or channels, which appeared early in the approximately 200-year history of investigations, has not been eliminated to date as a requirement for the characteristic periodic flow of a natural geyser. It was recognized at least 25 years ago that aqueous solutions of gases, particularly CO_2, could release gas and modify the operation of hot water geysers. A review of geysering flows in engineering equipment shed some light on the behaviour of natural geysers, but no comprehensive understanding of the phenomenon had been gained.

Measurements on a New Zealand well that produces low-temperature water with high concentrations of dissolved CO_2 and discharges in a periodic geysering flow have led to a detailed understanding of the dynamics of the flow to be gained. It has been demonstrated that, at least in this case, a separate chamber located at the bottom of the conduit reaching the surface is not a necessary requirement for producing a periodic geysering discharge. The buoyancy of the gas bubbles allows them to rise faster than the liquid and hence to combine to form large slugs of gas. These Taylor bubbles drive liquid ahead of them to produce the characteristic vigorous geyser eruptions that empty the upper part of the well and result in a “dormant” period with no discharge.

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