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A REVIEW OF GEYSERING FLOWS

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SUMMARY – This paper reviews geysering theories developed by some previous investigators. The review covers natural geysers and geysering phenomena in engineering equipment. Important aspects with regard to flow processes are discussed, such as boiling, flashing, geometry, and heat transfer mode along the channel. The mechanism of CO_2-driven geysering wells is summarized, based on measurements at Te Aroha, New Zealand. This study shows that neither a heat source nor chambers in the flow passage are necessary to produce a geysering flow.

1. INTRODUCTION

The word geyser is originally derived from an old Icelandic verb, *gjose*, which means to erupt. It refers to natural phenomena observed in geothermally active areas in which hot water and steam intermittently ejects or erupts into the atmosphere. Flows with the same intermittent character are found in some engineering equipment, and in this paper "geysering" has a broad meaning and applies to phenomena that occur in nature and in engineering equipment.

Natural geysers are rare and unique phenomena found where there is surface geothermal activity. Many of them are tourism attractions and need to be preserved. A recent study showed that geysers might exist on Saturn's giant moon Titan and Neptune's moon Triton (Lorenz, 2002), leading to the research of geysering becoming more fascinating.

Fluid flow in engineering equipment may be designed to be in the steady state or in some form of uniform transient, however geysering can occur in certain conditions and result in problems. Geysering is in the category of a two-phase flow instability, and examples are found in the missile industry (rocket engines), nuclear industry, petroleum industry, and in geothermal wells. In rocket engines for example, the fuel supply must be steady, and geysering in the fuel supply lines has caused problems (Murphy, 1965).

Natural geysers have attracted scientific attention for about 190 years (Rinehart, 1980), but in engineering equipment such flows have only been studied in recent times. It is significant that until recently there has been no cross fertilization of ideas between earth science and engineering.

The aim of this paper is to briefly review knowledge about the mechanics of geysering flows, especially in engineering equipment. Some important points emerge and are discussed. After that, a CO_2-driven geysering model is described from the transient two-phase flow point of view.

2. BRIEF REVIEW OF LITERATURE ON NATURAL GEYSERS

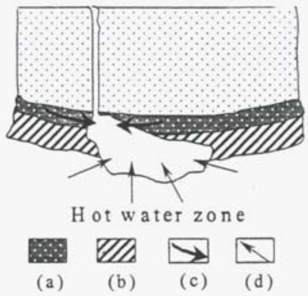
Natural geysers have some common characteristics. They all discharge liquid and vapour to the atmosphere to various heights for a period of time. Then they become quiet for a certain time until the next eruption occurs. This periodic process forms a geysering cycle. Each geyser has its unique performance. The height of eruption may vary fiom less than a meter to a hundred meters or more. The interval of the eruptions may be a few minutes, days, weeks, or even months. Some geysers erupt in a single discharge while others erupt in several successive discharges. The period and activity of a geyser may change with time for some reason. Generally, the variables responsible for the geysering characteristics have not been isolated.

Allen and Day (1935) reviewed the work up to that time. They reported Bunsen's theory, which was based on boiling beginning approximately at the middle depth of the channel. However, his theory did not satisfactorily explain the intermittent nature of the geysers and how the water was heated to boiling. Some researchers including Allen and Day (1935) who reviewed many earlier papers, supported a new idea that the boiling did not take place in the geyser channel but at a lower place, where the temperature was higher. This idea led to the concept that there was an underground chamber at the bottom of the channel, where water was heated to boiling before being discharged and the chamber refilled, periodically.

Many researchers (Allen and day, 1935; Anderson et al., 1978; Rinehart, 1980) accepted the concept that it is the boiling of water that drives the eruption of most of the geysers. However, some investigators thought that gases might play some roles in the eruptions. Rinehart (1980) suggested that some gases such as C02 might play an important role because the behavior of geysers discharging water with dissolved gas was markedly different to that of a steam-activated, hot water geyser.

Many investigators have conceptualized the subsurface plumbing system to explain the geysering process, especially the intermittent eruptions. Allen and Day **(1935)** concluded that there are 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 heat source is magmatic and is transported by steam. The water source is supplied by the inflow of could water fiom neighbouring cavities. The inflow of cold water is not constant but is greatest after eruption and then decreases until the next eruption.

Steinberg et al. **(1981)** developed a typical conceptual model as shown in Fig. 1. The chamber is connected to the surface by a narrow channel. Two feed points were assumed. One is for the deep inflow of geothermal water, and another is for the shallow inflow of cold ground water. This model was used to derive their theory of the geyser process.



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

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

Some laboratory models have been built to investigate the mechanism of natural geyser. One advantage of laboratory models is that the main parameters such as the pressure and temperature in the chamber, and the inflow rate of the cold water can be measured. Representative of laboratory investigations are those of Allen and Day **(1935)**; Forrester and Thune **(1942)**; Anderson et al. **(1978)**; Steinberg et al. **(1981)**; and Saptadji **(1995)**. Although each model had a different configuration and dimensions, all basically consists of:

- a chamber placed at the bottom
- a tube or tube-like channel
- an inflow of subcooled fluid into the heating area and the channel
- a heat source at the chamber

Anderson et al. **(1978)** observed that an eruption was initiated once boiling occurred in the chamber and vapour bubbles rose into the channel without collapsing. It was also shown that intermittent ovefflow occurs prior to eruption when boiling begins and the channel is nearly full.

Steinberg et al. **(1981)** built more complex models, the first using water. It was found that, after eruption, the inflow rate of the cold water increased very rapidly and that the majority of the vapour condensed when cold water entered the chamber. As the pressure increased during channel filling, the cold water inflow rate decreased. Continuous heating caused the pressure and temperature in the chamber to increase, and when the water became saturated boiling and eruption followed. In their first model the ratio of channel length (L) to the channel diameter (D) was **L/D = 2200mm/20mm = 110.** Their second model was smaller, with **L/D** of **160mm/4mm = 40** and used **fieon-113** as the working fluid. **As** a result of these experiments they suggested that liquid superheating was a possible important mechanism for initiating geysering. Their third model was used to investigate the influence of the mechanical pulses on the geysering period. The data showed that high mechanical stressing reduced the degree of superheating and caused more fiequent geyser eruptions.

Saptadji **(1995)** carried out **an** experimental study in the Geothermal Institute at the University of Auckland. Her laboratory models were based on the similar ideas as those of Anderson et al. **(1978)** and Steinberg et al. **(1981),** and revealed the flow regimes in the channel **of** the model and how they changed. In the experiment, the chamber was fully filled with water and the channel was filled to a certain level. As the chamber was heated, convection occurred in the chamber and the temperature increased. Several minutes later, small bubbles started to form. At higher bubble generation rates with bigger bubbles some of them separated fiom the wall and rose up the channel. The water level in the channel continued to rise at a faster rate resulting an overflow. After a few minutes, a large bubble appeared to enter the channel but collapsed at the bottom of the channel .and only small bubbles continued rising to the surface. This occurred several times, with bubble collapse at increasingly higher position in the channel. Finally, vigorous boiling occurred in the chamber, a large vapour bubble rose into the channel without collapsing followed quickly by other large bullet shaped bubbles (Taylor bubbles) that filled almost the whole cross sectional area of the channel forcing the water above out of the channel in an eruption.

3. REVIEW OF ENGINEERING LITERATURE ON GEYSERING

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), which typically use long lines to connect the fuel (propellant) 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 may empty the feed line of liquid and the liquid refill can seriously damage the fuel circuit. The fuel is dangerous if it is allowed to leak. Murphy (1965) carried out an experimental study to investigate geysering in vertical tubes in the form of thermosyphons (ie a tube with closed lower end opening into a reservoir at the top) with L/D ratios ranging from 1.5 to 30. Murphy found that the L/D ratio is the most significant parameter controlling the occurrence of geysering. The heat flux appeared to have minor effect.

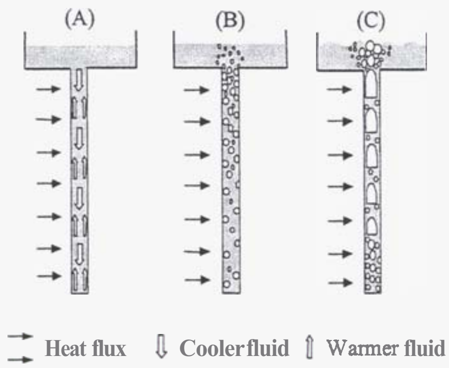


Fig. 2: Geysering in propellant feed systems

According to Murphy (1965), the mechanism of this geysering can be interpreted as follows (Fig.2). When the heat input through the tube wall, it warms the liquid adjacent to the wall. The density of this liquid decreases and the liquid rises upward as seen in **(A). At** the same time the cooler liquid from the top liquid tank (reservoir) descending down the center of the tube forming a convection. 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 is sufficiently increased and blocks the downward flow of the cooler liquid, hence stops the convection. Continuous heating through the wall causes a further rise in temperature of the fixed fluid until it becomes saturated and begins to boil 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.

3.2 Geysering in Nuclear Heating Reactors

In the last decade, some concerns have been raised about the possibility of geysering during startup from low pressure and low flow conditions in natural circulation nuclear reactors. Geysering causes safety problems as well as unwanted unsteady operation. Jiang et al. (1995) observed that, during a geysering cycle, especially when the vapor condenses, an energetic pressure wave is created in valves and other components in the system. Very strong mechanical vibrations of the whole system have been observed. Fig.3 shows the schematic diagram of the geysering in a 5 MW reactor riser. The terminology is confusing. Jiang et al. (1995) refer to one of their observed phenomena as flashing but in comparison to natural geysering, it would be better called ''unstable two-phase flow". What they refer to as "flashing instability" is what the geothermal community know as geysering. Paniagua et al. (1999) investigate a similar phenomenon, and for both sets of authors this can be summarized as follows, using Fig 3, which shows a vertical tube (called a riser) with a smaller diameter heated section at the bottom and a vertical liquid flow entering. For the tube section shown the ratio of L/D = 3000mm/60mm = 50.

The section shown is part of a liquid circuit. Fig.3A corresponds to upward flow of liquid. Because of the continuous heating at the bottom, subcooled boiling occurs in the heated section (Fig.3B). The generated vapour bubbles flow upward into the tube, which still contains sub-cooled water so they condense (Fig.3C). The fluid temperature in the riser gradually increases due to the continuous condensation of the vapour. This unstable two-phase flow process finally makes the fluid temperature at the top of the riser reach saturation. Flashing occurs at the top part of the riser (Fig,3D) because the upward flow causes the hydrostatic pressure to decrease. This will result in a decrease of the hydrostatic pressure below the boiling point and cause the flashing to migrate downward (Fig.3E). This 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 subcooled inflow enters the heated section, boiling disappears and cold water (with certain degree of subcooling) enters the riser. Flashing gradually disappears and only single liquid upward flow exists in the riser (Fig.3F) after which another similar cycle starts.

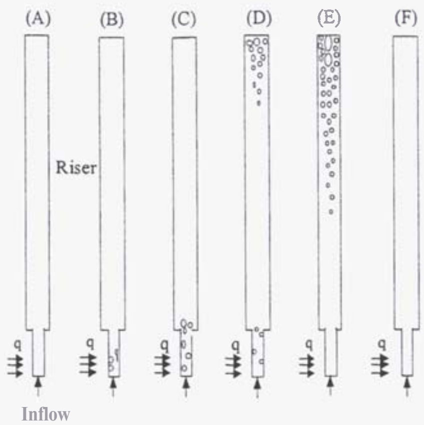


Fig. 3: Geysering in a nuclear heating reactor

3.3 Gas-driven Geysering Wells

We consider geothermal wells as engineering equipment here. Rinehart (1980) listed many typical examples of geysering wells in his book and noted that geysering wells discharging at less than the boiling point of water were reported in counties such as Iceland, Russia, France, and Slovakia.

The Crystal Geyser at Green River, Utah is one such well. It is a gassy cool water geysering well, activated by the evolution of carbon dioxide. The water temperature in the pipe before eruption is only about 15 °C. This geyser maintains a fairly constant pattern. It ejects a stream of water to 50m for about 5 to 10 minutes. Immediately after the eruption the water in the well is about 8 m below the surface, and about 3 hours after the eruption, it overflows with "foaming and hissing" in the pipe. The overflow increases in vigor reaching its maximum height in only 4 to 5 seconds after which the flow stops and the water level declines in the well. Many other gas-activated geysering wells are found in USA. Both of these wells are located in the regions where subterranean carbon dioxide and helium exist in high concentrations.

At Te Aroha, North Island of New Zealand, there are three geysering wells, namely the Mokena Geyser, the Wilson Street Bore, and the Domain Trust Bore. The water temperatures in these wells range from 90 °C at bottom to 70 °C at the top. When fully opened, the wells discharge like a geyser. Preliminary investigation (Michels et al., 1993) showed that the major component of the water in the well is bicarbonate, hence CO_2 is the main reason causing geysering.

These wells offer a very good opportunity to study the geysering process since they have high L/D ratio and simple geometry.

4. DISCUSSION

From the above review of the geysering mechanism, geysering can be referred to as intermittent boiling or flashing process. But this does not mean that intermittent boiling or flashing will always result in geysering. So some important points should be discussed.

4.1 Heat Transfer Mode

It is important to point out that in both natural geyser models (Fig.1) and nuclear reactor models (Fig. 3), boiling first occurs at the lower heating parts. The formed bubbles flow upward, then enter into the tube-like channel (or tube) and collapse due to the subcooled liquid in the channel. As the bubbles condense, heat is transferred to the surrounding liquid in the channel. Hence the liquid temperature in the channel becomes higher and higher, creating conditions that flashing in the channel. Bubble rise and condensation is the most significant process for transferring heat upwards because natural convection is inhibited by the L/D ratio and thermal conduction is much too slow.

4.2 Geometry and Flow Regime

It is found that not all intermittent boiling or flashing will result in geysering. For a tube channel, the ratio of the tube length to the diameter L/D is a very important factor as concluded by Murphy (1965). The review in this paper shows that geysering has occurred over L/D rations ranging from 30 to 110. This is because, when the intermittent boiling or flashing occurs, a very long and narrow tube is most likely to generate a slug flow regime with the formation of Taylor bubbles that expel the overlaying liquid out of the tube. It is also clear that a chamber is not indispensable to geysering.

5. MECHANISM OF CO_2-DRIVEN GEYSERING IN WELLS

Measurements on the Wilson Street Bore at Te Aroha have been presented elsewhere by Nurkamal (1999), Nurkamal et al (2001) and Lu and Watson (2001).

In 1999, Iman Nurkamal carried out a well test in Wilson Street Bore (WSB) at Te Aroha and supplied some useful data of this CO_2-driven geysering well. Based on these data, a conceptual model of a CO_2-driven geysering well was generated by a detailed interpretation of the geysering mechanism in WSB (Lu and Watson, 2001). The well is 70m deep, is cased to 0.1m diameter over almost its full depth, and water containing dissolved CO_2 enters close to the bottom. At high wellhead pressures the well flows steadily. It is considered that a steady mass flow rate of solution enters the well from the formation over the full range of possible wellhead pressures, but that below a certain wellhead pressure the flow becomes transient partway up the well. The geysering mechanism can be summarized as seen in Fig.4. State **A** is the start of the geysering cycle when the water just reaches the top of the well and overflows. Just before overflow, the solution in the well is in thermodynamic and chemical equilibrium. As soon as it overflows, the equilibrium is broken due to the decrease of hydrostatic pressure that causes flashing - CO_2 gas to be released from the new solution at depth. As the bubbles increase in the well, the hydrostatic pressure decreases at different depths resulting in more disequilibrium in the solution. This causes more CO_2 gas to come out of solution. From Fig.4 A to C, the flash point is going deeper, down towards the bottom. This allows more solution at the bottom to release CO_2 gas as bubbles. At Fig, 4B the bubble growth is very fast due to this rapid chain reaction along the well. The upper part of the well is filled by Taylor bubbles, which eject water in front of them producing eruptions at the wellhead. Because the inflow at the bottom of the well is so slow (about 0.025 m/s) it cannot supply enough CO_2 solution to release gas and maintain the slug flow in the upper part of the well. This can be seen from Fig. 4 C to E that the reference element RE is below the flash point curve. The decrease of gas supply reduces the void fraction in the well and as a result the water level falls. Meanwhile, the inflow at the bottom contributes to the increase of hydrostatic pressure at every depth, which prevents new CO_2 gas coming out fiom solution. Hence, the degassing process stops, with only the remaining gas in the well causing unsteady upward two-phase flow and making the water level fluctuate. At Fig, 4D, most of the remaining gas in the well has escaped and the void fraction is small. From Fig, 4D to E, the water level rises at almost constant speed until it reaches the wellhead at E. There is no new CO_2 gas coming out fiom the solution because the hydrostatic pressure increases at all depths below water level. After Fig,4E another cycle starts.

Preliminary numerical simulation has been carried out and the results showed a reasonable cyclic well discharge supporting this interpretation. Further field measurements are being planned to justify this theory.

6. CONCLUSION

The review of the geysering mechanism shows that the theories developed by the previous investigators can not be applied directly to the CO_2-driven geysering wells. It is the supersaturated CO_2 solution that causes the intermittent flashing instead of superheated water. A heat source is not indispensable in a geysering well. It is found that there is a transient two-phase

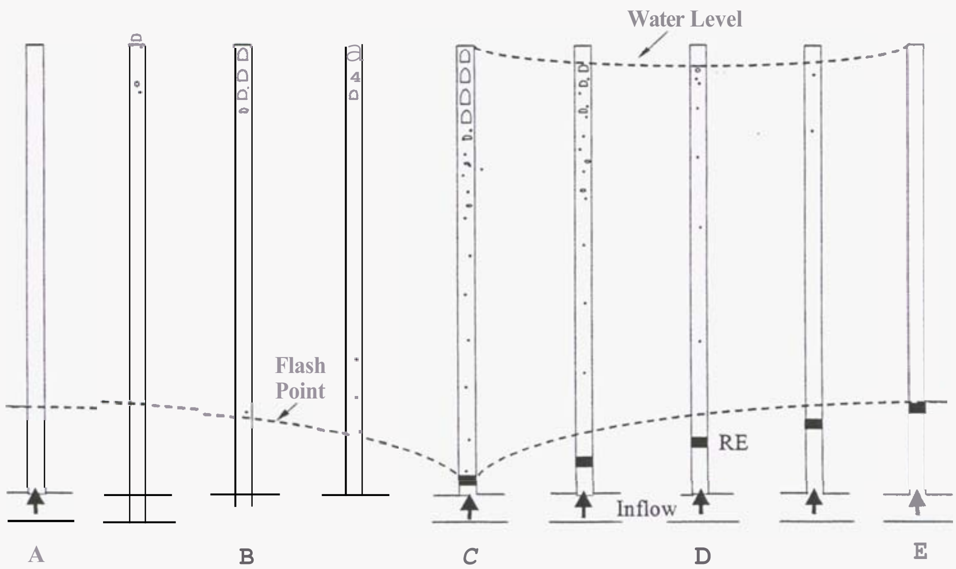


Figure 4: CO_2-driven geysering cycle in Wilson Street Bore

flow in the well, and that eruptions occur via Taylor bubbles. Transient two-phase flow studies are very important in understanding the behavior of gas-driven geysering wells and may be dominant in the study of boiling water geysers.

7. ACKNOWLEDGEMENTS

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