DETERMINATION OF FLOW RATES, VOLUMES AND TEMPERATURES IN OKIANGA GEYSER, ROTORUA

K.M. LUKETINA

Physics Department, The University of Auckland, NZ

SUMMARY - Temperature, chemical composition, and flow rate data were collected from Okianga geyser in order to learn about the hydrodynamics of its operation. Temperature profiles over time were logged for six depths between surface level and 2 metres depth. These profiles indicated the existence of pressure disturbances, the behaviour of convection currents, and the depths at which inflows and inversion layers occurred. Fluorescent dyes were used to measure flow rates but could not quantitatively indicate eruptive volumes. Total dissolved solids (tds), pH, and conductivity changed during the geyser cycle. During a dormant phase eruption was induced by raising and abruptly lowering the water levels, providing information about the hydrodynamics of the geysers at depths beyond which the temperature probes could not reach. It was inferred that large volumes of ground water of recent meteoric origin tend to quench the geyser's eruptive ability.

1. INTRODUCTION

This work is being carried out as part of my MSc studies in the Physics Dept of the University of Auckland on the dynamics of geyser eruption. The aim of the study is to make detailed measurements of as many operating variables as possible for several geysers. These variables include temperature/depth/time profiles, chemical analyses, pressure/depth variations, and changes in geyser cycle characteristics in response to rainfall, barometric pressure, and human interference with the aquifer supplying the geyser. Once these data have been collected computer modelling techniques will be applied to model the geysers, determine the critical values of operating parameters of the geysers, and further the understanding of the hydro- and thermodynamics of geyser operation.

This study involves the investigation of the geyser: Spring 488, known as Okianga, at Whakarewarewa. Fluorescent dyes were used to determine flow rates in the geyser. Water samples were analysed and measurements taken of the changes in temperature with time at several depths.

Collecting temperature, flow rate, and chemical data from a geyser when it is in both eruptive and dormant states provides information on the factors which critically affect eruption. Despite two centuries of investigation into the physical processes involved in geyser operation the mechanisms are still not fully understood. This study undertakes detailed shallow depth temperature analysis, revealing pressure disturbances which have not previously been discussed apart from mention by Kieffer (1977) in relation to seismic investigation of columnar geysers.

2. THERMOCOUPLES

The temperature/depth/time profiles of the geyser were measured using 6 T-type thermocouples attached to a Campbell CR10 datalogger. The thermocouple assemblies were custom-made by Teltherm Industries Ltd. Each one consisted of a single length of thermocouple wire sheathed in PTFE with the sensor end protected within a thin water-tight stainless steel cylinder filled with epoxy resin. The thermocouple wires ranged in length from 2 metres to 9 metres. The CR10 employed a 10TCRT reference temperature probe, and was kept in a thermally insulated container.

Readings from the CR10 and thermocouple systems were compared with those from two calibrated Baird and Tatlock mercury thermometers and found to be in agreement with each other and with the mercury thermometers to within $0.05^\circ$C, the limit of precision of the mercury thermometers. For a change in water temperature $\Delta t$ of between $0.6^\circ$C and $6.5^\circ$C the thermocouples reached $\Delta t/e$, the characteristic time, within 0.1 seconds, effectively recording the new temperature within 0.4 seconds. Temperature readings in the geyser were taken every 30 seconds.

3. OKI

3.1 Location and Characteristics of Okianga Geyser

Okianga is a small geyser at the side of the Puarenga Stream, about 100 metres downstream from the western boundary of the Whakarewarewa tourist complex. It lies in a small outcrop of rock on a sandy flat just above the current level of the stream. The stream flows around the outcrop and occasionally, during times of high rainfall, across it.

The geyser basin, the pool through which the geyser erupts, is roughly square in shape with a width of between 0.35 m and 0.40 m. There are hewn channels located more-or-less at corners of the square. Taking the top of the main outflow channel as a reference level, the square shape is uniform to a depth of 0.85 m, where the floor is flat. However, using a lead sinker of diameter 2.5 cm, we obtained a depth of 3.57 m down through what seemed, according to our measurements, to be the deepest of several fissures in the floor.
On Anzac Day, 25/4/96, Ron Keam and I witnessed nine eruptions with the first occurring at 11.20 am and the last at 5.02 pm. Thus the average period was about 40 minutes, with a range of 31 to 71 minutes.

3.2 Dye Analysis

We put a measured quantity of fluorescein dye into the geyser basin immediately after the fourth eruption and at first took samples of the water roughly five minutes apart, with the frequency decreasing to once every ten minutes, then once every eruption. A total of 20 samples was taken.

The use of dyes to measure flow rates in geysers has not been documented before although the method was used at Steamboat Springs, California by Donald White of the United States Geological Survey in the early 1970s (D. White, pers. comm.). Lyons (1993) has investigated in detail the effect of pH on dye fluorescence and found that for the pH range of our samples the fluorescence of fluorescein is decreased between 52% and 54% of maximum. I was unable to find any literature on the opposite effect: that of dye to the fluorescence.

Sample 19 was stored in a dark brown Lemon and Paeroa™ bottle because we had run out of the clear glass jars that the others were stored in. Its absorbance was about 1.6 times what it should have been in relation to the other samples. I assume that this is because the fluorescence of the other samples was more affected by exposure to light while I was overseas for a month between sampling and analysing. The instability of fluorescein under sunlight is documented by Smart and Laidlaw (1977). To compensate for the effects of pH and sunlight I multiplied the measured absorbance by factors of 1.89 and 1.6 respectively.

3.3 Flow rates

Flow rates $f$ were calculated using the following equation which assumes that there exists at all times uniform mixing of dye at concentration $C$ in the immediately accessible volume $V$ of the geyser:

$$\frac{\partial C}{\partial t} = -\frac{Cf}{V}$$

For cases where $f$ is approximately constant this gives:

$$\ln C = -\frac{f}{V} t + \text{const}$$

Thus:

$$C = C_0 e^{-\frac{ft}{V}}$$

or, alternatively

$$f = \frac{V}{t} \ln\left(\frac{C}{C_0}\right).$$

From equation (1), flow rates for the geyser in the range 0.08 $\text{ls}^{-1}$ to 2.47 $\text{ls}^{-1}$ were obtained. The highest rate of flow occurred during refilling after an eruption. To measure directly the erupted volume using dilution rates was impossible, as this would have required sampling immediately before and after an eruption. Also, it is likely that the water erupted included some from outside the volume which contained dye.

The geyser gave no visible warning of impending eruption, and after eruption the water level took some time to rise through the fissures into the geyser basin where a sample could be taken. However, the volumes lost to the immediate system measured for three cases between the last sample during overflow and the first sample after eruption were 1801, 4801, and 3401 l. The erupted volumes of dyed water will be slightly less than these. However, it is more than likely that the erupted volume contains undyed water from deeper than the immediately available volume, shooting up through the water in the geyser basin and entraining it. The fraction of dyed water lost between the last reading taken before an eruption and the first reading taken after an eruption is about five.

Over the nine eruptions witnessed, the geyser was erratic in height of eruption (2 m - 3.5 m), duration of cycle (31 min - 71 min), duration of eruption (9 s - 22 s), and rate of flow over the entire cycle between post-eruption samplings (0.12 $\text{ls}^{-1}$ - 2.47 $\text{ls}^{-1}$). The amount of tds in the water ranged from 2500 ppm during times of high flow down to 1940 ppm during slow flow, suggesting that this water rushing in bursts was hydrothermal in immediate origin, while there was a slow steadier influx of ground water.

3.4 Second Visit

I returned on September 17 with Nicola Mann and Eddie Verhoef to the geyser and found that it was boiling vigorously. However, it was not erupting. The weather in the intervening months had been particularly and continuously wet. The contours of the river banks had altered significantly due to flooding. It was clear from the debris scattered around the geyser area that at...
some stage in the last month or so the river had flowed over the geyser outlet. The river level on September 17 was at its usual non-flooding level.

We placed six thermocouples at the following depths in the geyser: 0.1 m; 0.5 m, about halfway down the pool; 0.9 m, just inside the top of a fissure; and 1.3 m; 1.7 m; and 1.9 m, inside the fissure to as far down as the thermocouple probe would penetrate.

We used sandbags to dam the outflow channels of the geyser and waited until the water level overflowed the blocked channels and vigorous boiling was again established. We then removed the sand bags and a preplay to a height of about 30 cm ensued immediately, followed by a full eruption to about 1 m about two minutes later. Immediately after the eruption we introduced a small quantity of rhodamine wt dye and over the course of the next eighty minutes took twenty samples of water. This timespan included three further eruptions, the last one occurring 50 minutes after the first. The intervals between eruptions were 15, 20, and 15 minutes, much shorter than in April.

Flow rates ranged from 0.18 1s⁻¹ to 9.61 1s⁻¹, about 4 times greater than the highest flow rate from the previous study. As in the previous study, the highest flow rates occurred during refilling after an eruption (See Graph 1h), and contained the highest concentration of tds. After the fourth eruption flow rates decreased markedly to less than 2 1s⁻¹. Apparently the geyser at this stage reverted to the non-eruptive behaviour it was exhibiting before we perturbed it.

3.5 Analysis of Flow Data
A possible mechanism for these changes in flow rate and eruptive behaviour between April and September and during the day of the second visit involves relative concentrations of hot water welling up from deep below and cooler ground water, a mixture of hydrothermal water and rain water, migrating horizontally at levels between ground level and several metres depth (Houghton et al., 1980). It may be that in April there was much less ground water than in September and thus in April the inflow to the geyser was slower and consisted of a greater proportion of hotter water which caused the geyser to erupt periodically. In September, however, the geyser was being recharged more from the ground water and was not able to reach temperatures at which geysering was possible, instead becoming a boiling spring. The average tds over twenty samples was 200 ppm lower in September than in April. The average flow rate in April was 0.07 1s⁻¹ compared to 0.38 1s⁻¹ in September. These observations indicate that the source of higher flow rate in September was ground water.

During a non-erupting phase the temperature of the geyser water which is a mixture of thermal and ground water is sufficient to cause boiling in the upper reaches of the geyser where the hydrostatic head is low (see Graphs 1b - 1g), but not in the lower reaches in the narrow channels into which the thermocouple probe cannot penetrate. The hot water coming into the geyser from below is convected to the top where it boils, releasing the heat. In this way, an explosive situation never develops, and heat is being given off more or less continuously and evenly.

3.6 Analysis of Temperature Data
Previous studies of temperatures at different depths in geysers have been used in the development of geyser theory. In one such study Rinehart (1969) measured temperatures to 175 metres depth in Old Faithful, Yellowstone National Park. From these data he was able to propose a model for that geyser’s bimodal behaviour of alternating long, and short cycles. Using modern rapid sampling technology I was now able to log temperatures at several shallow depths in Okianga simultaneously.

Graph 1b shows that the temperature of the water at a depth of 0.1 m sits at the boiling temperature for the hydrostatic pressure at that depth. (The boiling temperature is plotted as a straight line across the graph for all the water temperature graphs. This has been calculated from the atmospheric pressure at the time and the water depth, with an error of 0.1°C.) However, for all the lower depths the temperature of the water is lower than the hydrostatic boiling temperature, despite large bubbles of steam rising from at least halfway down the geyser basin, and the appearance that the geyser was boiling furiously throughout the basin.
Flat spots in Graph 1g immediately before eruptions show that the water attained a maximum temperature, suggesting that boiling was taking place at these moments. The flatness of the temperature graphs, with only minor fluctuations about an average, despite the strong turbulence observed in the water, is further evidence that the water column had reached maximum temperature, rising only in response to an increased head of water, forcing the boiling temperature higher.

The boiling of the water below the calculated hydrostatic boiling temperature indicates that the density of the water column was significantly below that of a column of still water of the same depth. There are two contributing reasons for this phenomenon. The first is that boiling at the surface, with large bubbles displacing a significant volume of water, reduces the density of the column, thus allowing boiling further down. The second is that the turbulence in the water causes pressure fluctuations which allow the water to boil at moments when the local pressure is low.

Raising the hydrostatic head 0.15 m by using sandbags caused the boiling temperature to eventually increase at all depths in the geyser, with the greatest proportional difference being at the top. A corresponding increase in water temperature of about 0.5°C at 0.9 m and 1.3 m followed, the amount expected for the difference in pressure. For the deepest two thermocouples the increase in boiling temperature observed was less than 0.1°C, indicating that the density of the water column above them was not raised significantly.

The geyser reached a quasi-steady state twenty minutes after the sandbags were put in place, when boiling was as strong as it had been before their installation. The sandbags were then removed and eruption followed immediately. This must be because with the sudden decrease in hydrostatic head the water in the upper reaches was able immediately to boil more vigorously, creating larger bubbles which ejected more water and further decreased the hydrostatic head, causing increased boiling further down until the entire column was engaged in eruption.

The rapid ejection of water during the eruption allowed the hotter deep water to flow into the system at a rate which enabled continued eruptions until the water and steam pressure in the aquifer was reduced, thus reducing flow into the geyser. Then the source of flow to the geyser returned to the pre-eruption situation of cooler ground water flowing slowly through.

6. Further Work

Further trips to this geyser and others have already been made and more data collected, including temperature readings with a frequency of 64 Hz. Direct pressure measurements have been made in the geyser with a custom-built manometer. This will be followed by more detailed measurements using electronic equipment. An attempt to model the behaviour of the geysers using the computer package HYDROTHERM will be made, and perturbations studied using the computer. A precursor of HYDROTHERM was successfully employed by Ingebritsen and Rojstaczer (1993) to model critical values of lateral recharge of heat and mass into geysers. These efforts are an attempt to understand how these particular geysers work, what factors allow them to work and what factors stop them from working. This information can tell us something about hydrothermal and ground water flow in the areas, and about the behaviour of the hydrothermal systems involved.

7. Acknowledgments

The fluorometers belong to the Geography Department of this university, and the analysis was done with the help of Peter Crossley, Senior Technical Officer of that department. My MSc supervisor, Associate Professor Ron Keam provided continued and timely academic support and encouragement. Field assistance was ably given by Nicola Mann and Edward Verhoef. Access to Waiotapu Thermal Wonderland and permission to study the geyser was extended by the management there. Some financial assistance for expenses was generously provided by Environment Waikato. The Physical Sciences Workshop of the University of Auckland was responsible for an excellently-made probe.

8. References


