RECENT FUMAROLE MEASUREMENTS IN THE KARAPITI AREA, CRATERS OF THE MOON, WAIRAKEI FIELD, NEW ZEALAND

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SUMMARY - Measurements of fumaroles with accessible vents in the Karapiti Area have shown that reproducible steam flow data can be obtained from pressure and temperature measurements across these vents. The steam jet velocities were between 20 and 100 m/s with temperatures between 98.5 and 112 °C. A significant inflow of heated air occurs at the margin of most vents; the resulting air entrainment can dominate measurements of apparent steam flow at the top of vigorously steaming craters. A linear relationship between heat output and steam cloud area was found which indicates for March 1999 a total output of c. 80 MW for all active fumaroles in the Karapiti Area.

1. Introduction

The heat output of large fumaroles in the Karapiti steaming ground area (Wairakei Field, NZ) was measured, in the past, to monitor changes in the natural heat transfer of the field (Allis, 1979). Since 1979, however, these measurements have not been continued. When some new instrumentation recently became available, we decided to continue with the monitoring of selected fumaroles and to check whether the volume of steam clouds over large fumaroles is indeed a reliable indicator of their heat output.

2. Study area and methods

A number of fumaroles at the western side of the Karapiti area ('Craters of the Moon'), with visible open vents, were used for this study. The selected fumaroles are numbered in Fig. 1, taken from a report of the last heat loss study of the area (Mongillo and Allis, 1988). Fumaroles in areas labelled D, F, and G in Fig. 1 were not studied because of the surrounding unstable ground.

The heat output of a selected fumarole was assessed, by measuring as close to the open vent as possible, the dynamic pressure ΔP and the temperature T at a certain position in the steam jet. Both a Pitot - static tube and a Pitotmeter were used; the dynamic pressure was measured with a digital pressure meter (Zephyr Solomat). The temperature at the tip of the probe was measured using a thermocouple or a thermistor. The speed V of the jet can be computed, since:

$$\Delta P = 1/2\,(\rho(T))\,V^2,$$

where $\rho(T)$ is the steam density, listed in steam tables as f(T). With the known vent area A_0, the volume flowrate and, hence, mass flowrate can be calculated, assuming that no air was entrained in the steam jet. The heat output Q of the fumarole is:

$$Q = A_0\ \mathrm{avg}[V]\ \mathrm{avg}[\rho(T)]\ \Delta H,$$

where ΔH is the difference in enthalpy H_s of steam at temperature T and that of H_l, the enthalpy of the condensation droplets at ambient air temperature.

Turbulence in the annulus containing an air-steam mixture, surrounds each jet and can extend into the jet. Because of this, a total of 10 measurements were taken at each point over a period of c. 1 minute, and averaged, yielding also the standard deviation (S.D.) of ΔP. Over easily accessible vents, the ΔP and T measurements were taken in sequence along a rectangular grid. The Pitot tube and Pitotmeter were calibrated in a wind tunnel (School of Engineering, University of Auckland); the pressure meter used in the field was checked against a bench type flow meter.

Measurements were made in several settings depending on the accessibility and size of each vent:

1) The steam jet was restrained by inserting a tube of cross-sectional area A_0 into the vent and blocking escaping steam around the tube entrance. This provides the most accurate measurement of Q. The resulting error is < 10 %.

2) For larger open vents with good access, measurements were made across the vent in a rectangular grid pattern; the resulting error depends mainly upon the correct reduction of

minor inflow of air around the rim of the vent and is c. 10 %.

3) Fumaroles discharging almost horizontally, but which are difficult to reach, were measured by locating the centre where ΔP and T are a maximum; the degree of air entrainment at the rim was sometimes assessed by locating a point with maximum inflow (showing negative ΔP readings). The resulting error in Q is of the order of 30 %.

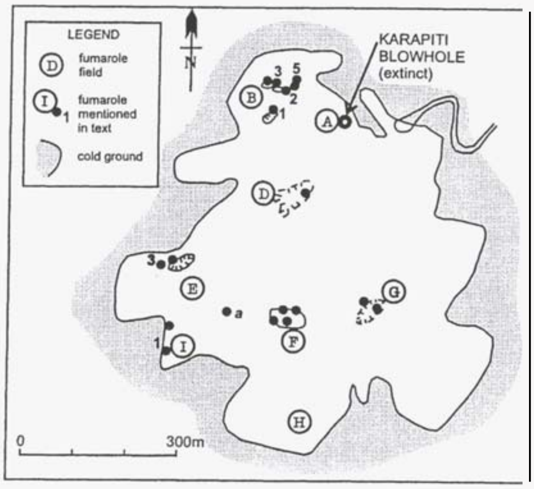

Fig. 1: Karapiti Fumarole Field, Wairakei.

4) The total mass flow of a mixture of steam and air can be measured at the surface of a crater with a poorly defined vent at the bottom. This method was widely used at Karapiti in the early 60's (Dawson, **1964).** The heat output, however, can only be obtained if the proportion of air can be assessed. The resulting error is >> 30%.

3. Results

3.1 Entraining a steam jet by a pipe

This setting was used to measure Q of a small fumarole that lies halfway between fumarole areas E and F (feature "a" in Fig. 1) and discharges steam close to local boiling point (c. **98.5 ° C). A** tube **(0.1m** diameter) was inserted into the vent; after stabilisation, an output of 0.3 MW was measured. The fumarole produces a rather small steam cloud (c. 20 m^2) which, however, can be clearly recognised on air photos taken in **1997** and **1998.**

A larger diameter (0.3 **m)** pipe was used to assess the output of fumarole **B1** which consists **of** a number of aligned, small steam vents along the scarp of a large crater. The collected steam flow was low, and some air was able to enter the pipe. The total steam flow (equivalent to c. 0.9 MW output) was assessed by correcting for the inflow of air. However, the error was greater than 10 **%.**

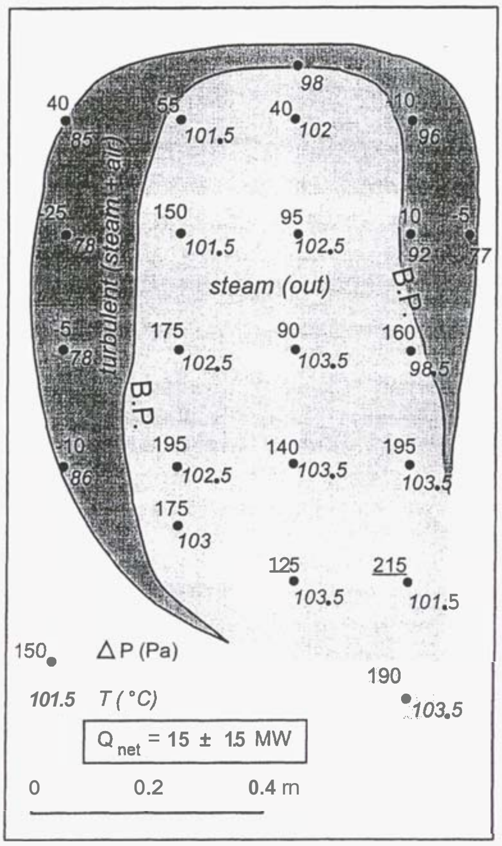

Fig. 2a: Observed mean pressure (dP), and temperature (T) in steamjet of fumarole E3.

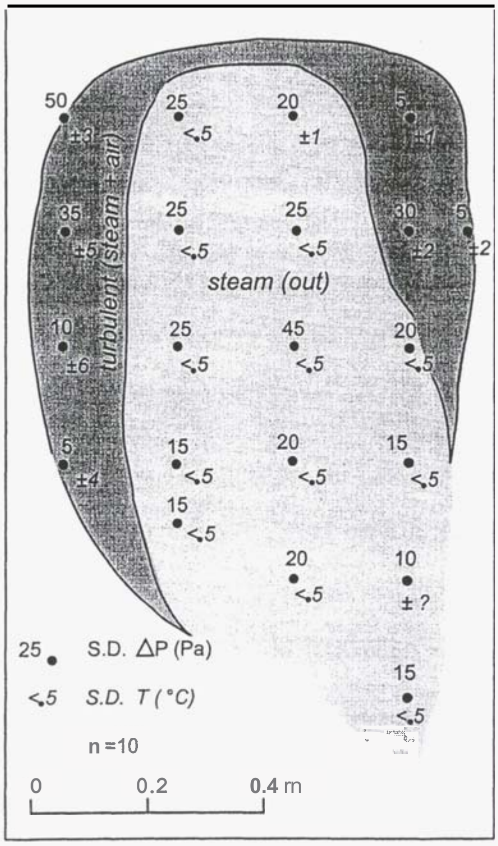

Fig. 2b: Standard Deviation (S.D.) of dP and T of fumarole E3 (n=10 observations).

3.2 Multiple measurements across the face of a steam vent

Such measurements were made across the c. 0.55 m^2 large vent of fumarole E3 with almost horizontal steam discharge. The fumarole lies behind a steaming crater (F714 in the older literature) which hosted another steam vent of similar size; the crater fumarole became progressively blocked in 1997 and the new fumarole E3 increased its discharge. Because of easy access, E3 was measured three times during March/April 1999 to check for reproducibility. All three data sets gave almost the same result (Q = 15 MW). Original data of the last survey are shown in Fig. 2a in a vertical section. The standard deviation (S.D.) of AP and T are shown in Fig. 2b.

The average velocity of the steam jet is moderate (c. 21 m/s) although turbulence in the upper half of Fig. 2 is significant as indicated by the rather large standard deviations of the pressure data; in the lower half the flow is less turbulent. Some minor, turbulent air inflow occurs around the upper edge of the vent as indicated by fluctuating temperature and pressure data. All our surveys showed that any significant mixing with air results in mixture temperatures below boiling point (here between 98.5 and 99 "C). This distinguishes pure steam flow from entrained steam/air flows. The direction of the flow is given by the sign of ΔP. Sporadic inflow also occurs where the standard deviation of AP is greater than the magnitude of ΔP. For this fumarole (E3), air inflow was small (c. *0.5* kg/s) but had to be reduced to obtain the actual steam (outflow) rate (c. 5.7 kg/s).

3.3 Single point measurement in the centre of a steam vent

The vents of a number of smaller fumaroles in the northern B area are exposed, but measurements are restricted because of unstable ground. In this case the survey was restricted to 'single point' measurements by locating the centre of the steam jet where ΔP and T attained a maximum. Since there was also some air inflow, that effect had to be assessed.

The results of such a survey are shown in Fig.3 for fumarole B3 with a horizontal steam jet where the speed of steam reaches almost 100 m/s in the centre of the vent (*AP* was 4.16 kPa; T max = 112 "C). The speed of the inward air flow at the top was also large (c. 43 m/s). Using an empirical ratio R (Vavg/ Vmax) of 0.6 to 0.7 (*see* Fig.4), an average steam speed of 60 to 70 m/s was inferred for the whole vent. Allowing for the air inflow, an output between **2.5** and 4.5 MW is indicated for B3.

Other fumaroles in the same area also discharge steam with superheat, namely T=110.5 "C at B4 (to the west of B3) and T=108.5 °C at B5 (see Fig.1). Their output was also assessed by 'single point' measurements. The combined output of all fumaroles in area B (including B1) was found to be c. 7.5 MW.

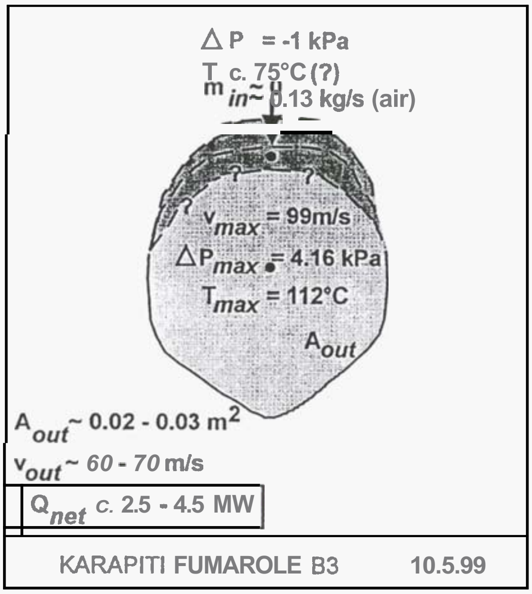

Fig.3: Observed pressure (dP) and temperature (T) in steam jet of fumarole B3.

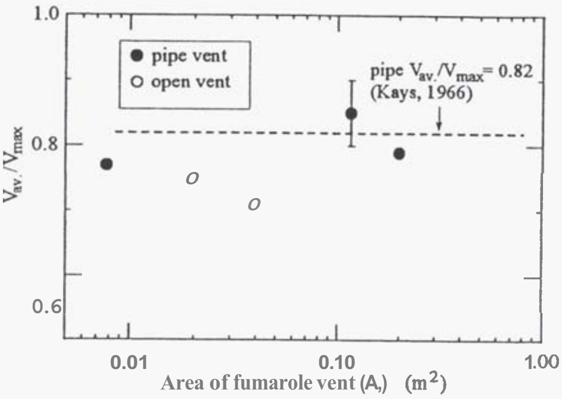

Fig.4: Plot of vent area (m^2) of fumaroles versus ratio (Vavg/Vmax) of speed of steam jet.

3.4 Flow measurements near the top of a steaming crater

Fumarole I1 in the south-western corner of the Karapiti Field discharged in March 1999 steam from a c.1.5 m deep, inclined crater with a feeding fissure at the bottom. Our first attempt to channel the steam flow by inserting a pipe was a failure. The rather large surface area of c. 2 m^2 of the original crater was then reduced to an opening of c. 0.3 m^2 by some planks, *sealed* with a clay layer. Pressures and temperatures were measured over a gridded area (c. 0.5 m^2) at the surface, c. 0.5 m above the new outlet. Temperatures were not greater than 96 to 96.5 deg C, i.e. c. 2 °C below boiling point. Assuming, initially, that all measurements were made in steam, an apparent mass flow rate of the order of 3 kg/s was calculated, almost half that of fwnarole E3. However, the steam cloud over I1 was almost an order of magnitude smaller than that over fumarole E3. It was concluded that we had measured the flow of an air-steam mixture.

The survey was repeated a few weeks later restricting this time the opening to c. 0.03 m^2. Using again a grid survey and placing the probe c. 0.1 m above the vent, it was found that the gas temperature had increased to c. 98.5 °C, the average speed also had increased almost twofold; hence, much less air was entrained in the steam jet. The mass flow rate was between 0.7 and 0.9 kg/s, transferring 1.9 to 2.3 MW of heat. The second survey has shown that vigorous air inflow into a crater with a fumarole at the bottom can increase the total mass flow to several times that coming from the steam vent alone, if measurements are made at the surface of such a pit.

We had observed a similar effect during some of our earlier studies in Indonesia. The study of fumarole I1 casts doubt on earlier fumarole measurements in the Karapiti area made at the surface level of other craters with powerful fumaroles at the bottom, for example, those reported by Thompson et al. (1964).

4. Discussion and interpretation

4.1 Average steam velocity from a single point measurement

An assumption has to be made about the ratio R, given by (Vavg/ Vmax), to convert a single point maximum AP reading into a meaningful average speed of the steam jet. Our earlier (unpublished) studies in Java had shown that for vents of c. 0.1 m^2 a value of $0.6 < R < 0.7$ was quite common. Since much of the earlier data have been lost, we collected a new set of data from fumarole studies made in New Zealand at Ketetahi, Hipaua (Tokaanu) and Karapiti, including some reported here. The R values from these studies have been plotted versus vent size in Fig.4.

The plot shows that for steam jets discharging through pipes, $0.75 < R < 0.85$, whereas for open, natural vents the ratio lies between 0.6 to 0.75. The range of R for pipes encloses the theoretical value of R = 0.82 cited in Kays (1966) for fully developed turbulent flow in circular tubes. The R value reflects the degree of turbulence near the vent opening. A value of $0.6 < R < 0.7$ was used for the analysis of single point measurements of fumaroles in the B area (see 3.3).

4.2 Steam cloud volume and heat output

In earlier fumarole surveys (for example, Thompson et al., 1964), it was assumed that there is a linear relationship between the volume of steam clouds over adjacent fumaroles and their heat output. Since steam cloud volumes are difficult to measure, it was further assumed that the projection of any steam cloud, as apparent in a vertical air photo, is also proportional to its volume and, hence, its rate of steam (heat) output. We used this assumption when we inferred from a comparison of steam clouds over fumaroles E3 and I1 that our first set of data from fumarole I1 was not representative for pure steam flow. Since we had obtained a good set of output data of widely spaced fumaroles, we were in a position to check, by using a set of air photos, whether there is such a linear relationship.

A turbulent steam cloud over a fumarole possesses buoyancy and momentum. The air-steam mixture in the upper part of the cloud travels upwards due to its buoyancy which is proportional to ($\Delta\rho(m)/\rho(a)$) where $\Delta\rho(m)$ is the average density difference of the gas mixture with respect to the density $\rho(a)$ of the ambient air. This part of the cloud reflects its total buoyancy (Scorer, 1958). In the lower part of the fumarole cloud, steam and entrained air travel upwards due to the momentum of the steam jet, which is proportional to steam velocity and, hence, steam output. Using basic cloud physics, a clear proportionality between steam cloud volume and heat output of any given fumarole is therefore indicated although it is uncertain whether there is linear proportionality.

Since the steam cloud volume at any given time is also a function of various meteorological parameters, such as air temperature, air pressure, humidity, exposure to radiation (the projected cloud area also varies with wind speed and topography), one has to use a non-dimensional parameter to reduce these effects. In the following, we use the steam cloud area Ai of a fumarole (or group of fumaroles) at a given time, normalised with respect to the total area [Atot] of all steam clouds over the whole field, i.e. using the fraction Ai/ Atot to characterise each steam cloud.

4.3 Relative changes of steam clouds over Karapiti with time

Since no air photos were taken at the time of our survey (March to May 1999) we had to use older photos for steam cloud assessment. Older air photos can be used if it can be shown that the changes in Ai/Atot for any given fumarole between two successive photos are small. We used, for this exercise, a set of vertical air photos (in colour) taken over the whole Karapiti area (Fig.l) in March 1989, March 1994, April 1997, and September 1998. The first three sets were photos on a scale of 1:2,000, the last one had a scale of c. 1:10,000. In measuring each area Ai, we only used the opaque portion of each cloud. The results are listed in Table 1.

Table 1: Proportion (Ai/A tot in %) of steam clouds

Feature	Date of air photo			
(Fig.1)	1.3.89	27.3.94	12.4.97	27.9.98
B	6.5	14	9.5	10.5
(B 1)	(1.5)	(3)	(1.5)	(1.5)
D	6	5.5	8	7
E	26	29	25	23
(E 3)	-	-	-	(18)
E to F	1	6	7.5	6.5
F	46	28	35	40
G	11.5	11.5	9	9
A tot (m^2)	6,700	2,550	4,850	5,400

The data show that during the last two years the temporal changes in Ai/Atot for most fumaroles that we have measured have been small; minor changes between 1997 and 1998 reflect mainly the error in the assessment. Fumarole area F shows larger changes, but we took no measurements in that part of the Karapiti Field. We encountered a small problem with fumarole E3 since the steam cloud over the whole area E contains also the steam cloud of another steaming crater (derived from the old fumarole F714). The two clouds are barely separated in the 1998 photo. Furthermore, as mentioned in 3.2, the E3 vent expanded during 1997 at the expense of the F714 crater output. Hence, the value Ai/ A tot of c. 18% listed for E3 in Table 1 contains a somewhat greater uncertainty. However, our assumption that the relative steam cloud areas of fumaroles measured during our recent survey are almost the Same as those in 1998 and 1997 is still reasonable.

4.4 Relationship between steam cloud areas, heat output and total heat loss

Using data from Table 1, the heat output Qi of fumaroles can be plotted versus the relative steam cloud area Ai. To preserve the accuracy of the data points, all data were plotted on a log-log scale, as shown in Fig. 5. This plot confirms that there is indeed a linear relationship between the two parameters. The plot also allows the assessment of other fumaroles within the Atot set for any given value of Ai/Atot. Furthermore, the intersection of the best fit line with Ai/Atot = 1 (top of the figure) gives the total heat output Q tot of all fumaroles in the Atot data set. In the case of the Karapiti area the present total heat output of all fumaroles is c. 80 MW.

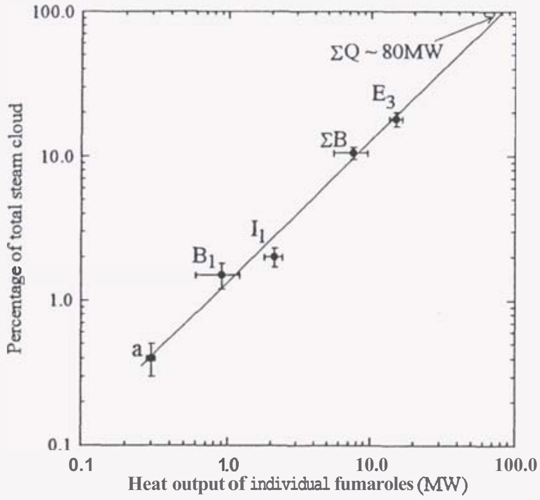

Fig.5: Heat output of fumaroles (MW) versus the proportion (Ai/ Atot) of each fumarole cloud with respect to total steam cloud area.

5. Conclusions

A recent survey of fumaroles with accessible, open vents in the Karapiti Area ('Craters of the Moon') of the Wairakei Field has shown that representative and reproducible measurements of the volume flow rate of steam jets can be obtained fiom pressure and temperature data across each vent area. The computed heat outputs are between 0.3 and 15 MW for vent areas between c. 0.01 and 0.5 m^2 respectively. Steam jet velocities of most fumaroles were between 20 and 50 m/s, except for a single jet in the northern part which discharges with almost 100 m/s. Observed temperatures were between 98.5°C (close to local boiling point) and 112 °C. Most of the fumaroles (4 out of 7) discharged superheated steam.

The survey showed that inflow of heated air and a surrounding turbulent flow of an air-steam mixture occur at the edges of most vents. The speed of air inflow appears to be proportional to the steam jet velocity and reached c. 40 m/s at the top of a jet which discharged steam with 100 m/s. Such inflow can be recognised from the flow direction (negative dynamic pressure) when measured with the modem electronic pressure meter which we used. Air-steam mixtures can also be recognised fiom their temperature, which is below that of local boiling. Our studies showed that temperatures of a few degrees below B.P temperature at the margin of the vent are already indicative of significant air entrainment. Such entrainment cannot be recognised from the structure of the jet. Fumaroles at the bottom of small steaming craters can entrain a significant amount of down flowing air. At the surface of such craters the upward mass flow rate of air entrained in the jet can exceed that of the steam flow. The best setting for reproducible steam jet measurements is therefore that of fumaroles which discharge horizontally from an accessible vent.

We found a clear linear relationship between the heat output of fumaroles and their associated steam cloud if the opaque part of the cloud area is normalised with respect to the total steam cloud area visible in good quality, vertical air photos. This allows an assessment of the total heat output of all fumaroles. For the Karapiti area this output was c. 80 MW during the period of our survey.

Acknowledgement

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References

Allis, R.G. **(1979).** Thermal history of the Karapiti Area, Wairakei. Geophysics Division Report **137,** DSIR, Wellington.

Dawson, G.D. **(1964).** The nature and assessment of heat flow from hydrothermal areas. NZ Journ. Geol. Geophysics, **7, 155-171.**

Kays, W.M. **(1966).** Convective heat and mass transfer. McGraw-Hill, New York.

Mongillo, M.A. and Allis, R.G. **(1988).** Continuing changes in surface activity at Craters of the Moon thermal area, Wairakei. Proc. **10** th NZ Geothermal Workshop, pp. **345-349.**

Scorer, R.S. **(1958).** Natural Aerodynamics. Pergamon Press, London.

Thompson, G.E.K., Banwell, C.J., Dawson, G.B. and Dickinson, D.J. **(1964).** Prospecting of hydrothermal areas by surface thermal surveys. Proc. UN Conference New Sources of Energy, Rome **1961,** vol.2., **386 - 401.**