Identification of gradient temperature and heat flow area of geothermal Ijen Volcano Indonesia

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Abstract. A researcher carried out a study about gradient temperature and heat flow in the field of regional area of solfatara Ijen Banyuwangi Regency, East Java province, Indonesia. It is according to the temperature from the surface to about 100 cm deep, while making use of thermocouples with the accuracy of ± 0.5 % and ± 1 °C. Coordinate position measurements using a Garmin GPS device. This research aims to study the distribution of the temperature at any given depth, which is the gradient of temperature at a depth of 2000 m and the value of heat transfer through conduction. Temperature distribution of the depth contour, there are zones with high-temperature, and they increase along with the increase in depth. The gradient of temperature is 35 °C m⁻¹ at a depth of 2000 meters generates 175.6 °C. The maximum heat flow value is always obtained in the presence of sulfur, while the average heat flow of solfatara on the field is 21.08 W m⁻².

Keywords: distribution, geothermal, gradient temperature, heat flow, ijen volcano.

1. Introduction

Geothermal energy is the source of heat that contained in hot water, water vapor, and mineral rocks that follow up plus other gases that are genetically inseparable in a geothermal system. Indonesia was the 2nd biggest country that has geothermal after the USA. However, the installed capacity of Indonesia is 1,438 MW. Nevertheless, the utilization is still at 3th while the Philippines is the second (1,904 MW) and the USA (3,700 MW). The target of the Government of Indonesia in 2023 is that Indonesia must be the first in the utilization of geothermal energy with a capacity of 3,729.5 MW [1]. Therefore, a preliminary, exploration, and exploitation survey need to be carried out to support geothermal utilization targets in Indonesia.

One of the locations of geothermal often prospects in East Java is Blawan – Ijen with a potential of 270 MW. This location of the Ijen crater (Figure 1) is characterize by the presence of
solfatara with a surface temperature of about 210 °C [2] and the emergence of hot water which occurred in the Subdistrict Blawan Sempol Bondowoso (Figure 2) with 21 manifestations of warm water with neutral pH and temperature which is approximately between the range of 39 to 51°C [2,3]. The existence of these sightings indicates that the region’s geothermal Blawan – Ijen is very complex against the rugged heat system. Determination of geothermal prospect areas in Indonesia for exploration studies based on the results of preliminary surveys conducted previously [2].

![Figure 1. Fumarole field with surface temperature 210 °C [4](image)](image)

To explore and exploit the necessary preliminary research, data based on geology and geophysics are essential in determining the depth, thickness, geothermal aquifer, the nature of the rock formations, temperatures, porosity, permeability of rocks, and chemical content of geothermal aquifer [5,6]. Some researchers have conducted on Ijen Vulcano with several geophysical methods for determining geothermal reservoir. Geo-electrical techniques that help in interpreting the reservoir resistivity value of 10.49 Ωm – 89.78 Ω m [7] and gravity or magnetic, which helps in understanding the value of the density anomaly with a high value occurs in the middle to the northeast. The Reduction To the Poles anomaly and upward continuation shows that the anomaly is in the middle of the study location towards the south [8].

![Figure 2. Location geothermal manifestations Blawan [3](image)](image)
Temperature measurement at a depth of a borehole is fundamental to explore and exploit underground resources, especially in the geothermal field [9]. The identification of the gradient temperature is an essential factor in determining the characteristics of the reservoir, which deserves to be produced. Geothermal exploration is to evaluate the distribution of the temperature and the heat transfer, which often occur in the reservoir towards the ground level [10]. Where several factors affect temperature gradients are heat flow, geothermal activity, and rock permeability, as well as residual heat, an ancient volcano [11]. The importance of temperature distribution and heat transfer is mainly to determine the characteristics of the reservoir. In this paper, we will be discussing the distribution of temperature in the area of solfatara Ijen. The gradient is the temperature, and the heat flow according to the drilled hole’s diameter and area of land covered by the research.

After the eruption of 50,000 years ago until now, it resulted in the formation of the Ijen Caldera, which was marked by the formation of five volcanoes around the caldera wall and seventeen volcanoes in the Ijen Caldera. The seventeen mountains in the Ijen Caldera from old to young consisted of Blau volcano; Widodaren volcano; Papak volcano; Pawenen volcano; Pendiil volcano; Cilik volcano; Gempol volcano; Kukusan volcano; Gelaman volcano; Wurung volcano; Genteng volcano; Anyar volcano; Lingeer volcano; Mlaten volcano; Cemara volcano; Gending Waluh volcano; and Ijen (Ijen Crater) [12]. Ijen caldera complex has a total land area of 210 km² (18 km x 15 km) with the boundary wall of the Kendeng caldera shaped like a crescent Moon that is located on the North and mounts Merapi, Ranteh, Jampit was borderline in the South (Figure 3) [13]. There are two types of calderas in the Ijen caldera complex, which are namely caldera rim and intra-caldera volcano. The caldera rim magma erupts by issuing a high composition of basalt to basaltic-andesite, which the intra-caldera volcano erupts by releasing low magma with content, which is mainly basaltic-andesite to dacite composition. In the area of the Ijen, the caldera complex has about 15 [4], where one of the mounts in Ijen is active and well known as the Ijen crater. The Ijen crater is a unique mountain with two eruptions of magma, which are high and low. Mount Ijen is at the intersection of the caldera rim and intra-caldera volcano [4].

Ijen crater is a young Ijen volcano that has such lithology tuff, breccia volcano, lava, sulfur, and a mixture of sand and tuff found in water areas of the crater. Tuff has color gray young, smooth, comfortable mashed, layered, and irregular. Breccia volcanic activity report is grey with yellowish towards the Pebble-sized up to shaped chunks, which has a component of the basal-andesite. The lava is composed of andesite, basalt, grey scoria, and porphyritic. Sulfur, pure nature, scattered in the crater of Ijen. This Rock is predicated on the Ijen volcanic activity report young and volcanic activity report Pajungan. Lava is composed of basalt, andesite scoria, gray, and porphyritic. Sulfur, pristine, scattered around the crater of Ijen [14].

2. Methods
Heat transfer is the science that predicts energy transfer in the form of heat that occurs due to changes in temperature between objects or materials. In the energy transfer processes, there is always a speed of heat transfer occurrence, which is better known as the rate of heat transfer. Then, heat transfer is also a science to predict the rate at which heat transfer, and it’s in certain conditions. There are three forms of heat transfer mechanisms known, and they’re namely conduction, convection, and radiation [5].

When there is a temperature gradient in the body, the heat energy will flow from high temperature to low temperature, and this phenomenon is known as heat transfer through conduction. In physics, observations show that there are two essential things about the flow of heat from temperature non-uniformity in the body (equation 1 and 2) [15].
\[ \frac{\dot{q}}{|\dot{q}|} = -\frac{\nabla T}{|\nabla T|} \]  \hspace{1cm} (1)

and

\[ |\dot{q}| \propto |\nabla T| \]  \hspace{1cm} (2)

from the phenomenon can be described by the Fourier equation (equation 3).

\[ \dot{q} = -k \nabla T \]  \hspace{1cm} (3)

If seen from components of x, y, and z then equation 3 becomes equation 4 to 6.

\[ q_x = -k \frac{\partial T}{\partial x} \]  \hspace{1cm} (4)

\[ q_y = -k \frac{\partial T}{\partial y} \]  \hspace{1cm} (5)

\[ q_z = -k \frac{\partial T}{\partial z} \]  \hspace{1cm} (6)

Negative sign arises due to the flow of heat from high temperature, leading to low temperature [5]. If Equation 3 is applied in the case of heat transfer on Earth, then it needs to be taken into consideration on the flow of heat to the Earth’s surface of the Earth while using the equations of cross-sectional 4 with an area (A) and the x-axis is the direction of heat transfer (equation 7 and Figure 3).

\[ q_x = -kA \frac{\partial T}{\partial x} \]  \hspace{1cm} (7)

This research was conducted with some regional temperature field survey on solfatara mount Ijen using thermocouples (Figure 4) that have an accuracy of ± 0.5% to ± 1 °C. GPS was used to measure the position, latitude, longitude, and altitude as well as soil driller for drilling into the ground to a depth of 1 meter and the hole diameter of 2.54 cm. Temperature measurement can use to find out the value of the temperature at each depth (Figure 5). Data capture stages are the
creation of drill holes, calibration the thermocouple, and temperature data collection by mapping (adjusted to field conditions). The research flow is presented in Figure 6.

Figure 5. Sensors thermocouples with a depth of 50 cm and 100 cm [16]

3. Result and discussion
That point where the mapping has already been conducted, temperature measurement will then be carried out in some random location following the conditions of the field. As for the data that you retrieved, it’s the position of the latitude, longitude, and altitude as well as the value of the
temperature of the thermocouple on depth 0 cm ($T_0$), 50 cm ($T_{50}$), and 100 cm ($T_{100}$) and about 10 minutes on each depth. The data is presented in Table 1.

| Point | $T_0$ (°C) | $T_{50}$ (°C) | $T_{100}$ (°C) |
|-------|------------|---------------|---------------|
| Ijen 1 | 21.2       | 23.8          | 24.2          |
| Ijen 2 | 30.3       | 31.2          | 35.9          |
| Ijen 3 | 19.5       | 19.9          | 23.1          |
| Ijen 4 | 22         | 23.7          | 34.1          |
| Ijen 5 | 35.3       | 38.2          | 40.5          |
| Ijen 6 | 37.6       | 38.5          | 40.1          |
| Ijen 7 | 63.2       | 70.3          | 68.5          |
| Ijen 8 | 22.6       | 23.8          | 24.6          |
| Ijen 9 | 17.3       | 18.2          | 19.9          |
| Ijen 10 | 40.6     | 40.9          | 42.3          |
| Ijen 11 | 26.2       | 26.7          | 32.9          |
| Ijen 12 | 201        | 213.7         | 245.9         |
| Ijen 13 | 40.1       | 43.5          | 61            |

Based on Table 1, modeled contours of temperature distribution on the surface of the ground ($T_0$) is in Figure 7, the depth of 50 cm ($T_{50}$) is in Figure 8, and depth of 100 cm ($T_{100}$) is in Figure 9 on the temperature distribution. In the contour of the ground surface (Figure 7), it has an interval of 10 to 215 °C. The maximum temperature in the solfatara area of Mount Ijen was 201°C at the point the Ijen 12, while the minimum temperature of about 17.3 °C at Ijen-9. Lastly, its average temperature on the surface is app. 44.3 °C.

![Figure 7. Distribution of Temperature on the surface of the ground](image-url)
Figure 8. Distribution of temperature at a depth of 50 cm

Figure 9. Distribution of temperature at a depth of 100 cm

On the chart of the distribution of temperature in contour with a depth of 50 cm ($T_{50}$) (Figure 9), it appears as though higher temperature zone contours are increasingly meeting while being compared on the contour of the surface temperature distribution ($T_0$). The maximum temperature in the depths of 50 cm, and it amounted to 213.7 °C emphasis Ijen 12 and the minimum temperature of about 18.2 °C at Ijen 9. The point with the average temperature was marked to be 47.1 °C.

On the distribution of temperature in contour depth 100 cm ($T_{100}$) (Figure 10), with high-temperature zone looks increasingly moves from on the distribution of temperature in contour depth 50 cm and the surface temperature. The maximum temperature of 245.9 °C, are on the point of the Ijen 12, while the minimum temperature was about 19.9 °C point Ijen 9 and an average temperature of 53.3 °C overall. Those results demonstrated that more and increase the depth of the higher temperatures that are measurable. It also has early indications that the slope
of the temperature of vertical research valuable in positive areas [17]. But at this point in Ijen 7 decline from a depth of 50 cm to 100 cm depth with temperatures 70.3 to 68.5 °C.

Based on the data, the results of measurements near the discharge pipe sulfur a land surface that have a temperature of 40.1°C, at a depth of 50 cm with temperature 43.5 °C and depth 100 cm with temperature 61 °C) gradient temperature are 35 °C m⁻¹ (Table 2). The interpretation of the gradient temperature using polynomial equations by incorporating with data (35 °C m⁻¹) and additional data at a depth of 500 m has a temperature of 80 °C [18] then retrieved the results any depth (Figure 10) so is estimated to be at a depth of 2000 m reservoir on the field the area of solfatara has a temperature of about 175.6 °C.

![Figure 10. Temperature gradient modeling](image)

Lithology in solfatara is breccia tufa on the soil surface to a depth of 1.91 m. deeper layers of tuff 1.91 m – 24.95 m. There are sulfur deeper inset 24.95 – 32.56 m with 7.61 m, and a thickness of a layer of most in the form of a tuff found at 32.56 m – 45 m, the surface of rock types so that up to 1-meter depth is breccia tufa [7].

The heat flow can be determined using geothermal temperature gradient data by using the thermal conductivity [19] equation 7. Heat transfer in conduction of cross-section area if the hole depth and T100 towards the T50 by using Equation 7 with type K breccia tufa rocks [7] with value k of 1.7 W m⁻¹ °C⁻¹ then result as Table 2 and Figure 11 with a value of k at a depth of 100 amounting to 1.7 W m⁻¹ °C⁻¹ [20]. From Table 2 and Figure 11 can be interpreted that there is heat flow value is negative (Ijen 7) this is because the results of the measurements of temperature at a depth of 100 cm lower than the temperature at a depth of 50 cm or direction of flow of heat flows from high temperature towards the low temperature. Whereas heat flow positive value indicates the measurement results of temperature at a depth of 100 cm higher than the temperature at a depth of 50 cm or flow of heat flow from the low-temperature leading to high temperatures and can be explained that the value of the minimum heat flow has value -6.12 W m⁻² at Ijen 7 and the maximum value of 109.4 W m⁻² at Ijen 12. The highest heat flow values in the presence of sulfur. While the average heat flows in the field solfatara was 21.08 W m⁻².
Table 2. The results of calculation of heat transfer conduction

| Point | $T_{50}$ (°C) | $T_{100}$ (°C) | $\frac{dt}{dz}$ (°C m$^{-1}$) | Heat flow (W m$^{-2}$) | Average (W m$^{-2}$) |
|-------|----------------|----------------|-------------------------------|------------------------|----------------------|
| Ijen 1 | 23.8           | 24.2           | 0.8                           | 1.36                   |                      |
| Ijen 2 | 31.2           | 35.9           | 9.4                           | 15.98                  |                      |
| Ijen 3 | 19.9           | 23.1           | 6.4                           | 10.88                  |                      |
| Ijen 4 | 23.7           | 34.1           | 20.8                          | 35.36                  |                      |
| Ijen 5 | 38.2           | 40.5           | 4.6                           | 7.82                   |                      |
| Ijen 6 | 38.5           | 40.1           | 3.2                           | 5.44                   |                      |
| Ijen 7 | 70.3           | 68.5           | -3.6                          | -6.12                  |                      |
| Ijen 8 | 23.8           | 24.6           | 1.6                           | 2.72                   |                      |
| Ijen 9 | 18.2           | 19.9           | 3.4                           | 5.78                   |                      |
| Ijen 10| 40.9           | 42.3           | 2.8                           | 4.76                   |                      |
| Ijen 11| 26.7           | 32.9           | 12.4                          | 21.08                  |                      |
| Ijen 12| 213.7          | 245.9          | 64.4                          | 109.48                 |                      |
| Ijen 13| 43.5           | 61             | 35                            | 59.5                   |                      |

Figure 11. Plotting of heat flow to the height of the surface

4. Conclusion
The results of processing and analysis data, at the temperature distribution of the contour, there are zones with a high-temperature increase along with the increasing depth. It can be said that solfatara areas are appearing on the surface of a small portion, and they have a more extensive geothermal system below. The gradient of temperature is 35 °C m$^{-1}$ at a depth of 2000 meters generates 175.6 °C. Heat flow has its minimum value, which is -6.12 W m$^{-2}$ at point Ijen 7 and the maximum value of 109.4 W m$^{-2}$ at Ijen 12. The highest heat flow values are always in the presence of Sulfur, while the average heat flow of solfatara is 21.08 W m$^{-2}$.

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