PROCEEDINGS, 50th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2025
SGP-TR-229

Geoflowtest - A Portable Device for Realtime Monitoring of Geothermal Production Well Testing

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Keywords: Real-time, well testing, portable, continuously monitor, Geoflowtest

ABSTRACT

This research paper introduces a novel real-time portable device designed for geothermal production well testing. Geothermal energy is a promising renewable resource, and effective management of geothermal reservoirs necessitates precise and immediate data acquisition during testing phases. The portable device integrates advanced sensors and data acquisition systems to continuously monitor essential parameters such as temperature, pressure, flow rate, and enthalpy. It is engineered for durability in challenging geothermal environments, adaptable to various well sizes and depths, and compatible with existing infrastructure. Wireless communication capabilities enable seamless data transmission to the encrypted web server dashboard, facilitating prompt decision-making and operational adjustments. The device, called as Geoflowtest, includes sophisticated algorithms for real-time data analysis and visualization, enhancing efficiency in well testing operations. Field trials and case studies demonstrate its effectiveness in optimizing geothermal production, minimizing downtime, and improving reservoir management strategies. The Geoflowtest represents a significant advancement, offering robust monitoring capabilities essential for maximizing geothermal energy extraction sustainably and economically.

1. INTRODUCTION

Geothermal energy is increasingly recognized as a sustainable and reliable source of power, offering a low-carbon alternative to conventional fossil fuels. The ability to harness geothermal energy depends on efficient exploration, development, and management of geothermal reservoirs (DiPippo, 2017). Critical to the successful operation of geothermal systems is the ability to monitor and evaluate the performance of geothermal wells during production testing, a process that provides essential data on reservoir characteristics, fluid properties, and overall system behavior (Mubarok et al., 2015).

Geothermal production well testing, commonly referred to as well testing, involves a series of controlled procedures to determine key parameters such as pressure, temperature, flow rates, and fluid composition over a given period (Grant & Bixley, 2011). These parameters are integral in evaluating the well's productivity, estimating reservoir capacity, and designing long-term sustainable extraction strategies. However, traditional well testing often requires complex setups, remote monitoring, and significant time delays for data collection and analysis. Moreover, it frequently involves expensive, stationary equipment and personnel mobilization, which can add to both operational costs and potential downtime. Considering these challenges, the development of portable, real-time monitoring solutions has the potential to revolutionize geothermal well testing by improving accuracy, reducing costs, and enabling more agile, responsive decision-making in the field (Robinson & Chang, 2022). Despite advances in geothermal exploration and production, there remains a gap in providing cost-effective, flexible, and real-time data acquisition tools during well testing. Conventional well testing equipment often involves bulky machinery, extensive set-up time, and a lack of immediate data feedback, which hinders operational efficiency and the ability to make real-time decisions. Additionally, the deployment of such equipment is typically confined to fixed setups, limiting the versatility required in remote, dynamic geothermal sites.

Given these challenges, there is a growing need for a portable, real-time monitoring system that can deliver accurate data during geothermal production well testing, enabling better-informed decisions and enhancing the overall testing process. The primary objective of this study is to present Geoflowtest, a novel portable device designed to monitor and collect real-time data from geothermal production wells during well testing operations. Geoflowtest combines the functionality of traditional well testing systems with enhanced portability, ease of use, and real-time monitoring capabilities. This device aims to (1) provide real-time measurement of critical parameters such as pressure, temperature, and flow rates; (2) offer ease of deployment and mobility, making it ideal for both small-scale and large-scale geothermal sites; (3) enable remote data transmission for continuous monitoring and analysis; (4) improve the overall efficiency of geothermal well testing by reducing the need for bulky equipment and extensive setup times; and (5) enhance decision-making by providing immediate, actionable data to operators and engineers.

Through this study, the feasibility and potential impact of Geoflowtest in revolutionizing geothermal well testing are explored. This paper focuses on the design, development, and initial testing of the Geoflowtest device. Key aspects of the study include device architecture and design, field testing-validation, and data analysis application. The findings from this research aim to demonstrate how Geoflowtest can offer a practical and scalable solution for enhancing geothermal well testing operations, contributing to the broader field of geothermal energy exploration and production. This study also contributes to the broader knowledge base surrounding advanced instrumentation for renewable energy systems, with relevance to geothermal energy. Furthermore, it sets the stage for future research on the optimization of geothermal testing procedures and the development of more advanced, integrated monitoring technologies (Robinson & Chang, 2022). By the end of this study, we hope to demonstrate that Geoflowtest represents a significant step forward in enhancing geothermal well testing, providing both immediate operational benefits and long-term advancements for the geothermal energy industry.

2. LITERATURE REVIEW

Geothermal well testing is a critical process in the exploration and development of geothermal resources (Grant & Bixley, 2011). It enables engineers and scientists to obtain data about the performance of geothermal wells and to assess the characteristics of the geothermal reservoir. Over the past few decades, geothermal well testing has become increasingly complex as demands for accuracy, real-time data, and efficiency have risen. To meet these demands, a variety of technologies and methodologies have been developed, each with its own advantages and limitations. This section reviews existing geothermal well testing techniques, monitoring systems, and the challenges faced by the industry. Understanding these existing approaches provides the context for the development of innovative solutions, such as Geoflowtest, which aims to address current shortcomings by offering portable, real-time monitoring capabilities.

2.1. Geothermal Well Testing Techniques

2.1.1 Conventional Methods for Well Testing

Several common techniques for measuring two-phase flow in geothermal applications are utilized, including: the total flow calorimeter (Bixley et al., 1998; DiPippo, 2007; Grant & Bixley, 2011; Helbig & Zarrouk, 2012; Siitonen, 1986); the lip pressure pipe (James, 1962; Mubarok et al., 2015; Sulaiman & Freeston, 1986); and the separator method (Cahyono et al., 2015; DiPippo, 2007; Grant & Bixley, 2011; Mubarok et al., 2015; Watson, 2013.

- Total Flow Calorimeter:
  The total flow calorimeter, as described by Bixley et al. (1998) and Helbig & Zarrouk (2012), is a straightforward and effective technique utilized to determine the mass flow rate and flowing enthalpy from geothermal wells. In this method, geothermal fluid is expelled and combined with cold water within an open-top tank, as depicted in Figure 1.

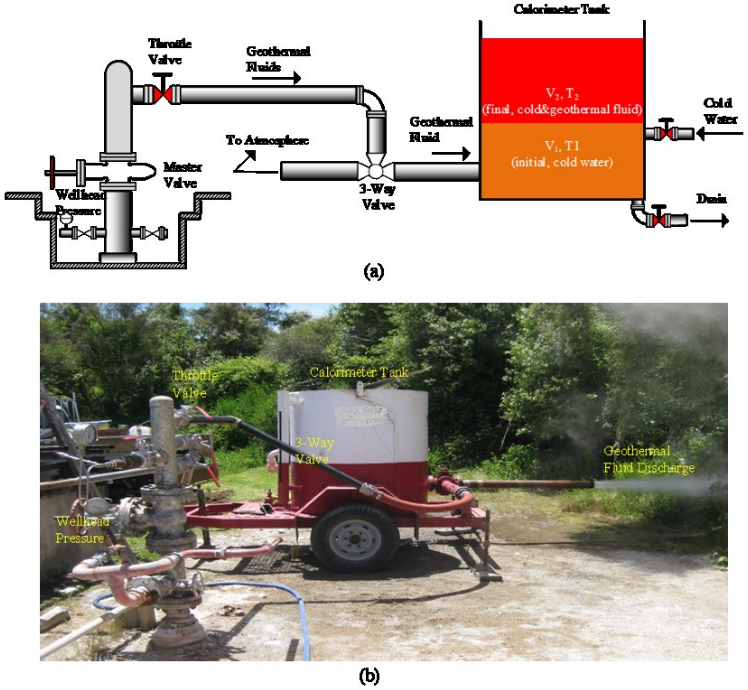


Figure 1. A schematic depiction of a geothermal calorimeter arrangement (a), along with an image illustrating the calorimeter testing process during pipe warm-up (b) (Mubarok et al., 2019).

The fluid inside the tank's initial and final volume and temperature are converted to a mass flow rate and flowing enthalpy through a simple mass and energy balance, as described by Grant & Bixley (2011):

$$h = \frac{Q}{\dot{m}_t} = \frac{(\rho_2 V_2 h_{f2}) - (\rho_1 V_1 h_{f1})}{(\rho_2 V_2) - (\rho_1 V_1)}, \tag{1}$$

where $\dot{m}_t$ is the total mass flow rate (kg/s), ρ_1 is the density of the cold fresh water (kg/m^3), V_1 is the volume of the cold water (m^3), ρ_2 is the density of the water-geothermal fluid mixture (kg/m^3), V_2 is the volume of cold water-geothermal fluid mixture (m^3), Q is the well's power output (kW), h_{f1} is the specific enthalpy of the cold water (kJ/kg), h_{f2} is the specific enthalpy of the mixture (kJ/kg), and h is the measured flowing enthalpy of the well (kJ/kg).

According to Bixley et al. (1998), the practicality of using calorimeters in geothermal wells is restricted to those with an output of approximately 25 kg/s (90 tons/hr) due to limited tank capacity. This flow rate is deemed insufficient for commercial electrical power production wells (Grant & Bixley, 2011). While increasing tank capacity could accommodate larger mass flow rates, the size of the tank and the additional cold water required would pose challenges in transportation to remote well test sites, making this method feasible only for geothermal wells with low flow rates. Calorimeters are commonly utilized for testing small size investigation wells (slim holes) and direct use wells, as illustrated in Figure 4.1b (Bixley et al., 1998). Challenges associated with calorimeters include steam loss from the top of the tank, heat loss through tank walls, and limitations in the size of the surface pipeline connecting the well to the calorimeter (Zarrouk & McLean, 2019).

- Lip Pressure Method

The lip pressure method, developed by James in 1962, involves discharging geothermal fluid to the atmosphere through a pipe and measuring the pressure at the pipe lip. Empirically derived correlations are then utilized to calculate the two-phase mass flow rate. This method is particularly valuable for well production testing due to its superior accuracy compared to a calorimeter within a short timeframe. There are two distinct implementations of the lip pressure method: vertical discharge and horizontal discharge. The primary difference lies in the configuration of the lip pipe. In the vertical type, the lip pressure pipe is directly connected to the top (control) valve in a vertical orientation as illustrated in Figure 2. Conversely, in the horizontal type, the lip pipe is horizontally connected to the straight pipe and inserted into the silencer/flash-drum as shown in Figure 3. For vertical discharge, the empirical correlation is expressed in Equation (2) as proposed by James in 1962:

$$\dot{m}_t = \frac{184\,A\,p_{lip}^{0.96}}{h^{1.102}}, \tag{2}$$

where $\dot{m}_t$ is the total mass-flow rate (kg/s), p_{lip} is the lip pressure (Pa), A is the cross-sectional area of the lip pressure pipe (m^2), and h is the enthalpy (kJ/kg). The enthalpy in this case is estimated based on the feed zone temperature from the warmed-up downhole temperature profile of the well. It is important to note that the vertical discharge is only suitable for measuring geothermal wells with a liquid feed, not two-phase reservoirs. The Equation (2) exhibits low sensitivity to the estimated enthalpy, thereby presenting one of its key advantages. However, limitations of this method are evident in the form of elevated noise levels during vertical discharge and the potential ground contamination with geothermal fluid rich in silica and heavy metals. Vertical discharge is a common practice in newly drilled wells to facilitate the removal of debris and cuttings from drilling operations. The discharge enthalpy and mass flow rate for the horizontal lip pressure method can be determined using the equation provided by Grant & Bixley (2011) and Mubarok et al. (2015).

$$\dot{m}_t = \frac{\dot{m}_{f(atm)} h_{fg(atm)}}{h_{g(atm)} - h}, \tag{3}$$

where $\dot{m}_{f(atm)}$ is the liquid mass flow rate (kg/s) through a weir box (Figure 3), $h_{g(atm)}$ is the steam enthalpy at atmospheric pressure (kJ/kg), and $h_{fg(atm)}$ is the latent heat at atmospheric pressure (kJ/kg). For the correlation between h, P_{lip}, $\dot{m}_{f(atm)}$ and A at atmospheric pressure (1 bar absolute), a new term Y is defined:

$$Y = \frac{\dot{m}_{f(atm)}}{A \times p_{lip}^{0.96}}. \tag{4}$$

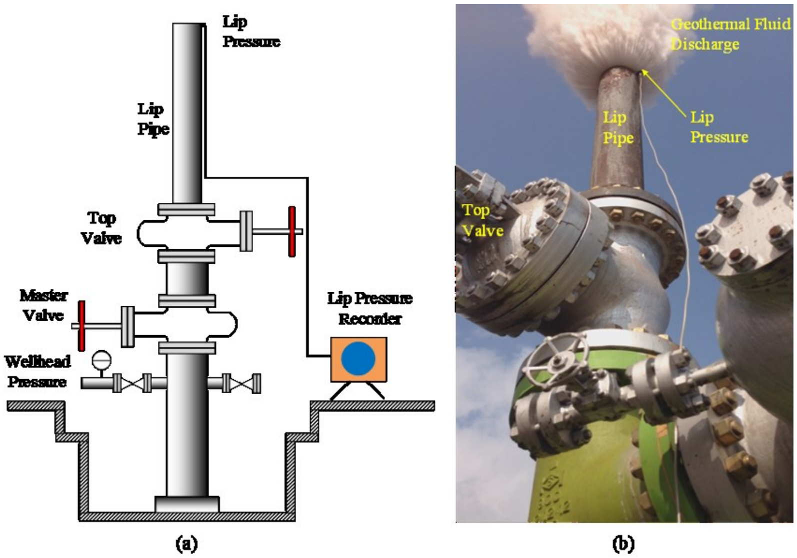


Figure 2. (a) A schematic of a vertical lip method facility and (b) an image of a vertical discharge test (Mubarok et al., 2019).

Grant & Bixley (2011) examined a plot of geothermal two-phase fluid enthalpy (h) and Y to produce Equation (4.5):

$$h = \frac{2675 + 3329Y}{1 + 28.3Y}. \tag{5}$$

Equation (5) is limited to an enthalpy range between 800-2200 kJ/kg (Grant & Bixley, 2011). The use of horizontal discharge results in increased precision for determining the mass flow rate compared to vertical discharge, as it enables the measurement of the authentic enthalpy of the borehole and can assess boreholes with two-phase feed areas (not restricted to liquid feeds). Nonetheless, the horizontal discharge method is more costly than vertical discharge due to the requirement for extra equipment and setup time (Figure 3) (Mubarok et al., 2015).

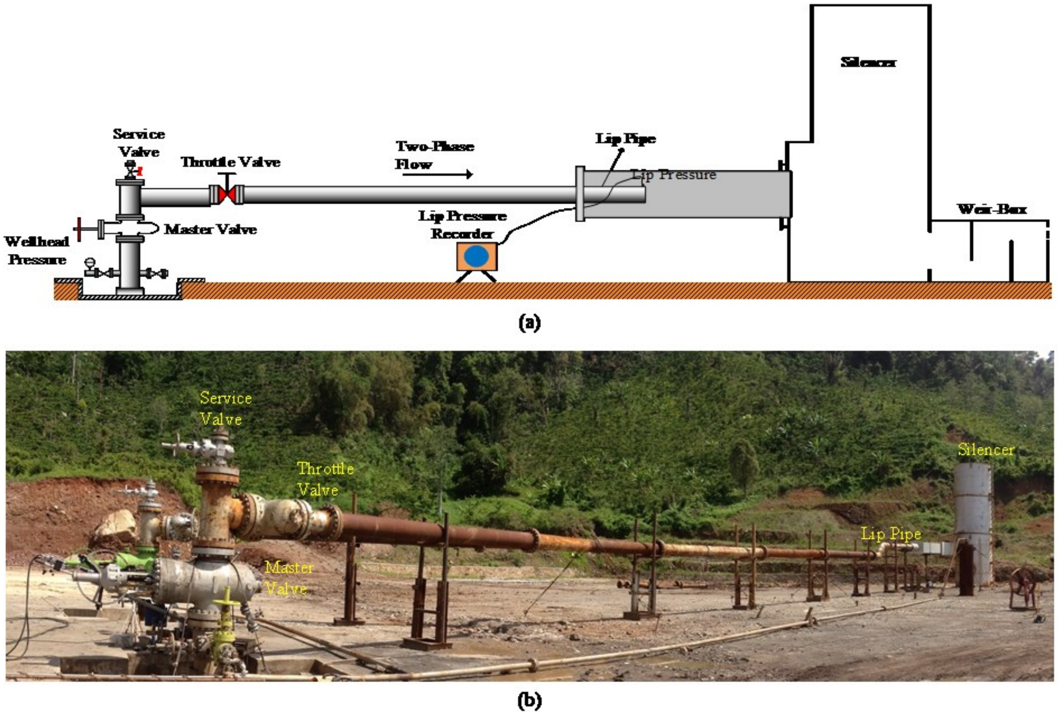


Figure 3. (a) A schematic of the horizontal lip method, (b) a picture of horizontal discharge at well pad K, Ulubelu geothermal field (Mubarok et al., 2019).

- Separator Method

  The Separator Method involves the separation of the two-phase fluid into steam and liquid brine within a separator vessel operating at pressures higher than atmospheric pressure. The method can achieve a separation efficiency of at least 99.9% (Grant & Bixley, 2011; Zarrouk & Purnanto, 2014). The flow of separated steam and liquid can be accurately measured using orifice plates; however, measuring separated liquid with an orifice is challenging as it can cause flashing of the saturated brine, resulting in unstable measurements (Watson, 2013). Consequently, separated liquid is typically measured using a silencer with a weir box (without the need for a lip pressure pipe) (Grant & Bixley, 2011). A detailed schematic diagram of the separator method can be seen in Figure 4.

  After the measurement of the separated steam and liquid flow, the calculation of the two-phase flow rate and total enthalpy of the well can be determined utilizing a mass balance approach:

$$\dot{m}_t = \dot{m}_f + \dot{m}_g, \tag{6}$$

where $\dot{m}_f$ is the mass flow rate of water (brine) (kg/s) and $\dot{m}_g$ is the steam flow rate (kg/s). The dryness fraction (x) and total enthalpy (h) (kJ/kg) of the fluid are:

$$x = \frac{\dot{m}_g}{\dot{m}_t}, \tag{7}$$

$$h = h_f + x h_{fg}. \tag{8}$$

The values of liquid (h_f) and latent enthalpy (h_{fg}) are obtained at the separator pressure. The separator method has been identified as a more precise approach for determining both mass flow rate and enthalpy, as stated by Mubarok et al. (2015). Nonetheless, the initial expenses are substantial due to the capital outlays required for a separator, silencer, and rock muffler (refer to Figure 4). Additionally, transportation and installation expenses significantly contribute to the total cost. Therefore, it is imperative to verify that the well will self-discharge before proceeding with mobilization (Mubarok & Zarrouk, 2017).

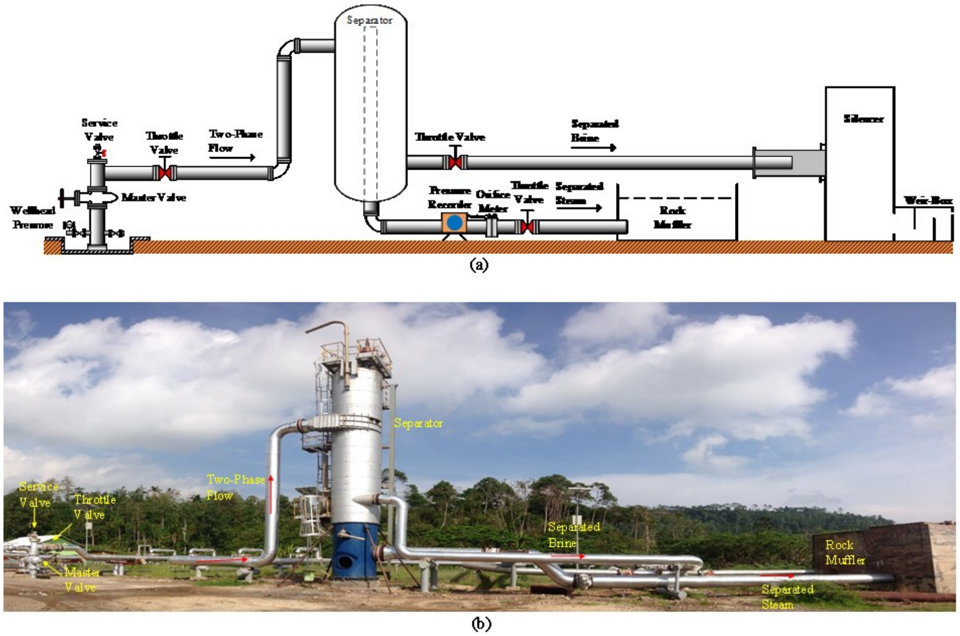


Figure 4. Presents a schematic diagram of the separator set-up (a) and an image showing the separator discharge test facility (b) (Mubarok et al., 2019).

Utilizing the measured mass flow rate and enthalpy from the calorimeter, lip pressure pipe, or separator methods, an output curve can be generated, as depicted in Figure 5. This output curve can then be used to estimate the well flow rate and enthalpy based on the wellhead pressure (WHP) during well operation.

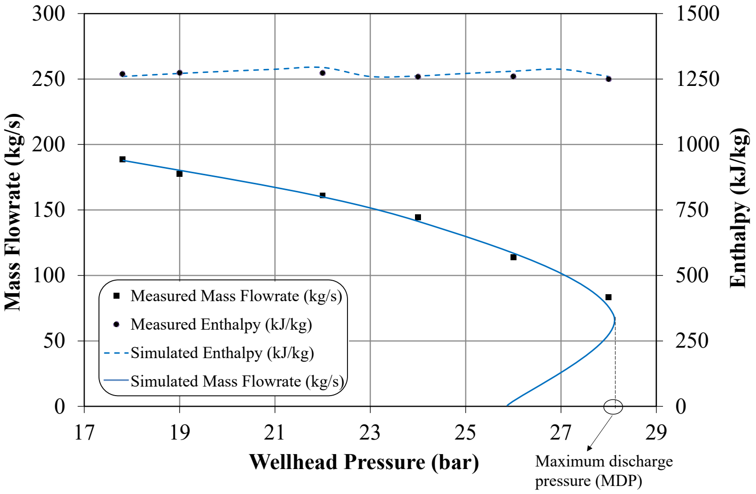


Figure 5. An illustration of the output curve, depicting the mass flow rate and enthalpy data obtained from production testing, along with the corresponding values simulated using WellSim™ wellbore simulation software (Mubarok et al., 2019).

The measurement needs to be conducted from the lowest wellhead pressure (fully open throttling) to the maximum discharge pressure (MDP) during production testing, where the MDP refers to the maximum pressure that still allows fluid discharge to the wellhead (Figure 5).

The wellbore simulation generates a projected profile of mass flow rate and enthalpy as a function of wellhead pressure. However, this output curve will evolve over time due to reservoir drawdown, rendering the predicted flow rate less accurate. It is customary in the industry to measure the output curve for each well every six months to obtain a more precise estimate of mass flow rate and enthalpy from each well (Watson, 2013). Nevertheless, this practice is not economically advantageous, as it necessitates temporarily taking wells out of production and incurring testing expenses.

2.1.2 Advanced Well Testing Techniques

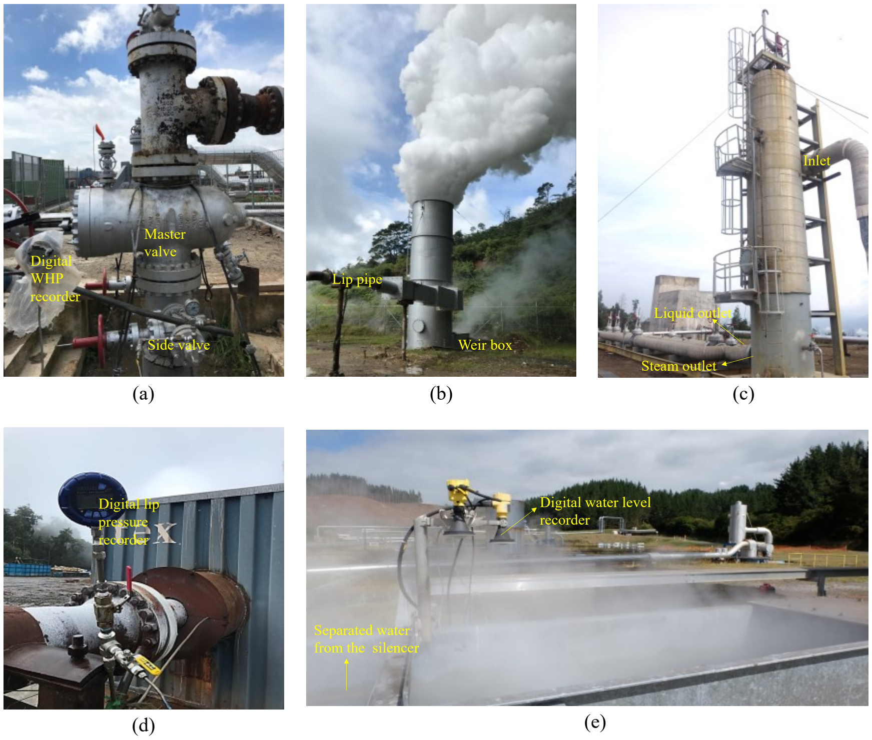
In recent years, there has been an increased focus on the integration of advanced technologies to improve the accuracy and efficiency of geothermal well testing. These methods involve the use of sophisticated instrumentation, sensors, and data analytics tools.

Geothermal wells often produce a mixture of water, steam, and gases, making accurate measurement of flow rates complex. Traditional flow meters may not be suitable for these conditions. A new real-time two-phase flow meter, invented and patented by Mubarok et al. (2019), is being employed to provide more accurate measurements in geothermal wells, allowing for real-time data collection and analysis of the well's flow composition.

2.2. Monitoring Systems in Geothermal Wells

Monitoring systems for geothermal wells have evolved significantly over the years (Zarrouk & McLean, 2019). From early mechanical gauges to modern digital systems, the trend has been toward increasing automation, digitalization, and real-time data transmission (Figure 6). In the past, geothermal wells were primarily monitored using static systems that involved the use of mechanical gauges for pressure and temperature measurements. These systems were limited by their inability to provide real-time data, and data had to be retrieved manually. While inexpensive and relatively simple, these systems were inadequate for the growing complexity of geothermal operations.

Advances in telemetry, wireless communication, and sensor technology have enabled the development of real-time monitoring systems. These systems typically include sensors for temperature, pressure, flow rate, and chemical composition, which continuously transmit data to surface stations or cloud-based platforms. The key features of these systems include real-time data acquisition, wireless communication, data integration and visualization.



(a) (b) (c)

(d) (e)

Figure 6. Photographs of production testing monitoring system facilities at (a) well head, (b) silencer, (c) separator, (d) lip pipe, and (e) weir box (taken by first Author).

Recent developments in portable monitoring systems are geared toward making real-time data acquisition more flexible and accessible. These systems are smaller, lighter, and more adaptable, enabling deployment in a variety of field conditions. Portable systems allow for easier transport between wells and faster setup times, making them particularly useful for temporary or emergency well testing.

Some systems include modular components that can be quickly adapted to specific geothermal wells, enabling rapid deployment in cases where traditional large-scale systems might not be practical or cost-effective. This portability is particularly useful for geothermal resource exploration in remote or less-developed areas where traditional infrastructure may be lacking.

2.3. Challenges in Geothermal Well Testing and Monitoring

Despite the advancements in geothermal testing and monitoring technologies, several challenges persist in the field that hinder optimal resource management and well performance assessment (Grant & Bixley, 2011).

Existing geothermal well testing techniques and monitoring systems have made significant strides in improving the accuracy and efficiency of data collection. However, challenges related to cost, data integration, mobility, and real-time monitoring remain prevalent. Geoflowtest aims to address these gaps by providing a portable, cost-effective, and real-time monitoring solution for geothermal production well testing. By combining advanced sensor technology with wireless data transmission and user-friendly software, Geoflowtest offers the potential to enhance field testing operations, reduce operational costs, and enable more agile decision-making in geothermal well management.

3. GEOFLOWTEST DESIGN AND METHODOLOGY

The Geoflowtest device represents an innovative approach to geothermal well testing, offering a portable, real-time monitoring solution that significantly enhances the efficiency and accuracy of geothermal production well testing. The Geoflowtest device is originally designed and invented by PT Pertamina Geothermal Energy Tbk (PGE) to meet the operational needs of geothermal engineers and operators in the field, offering flexibility, ease of use, and accurate data collection. By combining modular hardware components with an intuitive software interface, Geoflowtest aims to reduce setup time, improve real-time monitoring, and facilitate better decision-making for geothermal reservoir management.

3.1. Design Principles of Geoflowtest

The design of Geoflowtest is centered on several core principles aimed at maximizing performance, portability, and usability. A key advantage of Geoflowtest is its portability. The system is designed to be lightweight and compact, making it easy to transport and deploy in a variety of field environments. This is particularly important for geothermal projects located in remote areas, where traditional large-scale monitoring systems would be impractical due to logistical challenges. The device is built around a modular framework, which allows different components to be added or removed based on the specific needs of the testing operation. This design flexibility ensures that Geoflowtest can be adapted for a wide range of geothermal wells, from smaller exploratory wells to large-scale production wells. Given the harsh conditions often found in geothermal environments (e.g., high temperatures, corrosive fluids, and remote locations), Geoflowtest is built using durable materials that are resistant to environmental stresses. The device is encased in a weather-resistant and shock-proof housing to withstand both the physical rigors of transportation and the demanding conditions on-site.

Figure 7. Photograph of portable Geoflowtest device preparation setup before the production testing.

Geoflowtest is designed to provide real-time data acquisition, ensuring that geothermal operators and engineers can monitor well performance as it occurs. This real-time capability is essential for immediate decision-making and troubleshooting (Robinson & Chang, 2022). The device continuously records key well parameters, such as pressure, temperature, flow rate, and visualization using closed circuit television (CCTV) as shown in Figure 8. These measurements are updated in real-time, providing an accurate picture of the well's operational conditions. As data is collected, it is transmitted to the surface station or cloud-based platform immediately, enabling users to act on the information without delays. This facilitates timely interventions if unexpected behavior is detected in the well or reservoir.

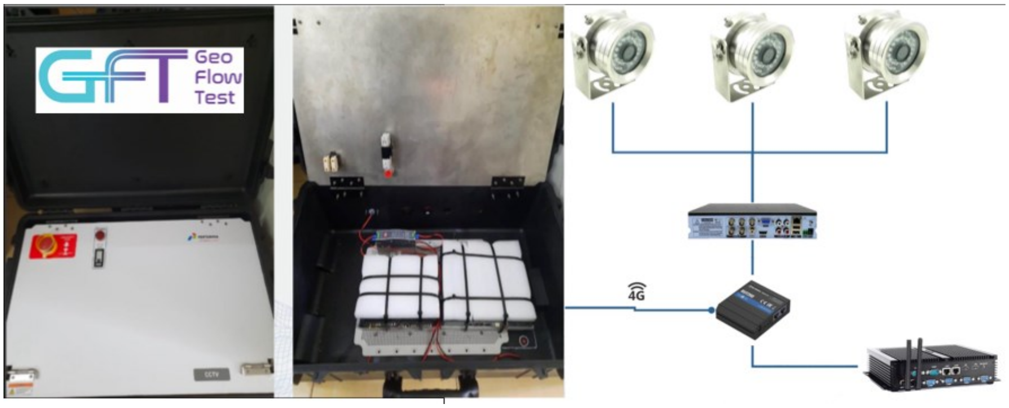


Figure 8. Closed circuit television (CCTV) system of Geoflowtest.

Geoflowtest aims to be user-friendly, allowing geothermal engineers with varying levels of technical expertise to operate the device efficiently. The system’s intuitive interface and automated features reduce the need for specialized training. The system is designed for quick setup and deployment (plug-and-play functionality). Users can easily attach the necessary sensors to the well, configure the device for the desired measurements, and begin collecting data within minutes. A mobile app or tablet interface provides real-time visualization of the data, along with user-friendly controls for adjusting settings and viewing performance metrics. The interface also includes data analytics tools that can automatically process and interpret measurements, providing actionable insights without requiring advanced technical knowledge. In term of adaptability, Geoflowtest can be used for various geothermal production types, including lip pressure (Figure 3) or separator method (Figure 4), by adjusting sensor configurations and software settings to align with the unique operational characteristics of each system.

3.2. Hardware Components of Geoflowtest

The hardware of Geoflowtest consists of several key components that work together to provide accurate real-time measurements of geothermal well parameters. These components are designed to be modular, rugged, and capable of operating in the extreme conditions typically encountered in geothermal environments. The heart of Geoflowtest lies in its advanced sensor array, which collects the necessary data from the wellbore. The key components used in the device include pressure transmitters (PT), temperature sensor (TT), water level sensor, modem, flow computer and human machine interface (HMI) display as shown in Figure 9.

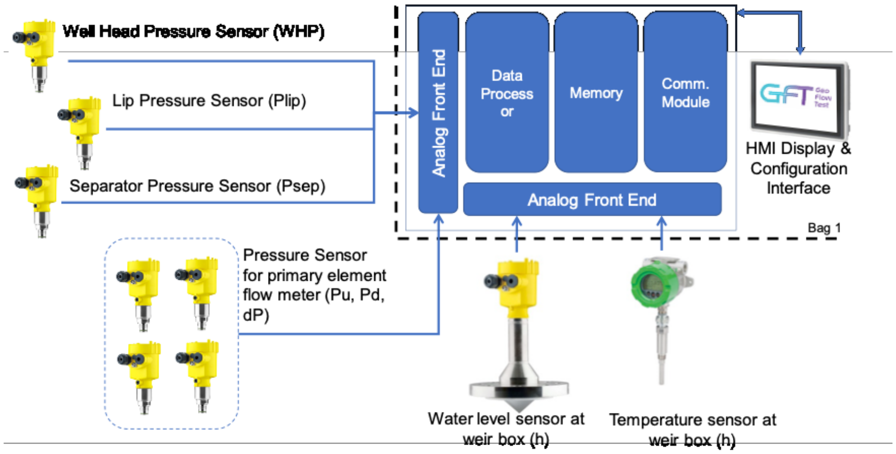


Figure 9. Sensors and key components unit of Geoflowtest.

The data logger (RTU) collects and stores the measurements from the sensors. It is equipped with high-speed processors and data storage capabilities to handle large amounts of data from multiple sensors. This data is then transmitted through the communication module. The data is transmitted via wireless communication methods, such as Wi-Fi, radio frequency, or cellular networks, depending on the location of the geothermal well (Mubarok et al., 2019). In remote areas where cellular networks may not be available, satellite communication can be used to ensure data transfer. Geoflowtest supports cloud-based data storage and remote access, allowing operators to monitor well performance in real time from anywhere. Cloud integration also facilitates data backup and the use of machine learning tools for data analysis.

Given the remote locations of many geothermal wells, Geoflowtest is designed with a reliable and long-lasting power supply system (Figure 10). The device uses rechargeable lithium-ion batteries that can operate for extended periods without the need for frequent recharging. To minimize energy consumption, the device incorporates power-saving modes, ensuring that it can operate for several days or even weeks without the need for external power sources. For long-term deployments in off-grid locations, Geoflowtest can be equipped with a solar panel to recharge its batteries, providing continuous operation in environmentally sustainable ways.

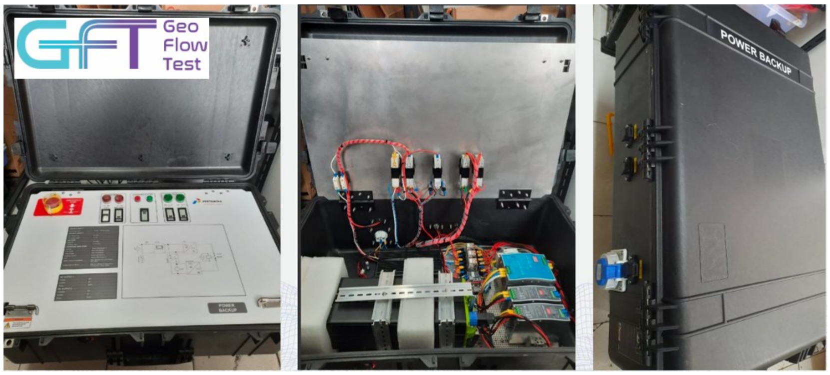


Figure 10. Battery and power back up of Geoflowtest.

The hardware components of Geoflowtest are housed in a rugged, modular enclosure designed to protect the device from environmental conditions (Figure 11). The housing is weatherproof, dustproof, and resistant to corrosion, making it suitable for the extreme conditions typically found in geothermal fields. The modular housing is designed for ease of deployment, with simple connectors and quick-release mechanisms that enable the device to be rapidly set up or moved between wells. The enclosure is also equipped with thermal protection to prevent overheating of the sensitive electronic components, ensuring reliable performance even under high-temperature conditions common in geothermal environments. The design of Geoflowtest is built around the principles of portability, real-time monitoring, ease of use, and scalability. Its modular hardware components –ranging from advanced sensors to rugged enclosures– ensure that it can operate effectively in the extreme conditions encountered in geothermal fields. The software framework provides seamless data collection, visualization, and analysis, enabling better decision-making and improved well management.

Figure 11. Protected modular housing and enclosures design of Geoflowtest.

3.3. Software Framework of Geoflowtest

The software framework of Geoflowtest consists of both embedded firmware that runs on the device and cloud-based or mobile software applications used for data visualization, analysis, and control. The embedded firmware controls the operation of the sensors, data acquisition, and communication modules. It ensures that data is collected at the correct intervals and transmitted securely to the surface station or cloud platform. The firmware also manages power consumption, sensor calibration, and error handling. The firmware includes built-in diagnostic tools for sensor calibration and real-time performance monitoring (Robinson & Chang, 2022) If a sensor malfunctions or provides out-of-range readings, the system will alert the user and provide troubleshooting recommendations. The firmware ensures that data from multiple sensors is synchronized and processed efficiently, even in complex testing scenarios where data is being collected from multiple depths or locations in the well. Data collected by Geoflowtest can be stored and analyzed in the cloud. Advanced analytics, including trend analysis, anomaly detection, and machine learning algorithms, can be applied to the data to gain deeper insights into well performance and reservoir behavior.

4. FIELD TESTING AND RESULTS

To evaluate the effectiveness and reliability of the Geoflowtest device, a series of field tests were conducted in a variety of geothermal well testing environments. These tests aimed to assess the performance of Geoflowtest in real-world conditions, comparing its data accuracy, ease of deployment, and overall usability against traditional well testing methods. This chapter presents the results of these field tests, detailing the key performance metrics, challenges encountered, and comparisons with conventional monitoring systems. The primary objectives of the field tests were to (1) verify the accuracy and precision of the data collected; (2) evaluate the device's ease of setup, portability, and deployment time; (3) compare the real-time data provided by Geoflowtest with data obtained from traditional monitoring methods; and (4) assess the overall functionality and reliability of the system under varying field conditions.

The field tests were conducted across two distinct geothermal sites –Ulubelu (Figure 12) and Karaha fields–, each with varying operational conditions. These sites were selected to provide a representative sample of the challenges faced in geothermal well testing, including temperature extremes, multi-phase fluid production, and remote locations.

For comparative purposes, traditional monitoring equipment was used alongside Geoflowtest at each test site. These traditional systems are typically stationary, requiring significant time for setup and calibration, and are not designed for real-time mobile data acquisition (James, 1962). During each field test, Geoflowtest was configured to collect the following parameters, including wellhead pressure (WHP), lip pressure, and water level at weir box. Data from Geoflowtest was calculated in an RTU and transmitted in real-time to a mobile device or cloud-based platform, where it was monitored by the field engineers in parallel with the traditional system.

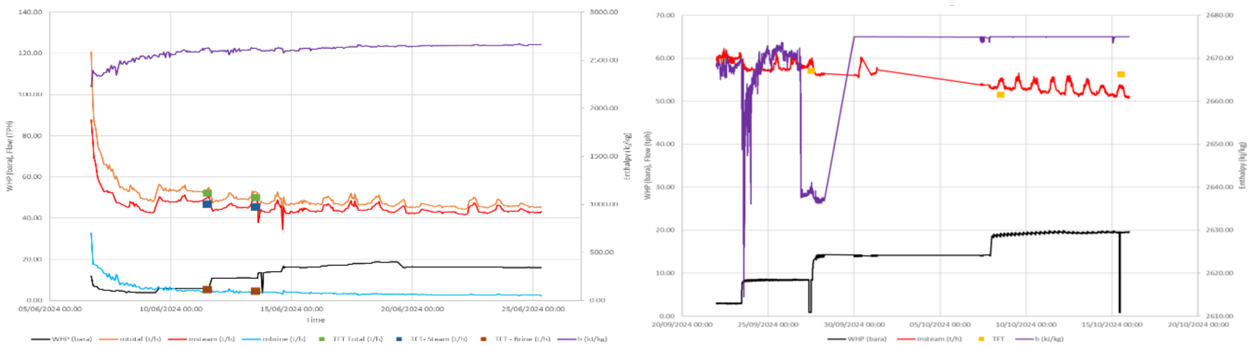
Figure 12. A photograph of lip pressure production testing at Ulubelu field using Geoflowtest device.

In all two test locations, pressure measurements taken by Geoflowtest were compared against those recorded by traditional mechanical and electronic pressure gauges. The data collected (Figure 13) by both systems showed close correlation, with an average discrepancy of less than 0.1% error in pressure, temperature, enthalpy, and mass flowrate readings. Despite the minor deviations, the flow data from Geoflowtest closely mirrored trends observed in traditional systems, demonstrating the device's capability to provide reliable real-time measurements of fluid flow in geothermal wells.

One of the key advantages of Geoflowtest is its ease of deployment. In each field test, the device was set up and calibrated in under 30 minutes, which is significantly faster than traditional systems, which typically require several hours for setup and calibration. The rapid deployment and minimal setup time allowed for efficient data collection during short-term tests and made Geoflowtest particularly valuable in temporary and exploratory testing scenarios.

Geoflowtest's mobile application and user interface were highly praised by field engineers for their simplicity and ease of use. Engineers could easily access real-time data on their mobile devices or tablets, view graphical representations of key parameters, and adjust sensor settings as needed. The mobile app provided clear, intuitive visualizations of pressure, temperature, flow rate, and enthalpy data, with minimal training required for new users. Engineers were alerted in real time to any out-of-range measurements, allowing for quick troubleshooting and intervention.

Throughout the field testing, Geoflowtest demonstrated high performance and robust functionality under geothermal well conditions, including high temperatures, multiphase fluid production, and varying pressure conditions. The device operated smoothly during the testing period, providing stable data even when fluid flow and pressure fluctuated. Despite the high temperatures and steam production, Geoflowtest maintained accuracy and resolution, as evidenced by the low deviation in the results compared to the tracer flow test (TFT) method, which was below 5%, as observed in the tests conducted at wells TLG-A and TLG-B (Karaha field), while also minimizing environmental impact. TFT allows for calculating the total enthalpy and two-phase flow rate from a well by injecting chemical tracers into the two-phase pipeline at known concentrations.



(a) (b)

Figure 13. comparison between real time data collection using Geoflowtest and tracer flow test data (TFT) at wells TLG-A (a) and TLG-B (b).

5. DISCUSSION AND APPLICATIONS

The field tests of Geoflowtest outlined in the Section 4 have demonstrated the system's robustness and accuracy in real-world geothermal well testing scenarios. The results confirm that Geoflowtest provides reliable, real-time data, while offering several advantages over traditional monitoring methods in terms of portability, ease of use, and deployment time.

The accuracy of the measurements recorded by Geoflowtest was found to be highly comparable to traditional monitoring systems. Pressure, temperature, flow rate, and enthalpy data were consistent with those obtained from established systems, with only minor deviations that fall within acceptable limits.

One of the most compelling advantages of Geoflowtest lies in its speed and ease of deployment. Traditional systems typically require hours or even days for installation and calibration, whereas Geoflowtest can be up and running in less than 30 minutes, as evidenced in the field trials. This rapid setup time significantly reduces the operational downtime during well testing, allowing for more efficient testing and quicker analysis.

Furthermore, the mobile interface and intuitive user design of Geoflowtest make it highly accessible to engineers with varying levels of technical expertise as shown in web-based dashboard in Figure 14. This ease of use is particularly important in geothermal fields where personnel turnover can be high, and quick adaptation to new technologies is often required. The ability to monitor data in real-time was a central advantage of Geoflowtest during field tests. Traditional systems often require periodic data downloads or manual checks to assess well performance, leading to delays in identifying potential issues. In contrast, Geoflowtest's real-time data transmission and cloud integration allow engineers to respond promptly to unexpected changes in well conditions, such as sudden pressure drops or temperature spikes. The immediate access to data also facilitates more proactive decision-making. For example, engineers can immediately identify if a well is deviating from expected performance metrics and take corrective action, such as adjusting flow rates or initiating a stimulation process (Mubarok & Zarrouk, 2017). This is particularly critical in geothermal wells where rapid changes in reservoir conditions can significantly impact production efficiency (DiPippo, 2007).

The high portability and rapid deployment of Geoflowtest make it ideal for use in both short-term and long-term geothermal well testing projects. Whether in exploratory drilling phases, during well optimization, or in production monitoring, the ability to quickly mobilize and deploy the system reduces the overall cost and time spent on well testing operations (Mubarok et al., 2015). This is especially beneficial for geothermal developers working in remote locations or regions with limited infrastructure, where traditional systems may be impractical due to logistical challenges.

The ability to quickly deploy Geoflowtest in the field can lead to significant cost savings for geothermal companies. With traditional well testing systems, the need for extensive equipment setup, calibration, and periodic data collection can lead to long downtimes and increased labor costs (Mubarok et al., 2019). Geoflowtest's ease of use and short setup time reduce the need for specialized personnel and equipment, lowering both capital and operational expenditures. Additionally, by enabling real-time data transmission and cloud-based storage, Geoflowtest minimizes the need for physical visits to the site to retrieve data, further reducing operational costs and increasing field efficiency. This is especially valuable in remote locations, where personnel travel and logistical coordination can be expensive and time-consuming.

Real-time access to accurate data allows for better-informed decision-making (Robinson & Chang, 2022). Engineers and reservoir managers can adjust operations on the fly based on the immediate analysis of pressure, flow, and temperature data. Furthermore, with the integrated gas composition sensors, Geoflowtest provides a more holistic understanding of well behavior, enabling more effective reservoir management strategies. Future development of Geoflowtest could focus on enhancing sensor accuracy in multiphase flow conditions, improving the robustness of the device for deep geothermal wells, and expanding the software's data analysis capabilities to integrate advanced predictive analytics.

The results from field testing confirm that Geoflowtest is a highly effective tool for real-time monitoring of geothermal well conditions. Its portability, ease of use, and accuracy provide significant advantages over traditional monitoring systems, improving operational efficiency, reducing costs, and enhancing decision-making in geothermal well testing and management. The potential applications of Geoflowtest extend across exploration, development, and production, making it a versatile solution for the geothermal industry. As geothermal energy continues to grow as a sustainable power source, technologies like Geoflowtest will play an essential role in optimizing the use and management of geothermal resources, ensuring long-term efficiency and sustainability.

Timestamp: Sun, 15 Sep 2024, 18:11:12.209
Interval: 00:00:04:388

Pressure WHP - SEN: 2.65 barg
Pressure Lip - SEN: 0.45 barg
Temperature - SEN: 75.14 celcius
Water Level - SEN: 5.52 cm
Enthalpy - LIP: 2500.05 kJ/kg
Total Mass Flow - LIP: 46.26 t/h
Steam Mass Flow (t/h) - LIP: 41.26 t/h
Brine Mass Flow (t/h) - LIP: 5 t/h

Figure 14. Real-time data and visualization of Geoflowtest web-based dashboard during well production testing TLG-B.

6. CONCLUSION AND FUTURE WORK

The Geoflowtest device has demonstrated its potential as an innovative solution for real-time monitoring of geothermal production well testing. Through a series of field tests conducted under diverse operational conditions, Geoflowtest has proven to be a reliable, portable, and accurate system for capturing essential well parameters such as pressure, temperature, flow rate, and enthalpy. These findings highlight its superiority over traditional monitoring systems in several critical areas – Portability and deployment speed; real-time data monitoring; accuracy and reliability; cost and efficiency benefits; versatility in applications; development of a portable monitoring solution; evaluation of geothermal monitoring capabilities; practical insights into data collection and analysis; and Improvement of operational efficiency.

While Geoflowtest has proven its effectiveness in initial field tests, several avenues for future development and research can further enhance its capabilities and extend its application. The following are key directions for future work: expansion of sensor capabilities, advanced data analytics (machine learning integration), increased durability for extreme conditions, and broadening geothermal applications. With further advancements in sensor technology, data analytics, and system durability, Geoflowtest can play a critical role in the efficient and sustainable management of geothermal resources. As the geothermal energy sector continues to expand, technologies like Geoflowtest will be vital in helping to maximize the potential of this renewable energy source, ensuring both economic viability and environmental sustainability for future generations.

7. ACKNOWLEDGEMENT

We like to acknowledge the support of PT Pertamina Geothermal Energy Tbk (PGE), particularly Operation & Engineering and Reservoir team, whose collaboration, ideas, and technical assistance were crucial to the design, development, and testing of the Geoflowtest device. The discussions and teamwork have been both enriching and inspiring. We also would like to express our appreciation to PT Sigma Cipta Utama (SCU) team who were instrumental in conducting the design and troubleshooting the Geoflowtest device. Their dedication and problem-solving skills were vital to the successful deployment of the system. Thank you to everyone who contributed in any way to this project. Without the support, this work would not have been possible.

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