Geothermics 74 (2018) 190–196

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

# Downhole fiber optic temperature-pressure innovative measuring system used in Sanshing geothermal test site

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ARTICLE INFO

*Keywords:*
Geothermal
Optic fiber
FBG sensor
Pressure
Temperature

ABSTRACT

Once a geothermal site has been selected for exploration, a full understanding of the formation temperature distribution on the surface and in the underground reservoir is always needed to assess the geothermal capability and productivity. Commercially available electronic measuring instruments cannot overcome the highest downhole temperatures obtained in the world's deepest and hottest geothermal reservoirs. In this study, fiber optic Bragg grating (FBG) measurement technology is utilized applied in an attempt to replace more expensive electronic sensors and to obtain more accurate downhole pressure and temperature data. This has been our target since 2013. For this purpose, a portable pressure and temperature (P/T) optic fiber wire-line instrument prototype was developed, and it can measure up to 1500 m in depth. The prototype was named SINOTECH-OPTIC-P/T in 2015. It has been tested in various well types, including a hot spring well and a pioneering geothermal exploration well (JY-01). The primary results have proved to be satisfactory. This paper summarizes the temperature and pressure measurement results obtained in JY-01 well at Sanshing geothermal site in I-lan County, Taiwan. The maximum measured well depth was 1200 m, and data measured includes a downhole temperature profile with the maximum temperature of around 75 °C.

## 1. Introduction

In Taiwan, the central government set up renewable energy development initiatives and road maps complementing its National Energy Program (NEP) upon the early launching in 2009. Since then, geothermal energy has been regarded as one of the key energy options, and relevant researches and planning were highly encouraged (Teng et al., 2013). In both conventional and enhanced geothermal resource planning, once a geothermal test site is elected, fully understanding the formation temperature distribution from the site's surface area down to the underground reservoir in order to economically assess the geothermal capability and productivity is very crucial (Long, 2008). Principal resource risks for geothermal energy are temperature (or enthalpy) and depth of the resource, as well as output and sustainability of flow from producing wells (Avato et al., 2013). The temperature data thus obtained is among the most important design criteria if the geothermal power generation plant is confirmed to be feasible. It has been noted that electronic measuring instruments traditionally have high initial cost when applied downhole in deep and hot reservoir. Hence in this study, a cost-effective measurement technology based on fiber optic approach was developed. One effort was replacing the electronic method by optic method, and the other was obtaining relevant downhole pressure-temperature data from certain investigation wells. All these efforts had been set up as a research target since 2013 in line with the First Phase National Energy Developing Program (NEP-1), under the supervision of the Department of Geology at National Taiwan University (NTU).

Under the request of NTU, the research team in this study is organized and responsible for conducting a preliminary study regarding downhole temperature and pressure measurement options on the global geothermal developing market during the funding period of NEP. However, most of the commercial downhole tools were expensive and due to research budget limit, the research team decided to develop a new optic fiber based system which is capable of measuring all the geothermal research wells in a cost effective way. The side benefit of doing so can also assist the local optic fiber industry to have a chance at joining the program so as to give their contribution and gain a potential opportunity in the geothermal application market.

*Abbreviations:* NEP, National Energy Program; NTU, National Taiwan University; DTS, distributed optical fiber temperature sensing; FBG, fiber Bragg grating; PBTD, plug back total depth

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https://doi.org/10.1016/j.geothermics.2018.03.005
Received 17 July 2017; Received in revised form 2 March 2018; Accepted 9 March 2018
0375-6505/ 

## 2. Optic fiber components

Raman-spectra distributed temperature sensing had been reported before the 1990s (i.e., Dakin et al., 1985; Kurashima et al., 1990). Via on-site downhole experiments, Hurtig et al. (1994) indicated that the fiber-optic temperature-sensing technology can be a promising way to characterize the hydraulic properties of fractured rock mass. Today, optic fiber sensing is well known to possess both the excellent functions of transmission and perception and relevant applicable sensors were thereby widely developed and used in general oil and gas as well as other energy related industries (Sakaguchi and Matsushima, 2000; Brown and Hartog, 2002; Nath et al., 2006; Brown, 2009) for years. For geothermal reservoir characterization and exploitation, Wisian et al. (1998) conducted a field comparison between conventional temperature logging systems and distributed optical fiber temperature sensing (DTS) system. The DTS used can reach a depth of 2 km with temperatures upto 200 °C. Absolute temperature differences up to 0.4 °C were noted between the tools. Ásmundsson et al. (2014) also summarized the high temperature instruments and methods developed in recent years through the HiTI project. The development of several downhole instruments allows DTS to function up to 300 °C and 400 °C. However, the performance of optical fibers for DTS in a hot geothermal well can be affected by thermal, mechanical, and chemical factors, such as those described by Reinsch et al. (2013).

Temperature-sensing using the optic fiber sensors for downhole application can be subdivided into two categories, including: (1) distributed temperature sensing (DTS) for a full-length survey and (2) fiber Bragg grating (FBG) sensor for a fixed-point survey. FBG is a type of optical fibers whose spectral response is affected by strain and temperature (Alemohammad, 2010). It had recently become one of the most commonly used and broadly deployed optical sensors, which reflect a particular wavelength of light that shifts in response to variations in temperature and/or strain (Mihailov, 2012). For downhole pressure-temperature sensing, FBG is readily available from service companies and has already been in use, e.g. in the oil and gas industry, for at least 10 years now. Nevertheless, the use of fiber-optic sensors for wireline measurements in particular is, in contrast, not common at all, particularly in the field of geothermal application.

In general, our FBG is a less expensive system than DTS by a local cost estimation study. Although DTS may be a better solution for downhole temperature sensing, due to equipment cost and flexibility for current exploration need in the Sanshing geothermal field, the wireline FBG type optic fiber system was tailored and used as major T-P sensors in the current study. Considering a local downhole application restriction, the FBG sensors have to be designed to line up with 1570 m long polyimide coating (cladded) optic fiber system, armored by stainless pipe (SUS304) with an outside diameter of 2.5 mm, and a thickness of 0.2 mm. The system then can be fully integrated into a wireline cable winch system. A 5-component (wave length @1530-1556 nm) FBG type temperature sensor group (T1–T5) is housed in at the down side of the cable at around the 9 m interval. The configuration diagram of the sensor arrangement is shown in Fig. 1. In addition, an auxiliary optical T-P coupling gauge cylinder, namely P&T(P), was integrated in the tail of FBG sensor group as a supplemental part for measuring downhole pressure. Inside the P&T(P) device, the pressure sensor P is consisted of a Bourdon tube and a connecting FBG pressure sensor (type os-3110) and a FBG temperature sensor (type FS-100). The temperature sensor T(P) is an in-device sensor which aims to compensate for the temperature of the co-existing FBG pressure sensor. The temperature shown by T(P) can also be used for double checking the temperature measured from FBG sensors (T1–T5) as depicted in Fig. 1. According to the information provided by supplier, the designed ambient temperature tolerance of the sensor system is 300 °C in theory.

Immediately after completing the construction of FBG sensors, laboratory calibration and field operations have been conducted to verify its reliability and validity in any available well condition (Chou et al., 2014; Yu and Lei, 2015). The early version system (2013–2014) can run through completed hot spring well (typically 1500 m deep artesian well, with temperature < 70 °C, thermal gradient 5.2 °C/100 m) without any major problem. However, during the construction of JY-01 well (1500 m deep) which uses drilling mud circulation system, the mud buoyancy hindered the downward wireline of T-P coupling FBG system. Hence the downhole operation became problematic. After repeated efforts, a heavy cone type steel connector at front of the system was modified, which finally resolved the problem. Fig. 2 shows the detailed T-P coupling gauge or P&T(P) (see Fig. 1) system with its improved downhole centralizers as a vital accessory.

## 3. Laboratory calibration testing

All the 5 FBG temperature sensor (T1–T5) components had been individually tested and calibrated in the laboratory (QC testing). This QC testing is aimed at a reliability check on sensor wavelength (nm) precision via linear resolution check. Table 1 shows the results of temperature linearity testing of all FBG temperature sensors (T1–T5) conducted in the laboratory at temperatures ranged from 0 to 300 °C. Consequently, by the calibrated temperature linearity, the target temperature Y (°C) can be calculated from wavelength change X (nm) as shown in Table 1.

In a temperature rising test, it had been noted that a rise of 40.6 °C, from 33.9 to 74.5 °C, took around 5 s to reach a 95% of balance temperature at 76.5 °C. On average, the calculated heating rate of all tested FBG sensors is about 8.12 °C per second. This also indicates that in a downhole temperature measurement operation using these FBG sensors, a 10 s buffer time might be necessary to catch the balancing temperature of specific measuring depth point. Considering that on-site condition, such heating rate will clearly depend on the temperature difference between sensor and surrounding medium, or rate of change. The temperature measuring accuracy of individual FBG is tested in the laboratory and can be picturized from the temperature factor of 0.0771–0.0819 (°C/pm). Moreover, as a research need, 0.1 °C of on-site temperature resolution might have been enough for this study.

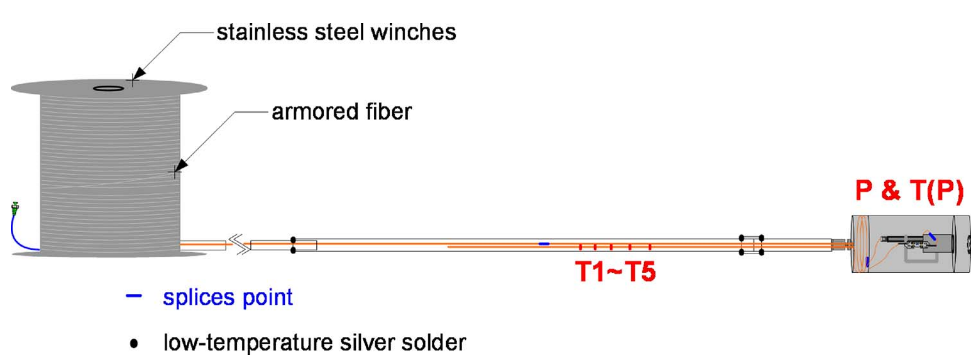
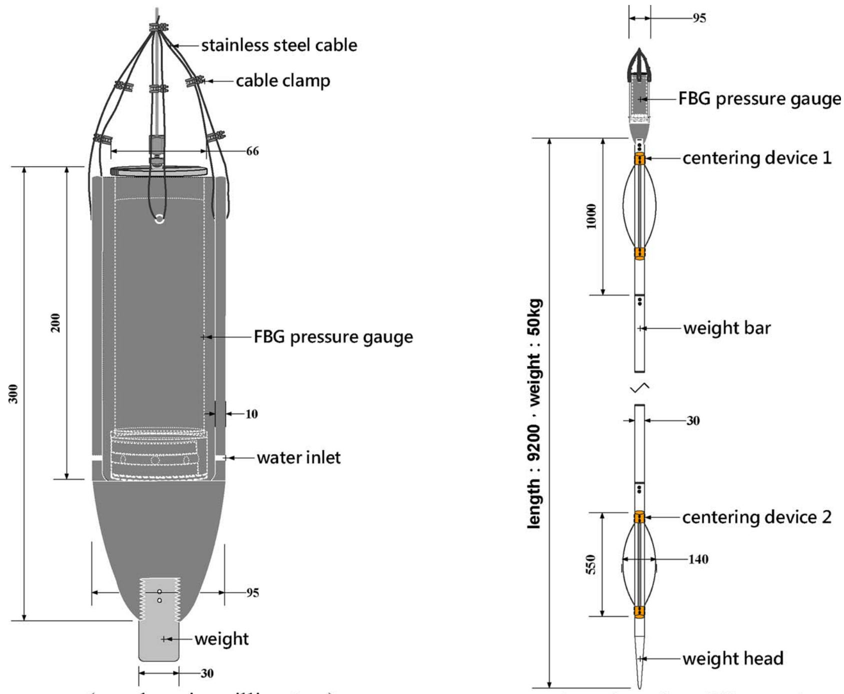



**Fig. 1.** Configuration of Downhole FBG Sensors.




(numbers in millimeters)
(a) Pressure measuring device

(numbers in millimeters)
(b) Downhole centralizer

**Fig. 2.** Improved Design of Downhole T-P Coupling Gauge Devices.

The linearity of invented prototype T-P coupling gauge device (the P&T(P) shown in Fig. 2), had been calibrated in Jan. 8, 2015 at the laboratory inside Sinotech Engineering Consultants, Inc. Fig. 3 shows the related facilities during the calibration test. An encapsulation shell of the P&T(P) gauge within the tri-axial chamber failed due to insufficient material strength, and local buckling damage was observed when the pressure increased to a confining pressure at 10 MPa. A replacing one-piece encapsulation shell was tailored and proven to be working properly which increased merely the skin thickness from 1.2 mm to 6.0 mm.

Subsequently, the modified P&T(P) gauge device was re-examined on Feb. 5, 2015. Test results of linearity calibration of P&T(P) gauge are outlined in Table 2. Results show that the gauge can withstand 18 MPa of water pressure, equivalent of 1800 m hydrostatic water pressure. Within the testing pressure range (4–18 MPa), good linearity of T-P sensor response can be observed in the temperate range of 25–70 °C in a thermostat container. The tests were performed at significantly lower temperatures than the required temperature of 300 °C given earlier. This is due to no existing high temperature test facility can be found locally at the moment. As a result, the maximum on-site operating temperature is limited for those with temperature higher than 70 °C with respect to this version of P&T(P) gauge.

## 4. Field verification testing

### 4.1. On site T-P measurement

Three types of on-site downhole temperature measurement can be made, including:

- Dynamic constant rate (5–10 m/min) data reading controlled by electric driven winch,
- Short-term (10 min) data reading on a fixed depth point (@10 m depth interval),
- Long-term data reading (1 Hz sampling rate) on a fixed depth point.

To check the field feasibility of the 1500 m long wireline optic fiber cable system developed and ensure the safety of all the FBG sensor group, field calibration testing together with certain shallow wells were carried out several times in the early stage of this study. Until a satisfactory condition were achieved, the JY-01 well located in Sanshing District of I-lan County (see Fig. 4) was used for reliability and corroborating testing of the developed system.

Two test sites can be seen in Fig. 4 including the calibration test site and JY-01 test well. The calibration test site was first used in October 2013 to do a primary system check in a shallow well with depth of 45 m. The vertical JY-01 test well is originally aimed at exploring the reginal D-fault adjacent to a major high temperature reservoir and a

**Table 1**
Temperature Linearity Test of FBG sensors.

| FBG Sensor No. | Design Wavelength (nm) | Temperature Factor (°C/nm) | Temperature Linearity $Y_i$: temperature @T °C $X_i$: wavelength change | $R^2$ | Wavelength @30 °C (nm) |
|---|---|---|---|---|---|
| T1 | 1530 | 95.5669 | $Y_1 = 95.5669*(X_1 - 1529.684)$ | 0.9998 | $Y_1 = 1529.998$ |
| T2 | 1536 | 94.1132 | $Y_2 = 94.1132*(X_2 - 1535.722)$ | 0.9997 | $Y_2 = 1536.041$ |
| T3 | 1548 | 93.3269 | $Y_3 = 93.3269*(X_3 - 1547.9)$ | 0.9998 | $Y_3 = 1548.221$ |
| T4 | 1560 | 92.4493 | $Y_4 = 92.4493*(X_4 - 1560.085)$ | 0.9996 | $Y_4 = 1560.410$ |
| T5 | 1566 | 92.1039 | $Y_5 = 92.1039*(X_5 - 1566.228)$ | 0.9997 | $Y_5 = 1566.554$ |


**Fig. 3.** Calibration Facility at the Laboratory.
① tri-axial high pressure chamber; ② thermostat container; ③ PID control heater; ④ optical sensing interrogator (MOI-sm125); ⑤ laptop computer with MOI-ENLIGHT software; ⑥ real-time monitor system; ⑦ pressure pump controller; ⑧ put P&T(P) coupling gauge into pressure chamber.

**Table 2**
Linearity Calibration of T-P Coupling Gauge.

| Testing Temperature (°C) | Confining Pressure (MPa) | | | |
|---|---|---|---|---|
| | 4 | 8 | 13 | 18 |
| | Measured Value (MPa) | | | |
| 25.0 | 3.933 | 7.903 | 12.960 | 17.834 |
| 40.0 | 4.020 | 8.001 | 12.985 | 17.942 |
| 55.5 | 4.045 | 8.029 | 13.018 | – |
| 53.5 | 4.053 | 8.036 | 13.027 | 17.986 |
| 70.5 | 3.980 | 7.974 | 12.998 | 17.966 |

major conduit of thermal resource area. The nature and exact location of D-fault are still unknown. This pioneering drilling started in 2013 and ended up with a total drilling depth of about 1500 m (below ground level; BGL) due to budget constraint and unsatisfactory temperature response. The well was constructed using the drilling mud circulation system and protected by relevant API casing system. At the end a speculated well bottom temperature of around 90 °C, far below expected temperature. The gravel-based overburden was found to cover from ground surface (also well head elevation) down to depth of 525 m. The major rock lithology encountered below the overburden is composed mainly of slate of Miocene Age (Lusan Slate Formation or its equivalence) and partly of argillite, meta-sandstone (Quartzite) of Paleogene. The thick and permeable overburden should have a significant impact of the hydrogeology in surrounding area.

In the JY-01 test well, the T/P measurements using developed FBG wireline instrument were conducted both during and after well construction. During well construction, the lowering of cabled FBG wireline system must overcome the heavy buoyancy against the cable system. After well completion, a slow water upwelling on-site in the wellhead can be observed every time the well is open for FBG wireline testing. Corroborating testing had been conducted and repeated several times to obtain the system reliability throughout 5th Feb. 2015 to 6th Aug. 2015. On-site operation conditions are shown, indicated, and described by numbered notes in Fig. 5. As a research deployment, part of the HSE (health, security, and environment) regulations was ignored.

### 4.2. Results of T-P measurement

The casing configuration of JY-01 well can be seen in Fig. 6(a). The conductor casing is around 400 m, followed by an 1100 m long, 7-inch diameter production casing. Since the connection portion of the two casings may have not been sealed, most of the shallow groundwater in the gravel deposits can flow into the well via casing annulus outside the casing ring into the well; thereby, downhole temperatures in the depth range of 0–400 m were measured at a constant range of about 30–34 °C, almost identical to that of ground surface. It has also been noted that above 400m, all temperatures measured did not significantly increase along increasing depth. In contrast, between the depth range

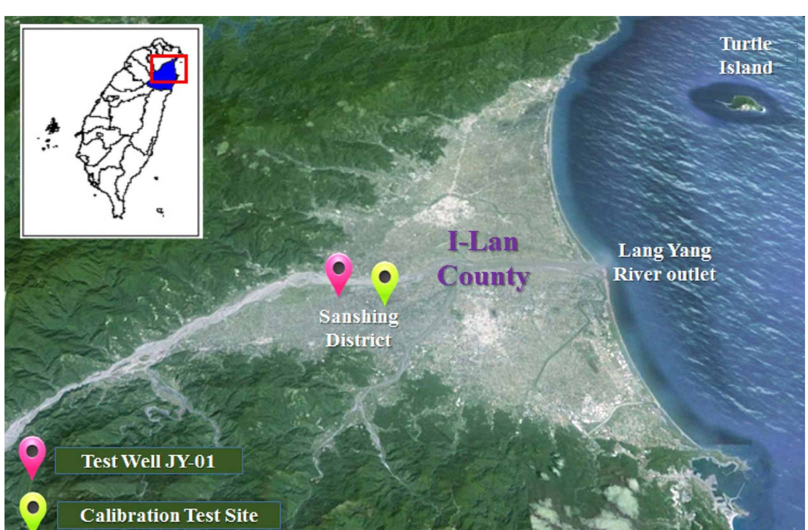



**Fig. 4.** Location of Jet-Yen Test Well (JY-01).


**Fig. 5.** Site Operations in JY-01 Test Well.
① JY-01's well head; ② Installation of centering device; ③ Connecting the T-P coupling gauge; ④ On-site temperature calibration.

405–905 m, the temperature profile significantly increased with increased depth, equivalent to a temperature gradient of 6.1 °C/100 m. Within the 905–1205 m range, it reduced to 3.8 °C/100 m. Because optic fiber sensor was used in the system, the measured pressure values from pressure gauge need be further corrected for temperature compensation. The field measurement results of T1–T5 temperature profile with respect to the JY-01 well at two different dates (June 2015 and August 2015) are shown in Fig. 6. The measurement data were almost comparable, indicating that measuring results can be repeated without obvious bias.

In the measurements shown in Fig. 7, plug back total depth (PBTD) of the tested well was found to be around 1195 m. Hence, the downhole temperature measurement beyond the depth 1195 m became impossible. In the earlier run (April and June 2015), the downhole pressure was measured at approximately 11.65 MPa (at 1192 m deep), and the temperature of T-P coupling gauge T(P) at about 73.0 °C. During the

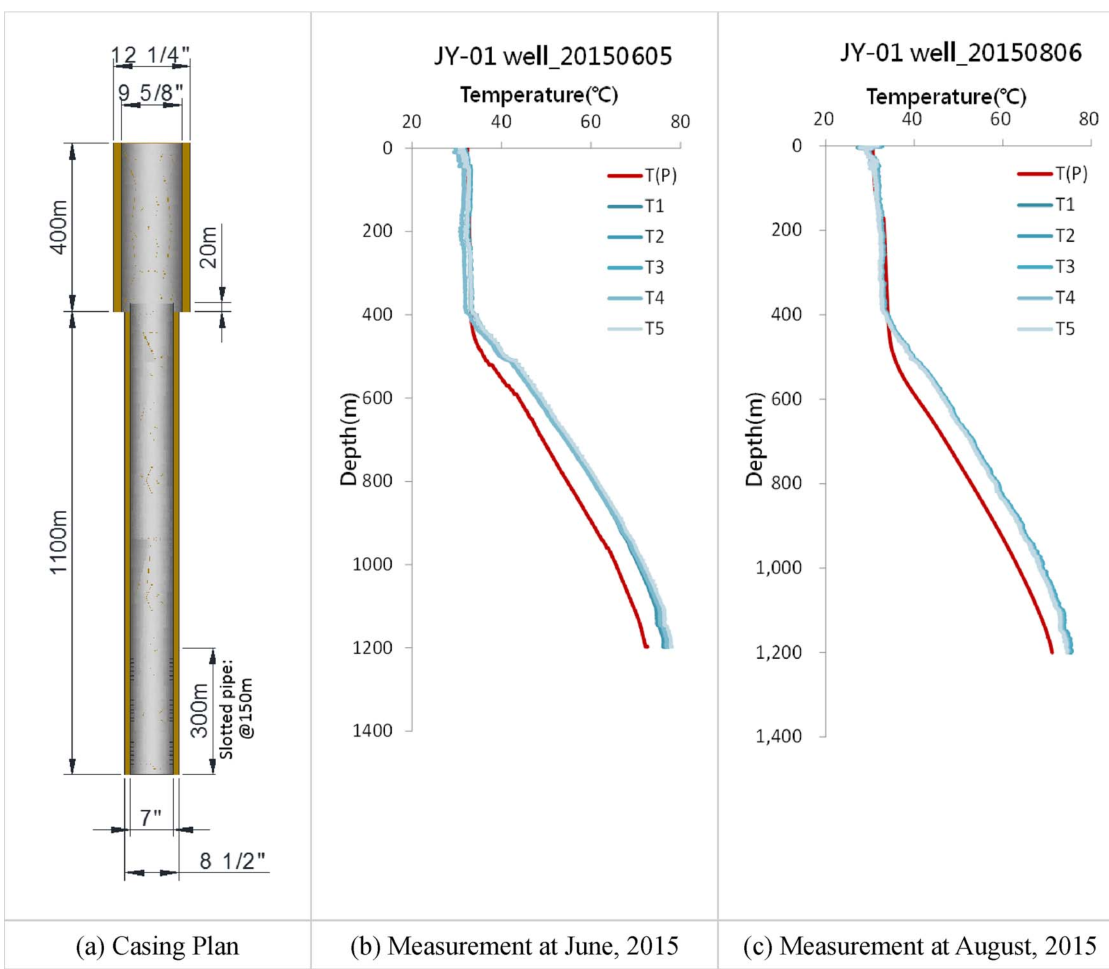



**Fig. 6.** Temperature Profile Measurement of JY-01 Well.

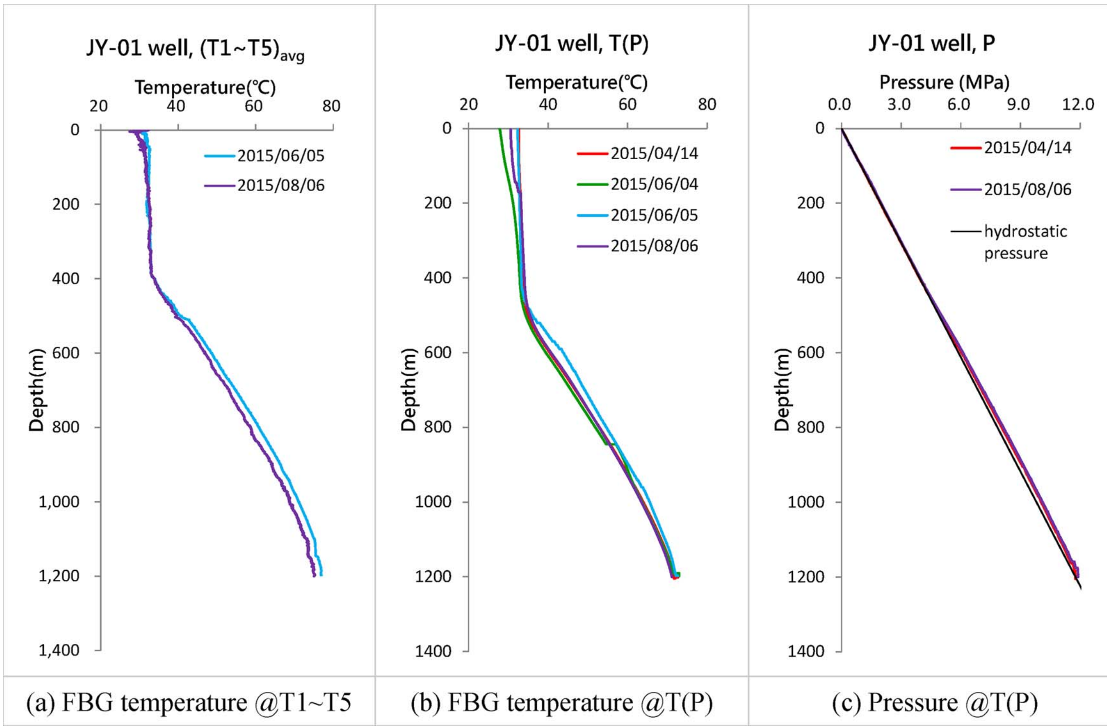



**Fig. 7.** Reliability Test Run for T-P Profile Measurement at JY-01 Well.

course of measurement, part of the FBG temperature sensors exhibited abnormal temperature responses which were found to be due to mechanical stress issue. This resulted in an unwanted overstress to the optic fiber. The problem was tackled by a re-arrangement of the cable connection layout of FBG array towards the adjacent P&T(P) sensor, which successfully kept the FBG sensors from redundant tension condition. After correction and on August 6th 2015, a conclusive run resumed which showed a downhole pressure at about 11.89 MPa (at 1192 m deep), with temperature at about 75.0 °C (T1–T5).

In Fig. 7, to show the reliability of the developed system, several runs of T-P measurements from April to August 2015 using prototype optic fiber tool are illustrated respectively in the plot. The results of temperature profile from the T(P) sensor unit (see Fig. 7b) reflecting a corroborating measurement can be obtained. In general, T(P) signal is less variable due to its isolation effect and less sensible to the ambient temperature change. Accordingly, temperature of T(P) is found to be consistently lower than those of T1-T5 as shown in Fig. 7a. In such circumstances, it should not be used as a field temperature indication. On the other hand, the temperature profiles shown by T1-T5 are closer to the actual well temperature.

## 5. Conclusions

A simple wireline downhole T/P measuring tool based on fiber optic FBG sensor was developed. In order to achieve enough flexibility required for early exploration in the Sanshing geothermal field and due to high potential cost of commercial equipment, the FBG application system was tailored to the site exploration research and used as major T/P sensors in this study.

The system developed covers a 5-component FBG (wave length @ 1530–1566 nm) type temperature sensor group combined with a T-P coupling gauge P&T(P). This combined sensor system is capable of fully conducting the downhole temperature and pressure measurement simultaneously in one trip of downhole operating.

The capability of the developed system is demonstrated by the results associated with the temperature and pressure measurements in the JY-01 well. Measured data played important roles in the site appraisal process of candidate geothermal sites. By now, a 1500 m depth-capable, retrievable T/P optic fiber wireline instrument had been developed and tested with general hot spring well and geothermal slim well by drilling mud circulation method. The primary results are proven to be satisfactory under limited conditions for temperatures under 75 °C and pressures under 11.89 MPa.

Due to temperature being lower than expected of JY-01 test well, we cannot test the downhole condition at higher temperature for now. However, following the continued development of geothermal exploration in the I-lan project site, deeper drilling and higher temperature cases can be expected in the near future. Therefore, the developed FBG type optic fiber system has to keep pace with these changes to become a useful tool in the downhole fiber-optic measurement.

## Acknowledgements

The authors would like to thank the National Energy Program (NEP Phase-1, and Phase-2) for funding the research. The research could not be successfully carried out without their continued and constant supports. Recognition is given to subcontractor 3L Technologies Inc. for their professional assistance on optic fiber parts and innovative retrievable downhole equipment.

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