Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Development of Groundwater Flowmeter: A Way to Estimate an Amount of Heat Collected by Geothermal Heat Pumps

Shigeo Kimura, Hiroshi Takeda, Masataka Nakamura, Takahiro Kiwata and Atsushi Okajima

Inst. of Nature and Environmental Technology, Kanazawa University, 2-40-20 Kodatsuno Kanazawa 920-8667, Japan

skimura@t.kanazawa-u.ac.jp

Keywords: Groudwater, Direct Use, Geothermal Heat Pump, Convection Heat transfer

ABSTRACT

The paper describes development of groundwater flowmeter, which measures both velocity and flowing direction with a single borehole. The information about groundwater velocity is important in order to estimate heat transfer rates from the flowing groundwater to heat exchangers buried in the ground. In fact it can be shown that the heat transfer rate is proportional to a square root of groundwater velocity. The developed probe makes use of steady state temperature patterns around a small cylindrical heat source, which makes the present technique unique comparing with other proposed or existing methods. Calibration tests prove that the probe can detect the horizontal water velocity as low as 0.001mm/s, and as high as 1mm/s. The field tests also show a good capability of the present measurement system for detecting groundwater velocity and flowing direction with a single borehole.

1. INTRODUCTION

Groundwater has a notable nature such as it has a constant temperature throughout a year, whose value is about the same as the average atmospheric temperature at the location. This means that the groundwater can be a good heat source when it is wintertime, where the temperature is usually well below 5 degrees in Celsius. On the other hand, the average temperature during summertime is above 28 degrees in Celsius in the most part of Japan, whereas the groundwater still has about the same temperature as it is in winter. Therefore, it can be used as a cold reservoir, into which the heat from air conditioners at buildings is disposed, e.g. Hyden(1985), Aldwel et al.(1985) and Ochifuji (2002).

In order to make use of groundwater as a hot or cold reservoir, there are several problems to be solved. Among others, and most importantly it is the information about flow direction and velocity of groundwater. Various types of ground heat exchanger, such as U-tube and coaxial double tube, e.g. Morita & Matsubayashi (1985), Morita & Tago (2000) and Fujii (2002), are used to collect and dispose heat in the saturated aquifer. But their ability and efficiency as heat exchanger really depends on thermo-physical properties of the aquifer at site and the flowing velocity of groundwater there, e.g. Kimura (1988) and Kimura et al. (1988). Particularly the latter imposes a significant influence on the heat transfer efficiency between the groundwater and the outer surface of heat exchanger, i.e. heat transfer coefficient, since the amount of heat transferred is proportional to a square root of the water velocity if the velocity is relatively large and the temperature difference between them is kept constant, as demonstrated by Kimura (1988).

There are several ways to measure the groundwater velocity and the flowing directions. One way to do that is to measure the slope of water table by observing the depths of water surfaces in several boreholes. Once one knows the slope, the flowing direction and its velocity may be estimated based on the Darcy's law. Another common way is to throw tracer, typically salty water, into one borehole and to measure the time for the tracer to arrive at one of the boreholes surrounding it, which is a more or less direct way to determine the velocity, e.g. Drost et al. (1968). But these classical methods necessarily require at least two observation wells, where the well-drilling is the most expensive and time-consuming element in the whole measurement works.

In order to reduce the cost and time required for the measurement of flowing velocity and direction, several methods by a single borehole have been proposed. They may be categorized into three different types. The first is to release a chemical tracer, typically distilled water or salty water within a particular position in the borehole, and to detect the concentration variation in space and time thereafter, e.g. Komatsuda et al. (1990). The second is to use naturally contained small particles in the water as the tracer without any seeding and optically traces the movement of those particles, e.g. Momii et al. (1993). The second one has an advantage over the first, because one can avoid any buoyancy effect generated by seeded water body of high concentrations. The third one is to use heat as the tracer, e.g. Hess & Paillet (1990). Since heat diffuses much faster than chemical spices do, it is suitable only for measuring relatively large velocities.

In this paper we describe about the newly developed groundwater velocimeter using a single borehole. Although the velocimeter uses a temperature field as an indicator of flowing velocity and direction, it is conceptually different from the conventional method, in which the heat released from the source in the borehole is used as a tracer of flow. The idea to use the heat as a tracer is not very appropriate, because the velocity is generally very small in the aquifer, and often the heat diffuses much faster than the water moves. Instead, the proposed method makes use of the steady state temperature field produced by mixed convection, and does not use the ever-changing thermally disturbed condition in time, i.e. a transient temperature field for tracing the water flows. This enables us to measure a wide range of velocities from less than 0.001mm/s to over 1mm/s. We report here that the basic idea of the proposed groundwater velocimeter, numerical validation of this idea, design and construction of flow meter, and its calibration procedure.

2. SINGLE-BOREHOLE FLOW METER AND NUMERICAL VALIDATION

2.1 A Proposed Method of Single-Borehole Flow Meter

A basic idea of single-borehole flow meter, which measures both velocity and direction of groundwater, is illustrated in Fig.1. We first assume that a heated cylinder of finite length is positioned vertically in a uniform porous medium with an infinite extent, and then consider about the steady state temperature field surrounding the cylinder. If there is no lateral flow (horizontal perpendicular to the cylinder), natural convection is dominant and the temperature field becomes axisymmetric. Therefore, the temperature detected at an arbitrary height and radial position should have the same value. However, if there is lateral flow, the temperatures at a fixed height and radial position in the upstream direction have smaller values than those at the same height and radial position in the down stream direction. This is due to mixed convection taking place around the cylinder. The rising water heated by the cylinder is washed away by incoming cold water in the region facing to the flow, and the thermal boundary layer there becomes thinner. On the other hand, the heated water carried to the region behind the cylinder creates a relatively large area of high temperature, which resembles to a long tail stretching from the cylinder. This convective process produces non axisymmetric temperature field. Furthermore, the deviation from the axisymmetric temperature distribution becomes greater when the velocity of lateral flow is large, and vice versa. This implies that the measurement of the temperatures around the cylinder can determine the strength of incoming lateral flow. At the same time, identifying the thinnest or thickest thermal boundary layer about the cylinder, it is possible to determine the direction of flow.

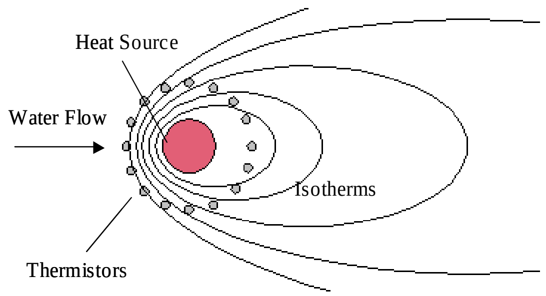

Figure 1. Temperature profile about a heated cylinder subject to lateral flow

2.2 Mathematical Formulation and Numerical Validation

In order to simulate mixed convection about the vertical heated cylinder, we assume that the flow in a fluid-saturated porous medium is governed by Darcy's law, and that the saturated fluid and the porous matrix are in a thermally-equilibrium state. Making use of the continuity equation of the saturated fluid enables us to derive a single equation on pressure field for the flow field. The nondimensional form of the pressure equation is given by

$$\nabla^2 p - \frac{\mathrm{Ra}}{\mathrm{Pe}} \frac{\partial T}{\partial z} = 0 \qquad (1)$$

The nondimensional energy equation is given by

$$\gamma \frac{\partial T}{\partial t} + \mathrm{Pe}\,\mathbf{v} \cdot \nabla T = \nabla^2 T \qquad (2)$$

The Ra, Pe and γ is the Rayleigh number, the Peclet number and the thermal capacity ratio of the saturated porous medium to the saturating fluid.

$$\mathrm{Ra} = \frac{g\beta K R (T_w - T_\infty)}{\alpha_m \nu}, \quad \mathrm{Pe} = \frac{V_\infty R}{\alpha_m} \qquad (3)$$

The boundary conditions are adiabatic and impermeable on the top and the bottom, and the uniform incoming flow with a constant temperature and potential flow conditions for the velocity and the pressure on the circumferential boundary. The cylinder surface is impermeable, and it has either a constant temperature or a uniform heat flux. The governing equations (1) and (2) are solved using finite differences. A number of grid points employed are $20 \times 20 \times 20$ in the respective coordinate directions. The non-uniform grid spacing is used, and fine grids are concentrated near the cylinder surface, where the steep temperature gradient is expected.

The code validation test was performed for forced convection, where the boundary layer solution for the heat transfer coefficient is available at high Peclet numbers. Figure 1 compares the present numerical results with the boundary layer solution for nondimensional heat transfer coefficient, the Nusselt number. As it is seen from the figure that the agreement is extremely good, particularly when the Peclet number is greater than one.

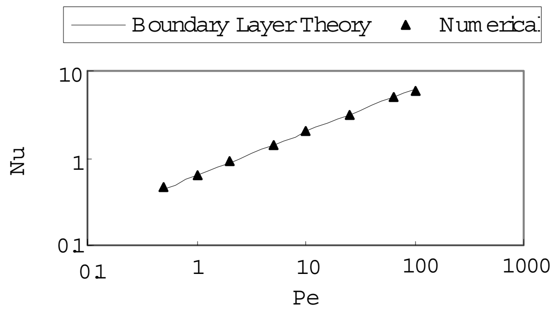

Figure 2. Comparison between numerical results and the boundary layer solution of the average Nusselt number for forced convection

Velocity fields are produced to various combinations of Peclet number and the Rayleigh number. The Peclet numbers are varied from 0.01 to 100. The Rayleigh number is varied from 0.1 to 2000. The ratios of the Rayleigh number to the Peclet number are in the range of 0.1 and 20. Since our primary objective is to find the deformation of the temperature field around the heated cylinder when the horizontal flow is specified. In Figure 2 we show the normalized temperature deviation relative to the mean temperature rise, as defined by equations.(4), (5) and (6), against the Peclet number reflecting the horizontal velocity strength.

$$T_{dev} = T_{rms} / \bar{T}, \qquad (4)$$

where

$$\bar{T} = \frac{1}{N} \sum_{i=1}^{N} T_i \qquad (5)$$

and

$$T_{rms} = \sqrt{\sum_{i=1}^{N} (T_i - \bar{T})^2 / N} \qquad (6)$$

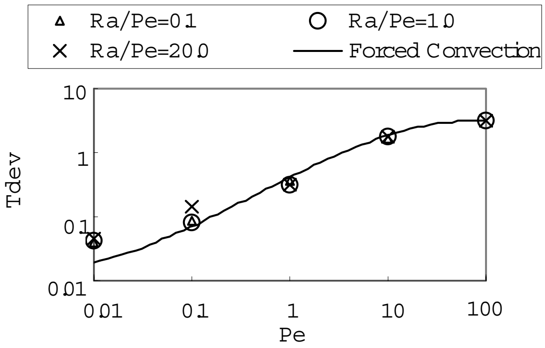

Figure 3. Temperature field deviations at the mid-height of the cylinder and *r*=2 as a function of Peclet number

3. DESIGN OF FLOWMETER

A picture of the flowmeter constructed is shown in Fig. 4. The length is 500mm and the diameter is 35mm. The flow detection takes place in a lower part of the probe, whose length is about 80mm, and covered by a permeable metal sheet with a large number of small holes. This part houses a cylindrical heater in the center, and 16 temperature sensors (thermistors) around it. The thermistors can detect the temperature changes as small as 0.01 degree in Celsius. The vacant space in the housing is filled with 0.4mm glass beads. A sketch of inner structure of this part is shown in Fig. 5. In case of measurement, the entire probe will be submerged below the water surface and held in the borehole, which is consist of a slotted casing pipe.

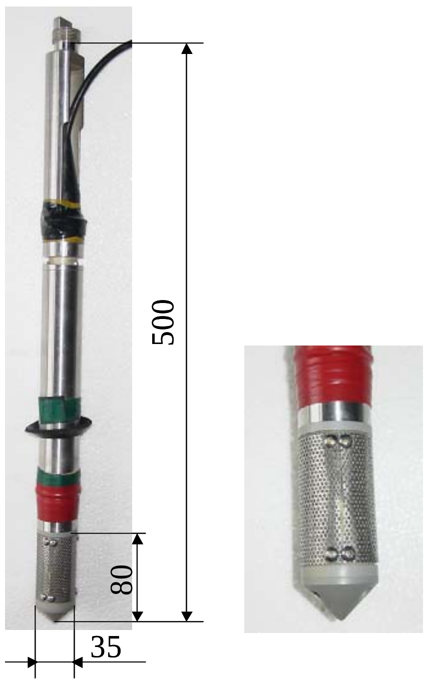

Figure 4. Photograph of flowmeter and enlarged picture of flow detecting part

In general, if the diameter of the flowmeter is larger, we can make it more sensitive to the lateral water flows. The more distance we take from the heat source, the more sensitive the temperatures to the incoming flow. Therefore, it will enable us to measure the slightest velocity of water. The lateral water flow mainly distorts the shape of thermal boundary layer around the cylinder, i.e. the outer edge of thermally affected region. However, we found that it is a frequent demand to use boreholes with the inner diameter about 4cm in the field. Our probe diameter is determined in order to meet this specification from more or less practical point of view.

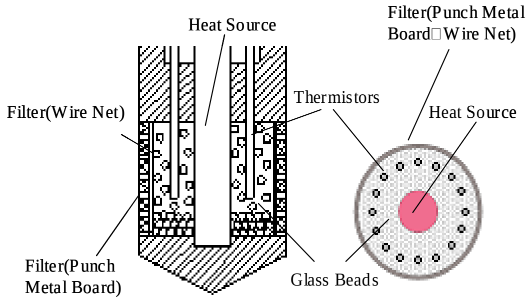

Figure 5. Inner structure of flow detecting part in the flowmeter

4. CALIBRATION WATER TANK

We constructed a calibration water tank to simulate groundwater flows. The tank is 2m long and has a 0.6m×0.6m cross sectional area. It has two water chambers at the respective ends, and the difference between their pressure heads drives a uniform flow in the sand-filled tank. The Darcy velocity in the tank can be varies from 0.0001mm/s to 1mm/s by carefully controlling the chamber pressures. The average size of the sand filling the tank has an equivalent diameter of 0.4mm. Water flow rate is measured by a magnetic flowmeter when the velocity is large, while the overflow volume of water in a specific time interval is used for the small velocities

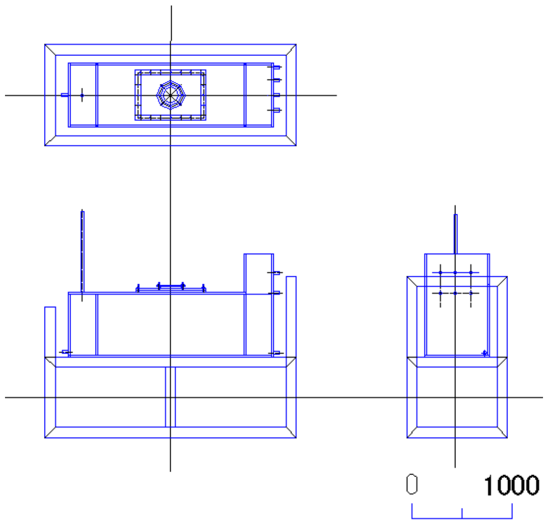

Figure 6. Calibration system

The entire water tank is mounted on the steel structure, as it is seen from Fig.6 and Fig.7. Under the sand-filled calibration tank, a water tank whose capacity is about 1 m^3 is placed. The circulating water is supplied from there to the upstream chamber of the calibration tank, via an electrically operating pump system. Two different pumps of different capacities are used depending on the needed flow rates.

Before we carry out any calibration, the whole calibration system was put in a thermally equilibrium condition. This can be done by leaving the system under operation in a air-conditioned room for at least one day.

Figure 7. Photograph of calibration system

5. CALIBRATION RESULTS

5.1 Calibration Curve for Directly Stuck in the Sand

First, we calibrate the flowmeter probe when it is stuck directly in the water-saturated sand. The constant and uniform horizontal flow is realized in the calibration tank by imposing the differential pressure across the sand layer. The measured Darcy velocity is found in the range of 10^{-5} cm/s and 10^{-1} cm/s. A steady state of temperature field is reached within 15 to 20 minutes. Large velocities require less time before it becomes a steady state. This is due to the fact that fast flow disperses heat much more quickly than the slow flow does.

Fig.8 shows the temperature deviation calculated by equations (4), (5) and (6). When the Darcy velocity is within a range of 2×10^{-4} cm/s and 10^{-2} cm/s, a strong correlation with a positive slope is found, which can be well described by equation (7).

$$T_{dev} = 61.33U^{0.86} \quad (7)$$

Solving the above equation for the unknown velocity *U*, we find the formula to determine the horizontal velocity from the measured temperature field within the probe.

$$U = \left(\frac{T_{dev}}{61.33}\right)^{1.16} \quad (8)$$

However, the correlation between the temperature deviation and the Darcy velocity becomes weaker, as the velocity exceeds $U = 10^{-2}$ cm/s .

In order to extend the capability of the present method, we examined the average temperature rise dictated by the sixteen thermistors around the heated cylinder at the steady state. The average temperature rises ΔT_m are plotted against the Darcy velocities. It is observed clearly that another strong correlation is present as the velocity exceeds $U = 10^{-2}$ cm/s . This occurs, because the thermal boundary layer (thermally affected region) formed around the cylinder becomes thinner for large lateral velocities. The correlation between the average temperature rise and the Darcy velocity is expressed by

$$\Delta T_m = 0.053\times U^{-0.84} \quad (9)$$

Solving the above equation for *U*, we similarly obtain the following expression.

$$U = \left(\frac{\Delta T_m}{0.053}\right)^{-1.19} \quad (10)$$

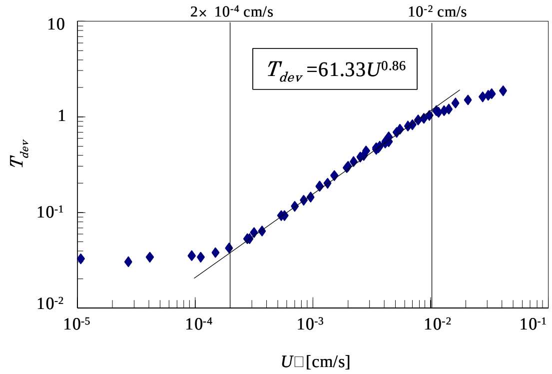

Figure 8. Temperature deviation as a function of velocity for directly stuck in the sand

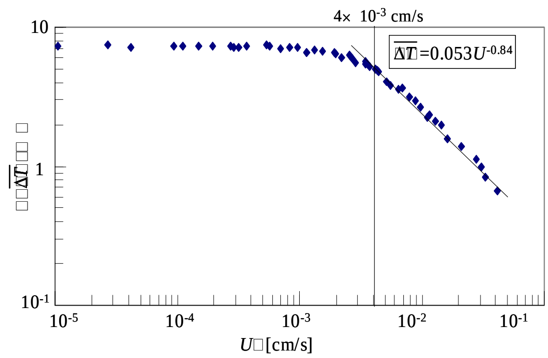

Figure 9. Average temperature rise as a function of velocity for directly stuck in the sand

5.2 Calibration Curve for Inserting in the Casing Pipe

In practice, the observation borehole is often enforced by permeable casing pipes, preventing from corruption of drilled bore. If there is an open space between the casing pipe and the positioned probe in the borehole, the groundwater flows mainly through this gap and does not go into the probe, which results in measuring smaller velocities. Therefore, it is essential to fill this space with some porous material. We choose glass wool for this purpose, since it is deformable and easy to fill the open space of arbitrary size. The casing pipe has inner diameter of 40mm. The obtained correlation curve is expressed by equation (11) and shown in Fig.10.

$$T_{dev} = 18.5U^{0.85} \quad (11)$$

An additional flow resistance caused by the casing pipe and the filling material is responsible for lowering the value of the temperature deviation. The casing pipe used for the present calibration has a 10% open area in the pipe wall with many horizontal slots. The pipe of different open area will result in a different correlation curve.

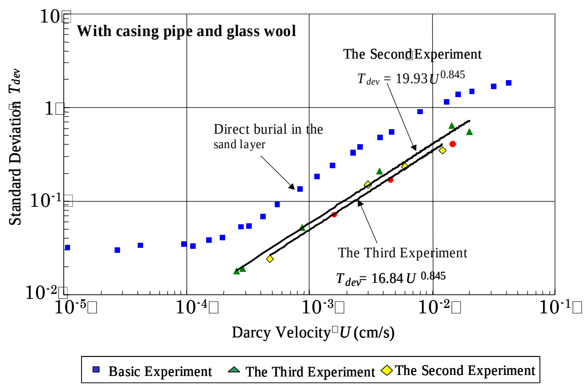

Figure 10. Temperature deviation as a function of velocity when the probe is held in the casing pipe

6. CONCLUTION

We reviewed some of the aspect of groundwater flowmeter using a single borehole in this paper. A new method to measure both flowing velocity and direction of groundwater using a single borehole has been proposed. The method utilizes a temperature field as an indicator, which is produced by mixed convection around a vertically positioned heated cylinder. A series of numerical calculations have been conducted in order to test the proposed idea. A strong correlation between the velocity and the temperature deviation is found for simplified boundary conditions. The deviation is caused by a temperature distortion due to the presence of lateral flow.

A flowmeter probe of 35mm in diameter has been built based on the proposed idea. We have been calibrated the probe using a sand-filled water tank over a velocity range of $U = 10^{-5}$ cm/s to $U = 10^{-1}$ cm/s. A strong correlation between the velocity and the temperature deviation is found in the velocity range 2×10^{-4}cm/s$\leq U \leq 10^{-1}$cm/s for this particular probe. In the course of calibration, a realistic condition to hold the probe in the borehole has been also simulated in the laboratory and proved its applicability in the field.

NOMENCLATURE

$g[m/s^2]$	gravitational acceleration
$K[m^2]$	permeability of porous medium
P [-]	dimensionless pressure
r [-]	radial coordinate; $r*/R$
R [m]	cylinder radius
T [K]	temperature
t [-]	dimensionless time
U[m/s]	Darcy velocity in horizontal direction
V [-]	dimensionless velocity
V [m/s]	uniform velocity at far field
z[-]	vertical coordinate; $z*/R$
α [m^2/s]	thermal diffusivity
β [K^{-1}]	thermal expansion coefficient
γ [-]	thermal capacity ratio of saturated porous medium to the saturating fluid; $(\rho C)_m/(\rho C)_f$
ν [m^2/s]	kinematic viscosity

Subscripts and Superscripts

w	heated cylinder wall
∞	far field condition
*	dimensional quantity

REFERENCES

Aldwell, C.R.: Heat Extraction from Irish Groundwaters, Hydrogeology in the Service of Man, Memoires of the 18 Congress of IAH, (1985), 79-94.

Drost, W., Klotz, D., Koch, A.,Moser, H., Neumaier, F. and Rauert, W.: Point dilution Method of Investigating Groundwater Flow by Means of Radioisotopes, *Water resour. Res*., **4**, (1968), 125-148.

Fujii, H.: A Study on Optimization Metods in Designing Vertical Ground Heat Exchangers for Ground-Coupled Heat Pump Systems, *J. Geotherm. Res. Soc. Japan*, **24**, (2002), 29-46.

Hess, A.E. and Paillet, F.L.: Applications of the Thermal Pulse Flowmeter in the Hydraulic Characterization of Fractured Rocks, *Geophysical Applications for Geotechnical Investigations*, edited by F.L. Paillet and W.R. Saunders, American Society for Testing and Materials, Philadelphia, Pa, (1990), 99-112.

Hyden, H.: Seasonal Heat Storage in Shallow Aquifer, Hdrogeology in the Service of Man, Memoires of the 18 Congress of IAH, (1985), 35-49.

Kimura, S., Yoneya, M., Ikeshoji, T. and Shiraishi, M.: Heat Transfer to Ultralarge-Scale Heat Pipes Placed in a Geothermal Reservoir (2nd Report): Transverse Flow, *J. Geotherm. Res. Soc. Japan*, **10**, (1988), 51-68.

Kimura, S.: Forced Convection Heat Transfer about an Elliptic Cylinder in a Saturated Porous Medium, *Int. J. Heat Mass Transfer*, **31**, (1988), 197-199.

Komatsuda, S., Shibutani, O., Hirata, Y., Hirayama, M. and Goto, K.: Development of a Groundwater Flow Velocity and Direction Meter Using Distilled Water as a Tracer in a Single Borehole, *IOS*, **71**, (1990), 877.

Momii, K., Jinno, K. and Hirano, F.: Laboratory Studies on a New Laser Doppler Velocimeter System for Horizontal Groundwater Velocity Measurements in a Borehole, *Water Resour. Res*., **29**, (1993), 283-291.

Morita, K. and Matsubayashi, O.: A Study on the Geothermal Output Characteristics of a Downhole Coaxial Heat Exchanger-Study on the Downhole Coaxial Heat Exchanger (2nd Report)-, *J. Geotherm. Res. Soc. Japan*, **10**, (1988), 109-129.

Morita, K. and Tago, M.: Operational Characteristics of the Gaia Snow-Melting System in Ninohe, Iwate, Japan, Proc. WGC2000, (2000), 3511-3516.

Ochifuji, K.: Present Status and Problems of Underground Thermal Energy Use and Storage, *J. Geotherm. Res. Soc. Japan*, **24**, (2002), 315-327.