

Enhancement of Sub-soil Thermal Conductivity for Geothermal Heat Pump Systems with Rainwater Collection

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ABSTRACT: A shallow rainwater collection tank is proposed to improve the thermal efficiency and significantly enhance the economic viability of geothermal heat pumps (GTHP). This system aims to use convective heat transfer within underground tanks as well as instant replacement of stored heat in the event of rainfall. Through a sensitivity analysis using Computational Fluid Dynamics (CFD), the temperature distribution and rainwater stream within the tank were successfully visualised. These results highlighted some of the influential design parameters that will improve the efficiency of heat transfer in the underground structure. The experimental study described here proposes practical design strategies for enhancing sub-soil conditions in order to optimise heat transfer properties in the adjacent ground. The results demonstrated the effects of water content, dry density and compaction energy on the thermal conductivity of the soil. In addition, a comparative analysis was undertaken between two measuring methods of thermal conductivity; the heat flow meter (HFM) and the dual-probe heat-pulse (DHP) method. Economically priced underground structures and construction procedures are suggested.

Keywords: geothermal energy, rainwater collection, heat transfer, soil properties, dual-probe heat-pulse method

NOMENCLATURE

d	Diameter [m]	θ_v	Volumetric water content [m^3m^{-3}]
l	Length of tank [m]	ρ	Density [kgm^{-3}]
q'	Energy input per length of heater [Wm^{-1}]	ρc	Volumetric heat capacity [$\text{Jm}^{-3}\text{°C}^{-1}$]
r	Radial distance from heater [m]	-Ei(-x) Exponential integral	
t	Time [sec]	Subscribes	
t_0	Heat pulse duration [sec]	b	Soil bulk
T	Temperature [°C]	m	Average minerals
λ	Thermal conductivity [$\text{Jm}^{-1}\text{°C}^{-1}$]	w	Water
κ	Thermal diffusivity [m^2s^{-1}]		

1. INTRODUCTION

Geothermal heat pumps (GTHP) have been recognised as a renewable technology which has one of the fastest growing markets [1]. Since their use became common in North America, the uptake has spread significantly in North America and Europe. However, the attention is still much lower in some countries, such as the UK and Japan. The slow recognition in the UK [1] and reduced incentive caused by reasonable electricity prices in Japan [2] have led to there being limited uptake of this technology. Each country has unique barriers including high installation and running costs and the issue of an unstable heat supply. This paper intends to tackle these barriers by developing a novel technological design solution.

Enhancement of operational efficiency is essential to solve the problems. Some studies discovered that underground water improved the performance remarkably [3][4]. Subsequently, some studies attempted to utilise rainwater to gain similar advantages to those from the underground water. However, few design strategies of GTHPs with rainwater collection have been proposed [5][6]. Therefore, design guidelines with effective rainwater use are yet to be developed. In addition, the cost of construction must be taken into consideration.

2. MODELING FOR SENSITIVITY ANALYSIS

2.1 Calculation Model

Sensitivity analysis was conducted using FLUENT 6.1.18. software. The model consisted of a buried vertical column tank filled with rainwater, grout, surrounding soil, air and soil (Figure 1). Rainwater was assumed to be collected on a nearby building and entered the tank at the bottom through a pipe as illustrated in Figure 2. The

tank incorporated a heat exchanger, in which slinky coils were stacked to make units. The size of the slinky coil was 0.91 m in diameter consisting of 0.019 m of high density polyethylene pipe [7]. Therefore, geothermal energy was cross-sectionally transferred through the tank walls, the rainwater, the heat exchanger and the circulating fluid (e.g. water or brine). The energy is eventually sent to heat pumps as one of the heat sources. The model was built with an axisymmetric centre line, which was also the centre line of tank.

The simulation was run until the results

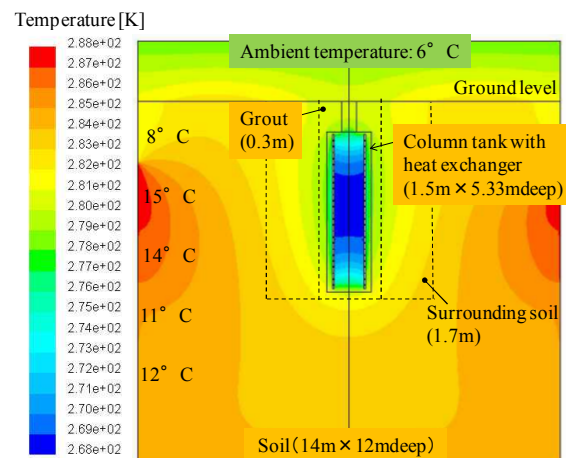


Figure 1: Temperature distribution in simulation series 3 (Conditions; Heat exchanger consists of a series of coils: No rainwater input: Output from heat is 0.4kW)

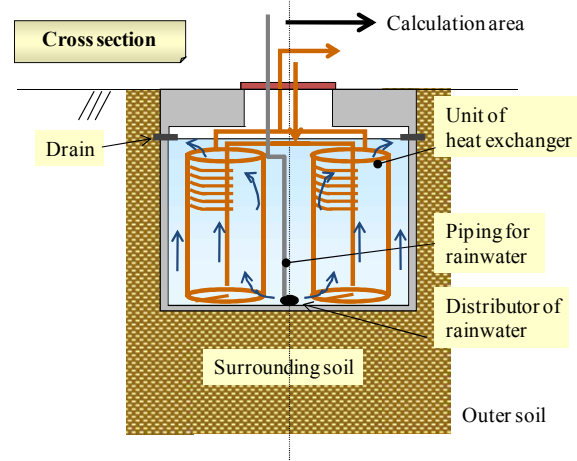


Figure 2: Model with four units of heat exchanger in a short tank converged at a steady state. Calculation models with one unit of heat exchanger

were simplified to two-dimensional areas with minimum calculation area. However, cases with four units of heat exchanger had to be set in three-dimensions as illustrated in Figure 2. The resulting distributions of temperature (Figure 1) and velocity for water within the tank were visualised.

2.2 Study Cases

By varying several of the design parameters, their effects on energy collection potential were compared. Thermal capacity was determined, when the surface temperature of the heat exchanger reached a limiting value. The limiting value of 3 °C and 0 °C (see Table 1) was to prevent soil freezing. Underground temperature gradation and flow rate of rainwater inflow were calculated from the average weather data for winter in Nottingham, UK. The data had been recorded at a weather station situated at the School of the Built Environment, The University of Nottingham. Conditions of the study cases are summarised in Table 1.

3. RESULTS OF SIMULATION

3.1 Effects of Tank Shape

Results for varying the ratio of tank diameter to length, d/l , are displayed in

For the same tank volume, a longer column tank improved the thermal output. Since the radius of the heat exchanger remained the same, the larger heat exchange area on both the heat exchanger and the tank surface was likely to create more heat transfer per a tank. Models with four units of heat exchanger had larger heat exchange area; however, it appeared that the tank surface area limited the amount of thermal energy collected.

It was also seen that longer tanks realised more equal rainwater distribution. The change of d/l led to different layouts of the inner components among the tank shape, as well as the heat exchanger and the rainwater

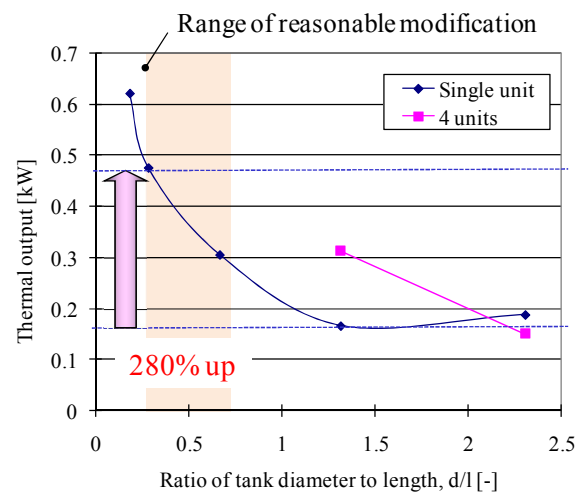


Figure 3: Effects of ratio of tank diameter to length, d/l

Table 1: Conditions of each simulation series

Series	Varied design parameter		Range	Rainwater inflow	Criterion to define capacity	Other conditions
1	Ratio of tank diameter to length, d/l	[-]	0.2 - 2.3	0.23 m ³ h ⁻¹ at 6°C	Minimum water temperature is 3°C	4 units in a box shape tank are also calculated for shallower tanks
2	Thermal conductivity of grout, k_{grout}	[Wm ⁻¹ K ⁻¹]	0.9 - 2.42	No	Minimum average temperature on heat exchanger is 0 °C	For l_{grout} 0.12 and 0.3 m respectively. $L_{grout} + l_{soil}$ is 2 m.
3	Thermal conductivity of surrounding soil, k_{soil}	[Wm ⁻¹ K ⁻¹]	1.7 - 4.34			
4	Thickness of surrounding soil, l_{soil}	[m]	0.7 - 2.5			
5	Thermal conductivity of tank material. k_{tank}	[Wm ⁻¹ K ⁻¹]	0.4 - 15			

*) k_{tank} is 0.47 Wm⁻¹K⁻¹

*) R_{dia} is 0.28 after series 2

*) k_{grout} is 1.66 Wm⁻¹K⁻¹ after series 3

*) l_{grout} is 0.12m and k_{soil} is 3.47Wm⁻¹K⁻¹ in series 4

Figure 3. This was the most influential design parameter in this sensitivity analysis.

distributor at the bottom. Furthermore, deeper underground soil stores geothermal

energy more stably through a year, so that a long tank was more advantageous. However, digging deep holes potentially increases installation costs. Hence, it is vital to select the most well balanced d/l between efficiency and economy.

3.2 Effects of Thermal Conductivity

The results of a sensitivity analysis with varying thermal conductivity are shown in Figure 4 and Figure 5. These indicated that modifying the thermal conductivity of the surrounding soil produced a marked improvement in heat collection performance.

3.3 Thickness of System Components

The final finding was the sensitivity of the result to the thickness of grout, l_{grout} . When the thermal conductivity of the surrounding soil, k_{soil} , is larger than that of the grout, k_{grout} , reducing the thickness, l_{grout} , reduced the thermal resistance and increased thermal output from the heat exchanger as illustrated in Figure 4.

4. METHODOLOGY OF EXPERIMENTS

4.1 Purposes of Experiments

The numerical study identified the essential design parameters for modifying the performance of the underground structure. Though the findings suggested increasing the thermal conductivity of the surrounding soil, to discover the method is another critical objective. Hence, a series of experiments were conducted in the laboratories in the School of the Built Environment, the University of Nottingham.

The thermal properties of soil were measured by the dual-probe heat-pulse method (DPHP). However, various methods to analyse the experimental data have been suggested and calibration is complex [8]. Therefore, the obtained thermal conductivity was compared to one measured by a conventional method, a B480 P.A. Hilton guarded heat flow meter (HFM).

4.2 Theory of the Dual-Probe Heat-Pulse Method

The DPHP was originally proposed by Campbell et al. in 1991 [9] and the use has been popular due to the affordable and convenient characteristics [10]. The small apparatus consisting of two probes can measure four thermal properties; thermal conductivity, thermal diffusivity, heat capacity and water content. The probes respectively enclose a thermocouple and a wire of 0.03 m in length, which functions as a heater. The heater is charged for a short time and the temperature change in certain

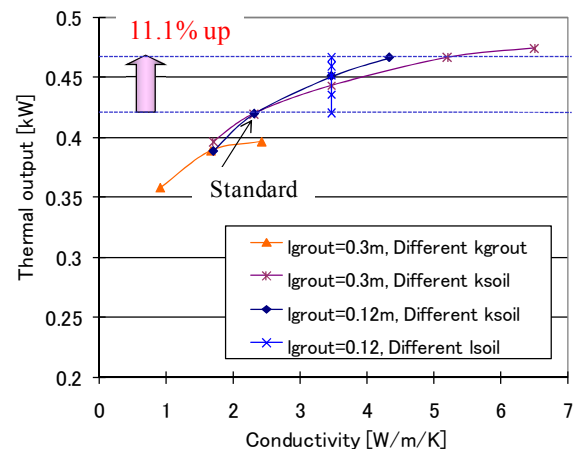


Figure 4: Sensitivity analysis with different thermal conductivity

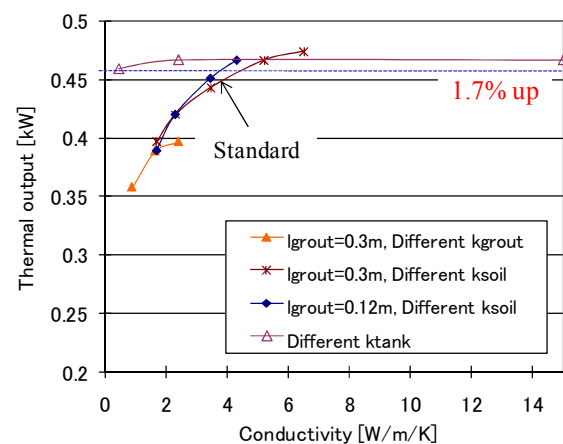


Figure 5: Effects of thermal conductivity of tank material

distance from the heater is recorded at the place where the thermocouple is placed.

The collected dynamic data is analysed to compute the thermal properties with equations, such as Eq. 1 to Eq. 3 [10].

$$\Delta T(r, t) = \frac{q'}{4\pi(\rho c)\kappa} \left[E_i \left(\frac{-r^2}{4\kappa(t-t_0)} \right) - E_i \left(\frac{-r^2}{4\kappa t} \right) \right]$$

$$t > t_0 \quad (\text{Eq. 1})$$

$$\kappa = \lambda / \rho c \quad (\text{Eq. 2})$$

$$\rho c = \rho_b c_m + (\rho c)_w \theta_v \quad (\text{Eq. 3})$$

Eq. 1 enables to predict a dynamic change of temperature at a certain distance from the heater. Eq. 3 is a simplified formula by neglecting the minor contributing elements in soil and introducing soil bulk density.

The DPHP differs from the HFM, in which thermal conductivity is calculated at a steady state from required energy consumption to maintain the input temperature of cold and hot plates. This difference is particularly influential when the samples contain moisture. In the HFM, redistribution of water is seen until the new moisture gradation reaches a stable state [11]. This redistribution does not occur with the DPHP.

4.3 Materials and Setup

Subsoil samples were collected from the Creative Energy Homes construction site at the School of the Built Environment in the University of Nottingham (52°94'N, 1.20°W). The soil had been excavated from a depth of between 1 and 3 m. It was collected from two different locations within the same site to examine the dependence of soil characteristics on sample location. The particle size distribution was determined by the dry sieving method [12]. It was found that the soil contained approximately 11% gravel, 80% sand and 9 % silt and clay. Here, categories were defined from the particle diameter.

Samples for the HFM were set in trays and covered with cling film to prevent

moisture from evaporating quickly. The effect on thermal conductivity of the cling film was compensated for based on results measured for dry soil with and without film. The tray had a square surface sized 0.28 m × 0.28 m. Two kinds of tray were prepared; 0.05 m and 0.015 m in thickness. An adequate thickness was selected to have more than three times the largest particle size of each sample. Hence, the largest particle diameters were limited to 14 mm and 2 mm for each tray.

The test rig for the DPHP was assembled with a set of specific heat sensors (Model Sh2, East 30 Sensors, Pullman, WA), a heater controller (Model HC1, East 30 Sensors, Pullman, WA), a datalogger (CR1000, Campbell Scientific Ltd., Loughborough, UK), a sample box and a data collection computer. The probes measured 30 mm long and 0.9 mm in diameter with a distance of 6 mm in between. Calibration was carried out using water thickened with agar to reduce convection. The adjustment was included in the data analysis. Samples were sieved to limit the largest particles to less than 2 mm for the sake of accuracy. The sensor was buried in the centre of the sample, which measured 0.165 m × 0.15 m × 0.15 m high. The wire heater was electrically charged for 8 seconds, and then the power input and the temperature at the thermocouple were recorded every second for 60 seconds. Thermal diffusivity and heat capacity derived to fit a curve predicted by Eq. 1 using the solver function in a Microsoft Excel spreadsheet. Subsequently, thermal conductivity was calculated from Eq. 2.

4.4 Study Cases

A series of experiments were implemented with various combinations of conditions as listed in Table 2. Common methods in soil mechanics were referred to as described in British standard BS 1377-2:1990 [12]. Compaction energy was

Table 2: Study cases of experiments

Series	Thermal properties to be measured	Measuring method	Largest diameter in sample [mm]	Moisture content range [m ³ m ⁻³]	Ramming Energy [Mgmm ⁻³]
1	Thermal conductivity	HFM	14	0.07 to 0.17	British Standard (52.1)
2		DPHP	2	0.09 to 0.17	
3				0.09 to 0.16	
4	Dry density *1)	-	14	0.11 to 0.13	4.5 to 52.1
5	Thermal conductivity	DPHP	2	0.10 to 0.21	4.5, 28.9 and 52.1

*1) Compaction machine and a standard 1,000 litre mould are used

delivered by dropping a rammer with known weight from a measured height onto the top of the soil samples. Several kinds of water content below Optimum Moisture Content (OMC) were selected to observe the tendency for each experiment series. Target water content for each sample was achieved by mixing tap water to oven-dried soil. The effects of the largest particle size in each sample, the water content and the compaction energy were investigated by measuring thermal conductivity and dry density.

5. RESULTS AND DISCUSSION

5.1 Measurement with the Heat Flow Meter

Thermal conductivity was plotted against degree of saturation, which is the ratio of volume of water to the volume of voids. The results showed that the soil sampled from the two different locations had almost the same thermal conductivity (Location 1 and Location 2 in Figure 6). The results demonstrated that samples with larger particles and higher degree of saturation had higher thermal conductivity. It was also seen that higher dry density tended to have higher thermal conductivity as displayed in Figure 7. Therefore, it could be understood that thermal conductivity was a function of these three parameters.

5.2 Measurement with the Dual-Probe Heat-Pulse Method

Results with the DPHP also showed that

both a higher degree of saturation and a higher dry density provided higher thermal conductivity as shown in Figure 7. However, these values were larger than those measured by the HFM. The trendlines indicated that the two measuring methods

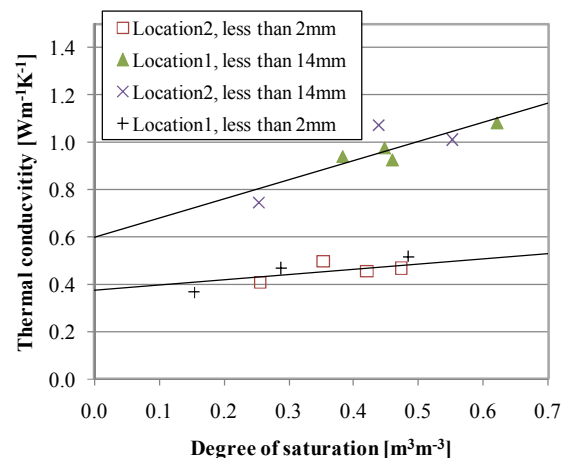


Figure 6: Measurement with the HFM

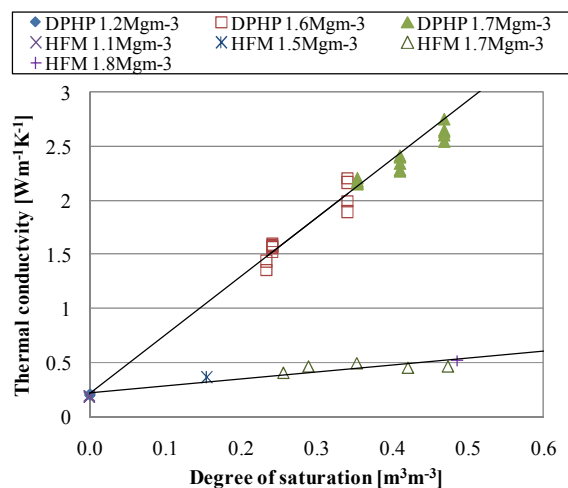


Figure 7: Comparison between the HFM and the DPHP (Data is plotted with different dry density [Mgm⁻³])

were likely to give similar results for dry samples. In fact, the two methods showed close values with difference of 1 % for dry samples. The HFM method caused moisture redistribution and the thermal conductivity was measured when the sample reached a thermally steady state. Hence, it could be said that the DPHP was more suited to estimate thermal properties before moisture redistribution occurred. For this paper, the data from the DPHP was selected to discuss further results.

Other characteristics of two measuring methods were compared. Though the DPHP was selected to be used, the methodology of data analysis needed to be assessed to meet demands, such as accuracy and ease of calculation. As a measurement tool, the DPHP was more reasonable in price and more mobile due to the lighter and smaller apparatus. In addition, the DPHP required only 60 seconds to collect enough data, while the HFM could take days to reach steady state, particularly for wet samples. Therefore, the DPHP was more convenient for multi sample assessment such as the experiments for this paper. During these experiments, soil particles had to be sieved to be smaller than 2 mm for accurate measurement. However, larger sensors could be developed for samples with larger particles.

5.3 Effects of Compaction Energy

Figure 8 shows the effects of compaction energy on dry density and thermal conductivity (series 4 and 5, Table 2). There was a clear tendency that larger compaction energy increased dry density, even if the original soil had low density with low degree of saturation such as natural soil. When thermal conductivity was compared For a degree of saturation of around 0.2, improvements were seen in the more compacted soil.

Study series 4 sought the highest dry density and thermal conductivity under the same compaction energy. The additional compaction tests were conducted to define

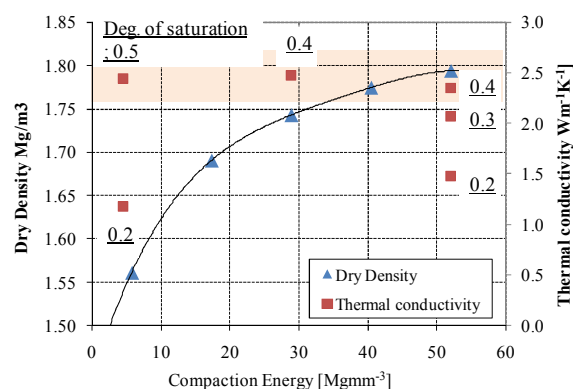


Figure 8: Effects of compaction energy and degree of saturation

the OMC for compaction energies of 4.5 Mgmm⁻³, 28.9 Mgmm⁻³ and 52.1 Mgmm⁻³. It was revealed that increasing the water content up to the OMC gave nearly the same thermal conductivity regardless of the difference in compaction energy. OMC increased as compaction energy became smaller. However, this suggested that ramming on construction sites was not; on its own, the only method to improve thermal conductivity. Ideally the soil water content should also be raised to its OMC and kept in that condition during the operation.

6. CONCLUSIONS

The effect of various design modifications on the thermal performance of geothermal heat pumps was investigated. Numerical analysis with FLUENT indicated the most important design parameters, including efficient use of rainwater circulation within buried tanks. The experiments clarified suitable conditions to measure the thermal properties of subsoil with the heat flow meter and the dual-probe heat-pulse method respectively. The results demonstrated that soil with larger particles, higher dry density and larger degree of saturation showed higher thermal conductivity. A series of compaction tests also disclosed that ramming on construction sites could be reduced by mixing water to achieve higher thermal conductivity when soil is buried back into the ground.

REFERENCES

- [1]Lund, J., Sanner, B., Rybach, L., Curtis, R. and Hellström, G. 2004. Geothermal (Ground-source) Heat Pumps A World Overview [online]. [Accessed 31st May 2008]. Available from: <<http://geoheat.oit.edu/bulletin/bull25-3/art1.pdf>> . USA.
- [2]Nagano, Katsunori. 2006. Development of Ground Source Heat Pump Systems in Japan [online]. [Accessed 15st April 2008]. Available from: <http://www.heatpumpcentre.org/Workshops/Workshop_Tokyo_May_2006/Sum_GSHP_Nagano.pdf> . Japan.
- [3]Gehlin, Singnild. 1998. Thermal Response Test – In-Situ Measurement of Thermal Properties in Hard Rock. Licentiate thesis, Lulea University of Technology. Sweden.
- [4]Lim, Kyoungbin, Lee, Sanghoon and Lee, Changhee. 2007. An experimental study on the thermal performance of ground heat exchanger. Experimental Thermal and Fluid Science. [no date]. Korea.
- [5]Sanken Setsubi Kogyo Co., Ltd. Radial well type geothermal energy collection system (translated from Japanese) [online]. [Accessed 12 Sept 2006]. 2005. Available from: <<http://skk.jp/archives/000078.html>> . Japan.
- [6]Gan, Guohui, Riffat, Saffa B. And Chong, C. S. A. 2007. A novel rainwater-ground source heat pump – Measurement and simulation. Applied thermal engineering. Vol. 27(2-3). pp 430-441. UK.
- [7]Smith, Marvin. 2006. Shallow Heat Exchanger Performance and Cost-Reduction Potential [online]. [Accessed 15th Aug 2007]. Available from: <http://www.igshpa.okstate.edu/conf/select ed/marvin_smith.pdf> . USA.
- [8]Welch, S. M., Kluitenberg, G. J. And Bristow, K. L. 1996. Rapid numerical estimation of soil thermal properties for a broad class of heat-pulse emitter geometries. Measurement Science and Technology. Vol. 7. pp 932-938. USA.
- [9]Campbell, G. S., Calissendorff, K. And Williams, J. H. 1991. Probe for measuring soil specific heat using a heat pulse method. Soil Science Society of America. Vol. 55. pp 291-293. USA.
- [10] Bristow, Keith L. 1998. Measurement of thermal properties and water content of unsaturated sandy soil using dual-probe heat-pulse probes. Agricultural and Forest Meteorology. Vol. 89. pp 75-84. Australia.
- [11] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. 1996. ISO 10051:1996(E). Thermal insulation – Moisture effects on heat transfer – Determination of thermal transmissivity of a moist material. Switzerland, ISO.
- [12] BRITISH STANDARD INSTITUTION. 1990. BS 1377-2:1990. Methods of test for Soils for civil engineering purposes Part 2; Classification tests. London, BSi.