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Improved Determination of Heat Flux Density in Porous Media Using Modified Block Method

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ABSTRACT

Characterizing the ground thermal regime and estimation of water balance and mass exchange processes occurring across porous media often require knowledge of heat flux through the surface layers. Accurate measurement of the parameter has therefore continued to receive increasing attention by Scientists and Engineers. Improved determination of heat flux density in porous media using the modified Block method was thus investigated in this study with a view to addressing the hitherto associated accuracy concerns. Heat flux densities of granular and solid geologic materials represented by Granite and Clay samples were evaluated using Arctic Silver® Thermal Interface Material (TIM), to measure impacts on thermal resistance errors. Results showed heat flux density of the clay sample increasing from 9.99 to 64.02 W m^{-2} with TIM while that of the granite sample increased from 26.28 to 48.95 W m^{-2} with TIM. Hence, accuracy concern was therefore largely addressed with regards to contact measurements and the correction of the underestimation problem was validated with TIM. Modified block method thus yielded improved results of heat flux density in clay and granite with thermal interface material.

Key words: Block method, heat flux density, thermal contact resistance, granite, clay, porous media

INTRODUCTION

Heat flux density is the quantity of heat flowing across a unit area of a virtual plane in the sample per unit time and may be caused by conduction, convection and radiation. The measurement of the heat flux density of geologic materials has received a lot of attention in recent years as a result of the growing interest in the disposal of nuclear waste, underground storage (compressed natural gas, liquefied natural gas, liquefied petroleum gases, compressed air, oil or water), permafrost, geophysics, engineering, agriculture, meteorology and geothermal energy. The amount of thermal energy that moves through an area of porous medium in a unit of time is the heat flux or heat flux density of the medium. Understanding the phenomenon of Near-surface heat flux is necessary because it explains coupled energy transfer processes between the surface and the subsurface. Experimental measurement of Heat Flux Density (HFD) in porous media often involves the use of heat flux plates placed horizontally in the media near the surface. The plate sensors of known and constant thermal properties are usually small, rigid and disc-shaped (Falckenberg, 1930; Philip, 1961; Robin *et al*., 1997; Howell and Tolk, 1990). Heat flux plates have however continued to yield unreliable results for the reasons of flow distortion close to the plate, liquid water and vapour movement divergence and thermal contact resistance between the plate and the porous matrix. Contact resistance is often regarded as the major source of errors in thermal properties measurements (Bruijn *et al.*, 1983; Sauer *et al.*, 2003; Sauer *et al.*, 2008; Van Haneghem *et al.*, 1983). The high thermal contact resistance makes the measurement of ground temperature and heat flux densities difficult, especially under thermal transitory field conditions where diurnal air and vapour movement caused by wind gusts and thermal gradient exists (Hadas 1974, 1977). The constant underestimation of ground heat flux has been traced to the presence of thermal contact resistance, the exact magnitude of which, according to (Sauer *et al.*, 2007), is very difficult to estimate especially under field conditions and rather remains an area of persistent uncertainty. Block method (Van Wijk, 1964, 1967; Schneider, 1969), which employs a fabricated block of an appropriate material at a uniform temperature placed on the sample surface had been used in the past to determine thermal properties of porous media. As a matter of fact all measurements and calculations, including heat flux density, made using the old Block method were generally regarded as unacceptable, thereby leading to the abandonment of the technique due to accuracy concerns from thermal contact resistance between the block and the sample surface (Stigter, 1968). This was in spite the fact that the method provides a simple way of measuring heat flux density in undisturbed natural soil near the surface. In revisiting and modifying the Block Method, after more than four decades of abandonment, in order to address the accuracy concerns, thermal conductivity of Clay and Granite was determined by Akinyemi *et al.* (2011) while thermal conductivity and thermal diffusivity of some rock samples were measured by Akinyemi *et al.* (2012) with good measure of reliability, supported with sufficient validation, achieved in both investigations. This work is therefore aimed at extending previous experimental and evaluation efforts on the modified Block method to achieve reasonably accurate determination of HFD in porous granular and solid geologic materials represented by Clay and Granite, especially with a view to correcting the constant underestimation and persistent uncertainties associated with such measurements.

MATERIALS AND METHODS

Block device was used to make measurements of thermal conductivity of clay and granite, while KD2 thermal analyzer was used to make instantaneous measurements for validation. Result of thermal conductivity obtained from the Block device was consequently used to determine the heat flux density on the samples of interest.

Block device set-up: Block method device was fabricated from Perspex (10×10×4 cm) with $\lambda_p = 0.18568$ W/mK, $C_p = 1.728\times10^{-4}$ J m^{-3}K). Details of the fabrications of the Block device, experimental procedures using the device, as well as the general descriptions of the KD2 for instantaneous measurements and validations have been comprehensively explained in previous work (Akinyemi *et al.*, 2011).

Theory: The temperature near the center of the contact plane is calculated from the theory of two bodies which are suddenly brought into contact along the plane z = 0 at the instant t = 0, the temperature changes according to the equation (Carslaw and Jaeger, 1959):

$$\frac{\delta\theta_i(z,t)}{\delta t} = a_i \frac{\delta^2\theta_i(z,t)}{\delta z^2} \tag{1}$$

where, i = 1 for block and i = 2 for sample. Thermal diffusivity a (m^2 sec^{-1}) = λ/ C = λ/pc, with λ (W/mK) is the thermal conductivity, C (J m^{-3} °C) is the heat capacity per unit mass, p (kg sec^{-3}) is the density and c (J $kg^{-1o}C$) is the specific heat. Using the Laplace Transform of θ_1 (z, t), the general solution is given as (Van Wijk, 1967):

$$L\ \{\theta i\ (z,t)\} = Ai \exp\ (-z \sqrt{\frac{p}{a_i}}\ B_i \exp\ (+ z \sqrt{\frac{p}{a_i}} + s_i\ (z,p) \tag{2}$$

Theoretical calculations made by Van Wijk (1967) and expanded by Stigter (1968) which were based on solving the Fourier equation for two finite bodies having different initial temperatures and brought at time t = 0 in contact at plane z = 0 have been employed. The solution for the temperature of the block's contact plane is given as:

$$\theta_1(0,t) = \frac{T_{1in}\sqrt{\lambda_1 C_1} + T_{2in}\sqrt{\lambda_2 C_2}}{\sqrt{\lambda_1 C_1} + \sqrt{\lambda_2 C_2}} + \frac{2}{\pi}\frac{\lambda_1 E_1 + \lambda_2 E_2}{\sqrt{\lambda_1 C_1} + \sqrt{\lambda_2 C_2}}\sqrt{t} \tag{3}$$

where, T_{1in} is initial surface temperature of the block.

In the experiment with a uniform temperature of porous media, equation 3 reduces to:

$$\theta_1(0,t) = \frac{T_{1in}\sqrt{\lambda_1 C_1} + T_{2in}\sqrt{\lambda_2 C_2}}{\sqrt{\lambda_1 C_1} + \sqrt{\lambda_2 C_2}} \tag{4}$$

From Eq. 3, a plot of $\theta_1(0, t)$ vs $\sqrt{t}$ is expected to yield a straight line graph with intersect $T_1(0,0)$ at t = 0. Using temperature readings from Block (1) and that from the porous medium of interest (2), a set of two equations can be generated and solved to determine α as well as T_{2in} i.e., surface temperature of the porous medium at t = 0. The temperature of the porous medium T_2 (z, 0) beneath the Block was measured at the depths of 2, 4, 8, 16 and 32 mm. The thermal conductivity, λ, of any substance is usually defined by the fundamental law of conduction, the so called law of Fourier, which in one dimension may be stated as:

$$HFD\,(z,t) - \lambda\frac{\partial\theta(z,t)}{\partial z} \tag{5}$$

The quantity of heat flowing across a unit area of a virtual plane in the soil per unit of time is called heat flux density and can be calculated from the slope of the graph $\theta_1(0,t)$ against $\sqrt{t}$.

$$HFD\ (0,\ 0) = -\ \lambda_2\ E_2 = (1+\alpha)\ \sqrt{\lambda_1 C_1} \times \sqrt{\pi/2} \times \text{slope of the graph} \tag{6}$$

where, λ_2 is the thermal conductivity of the sample and:

$$\alpha = \sqrt{\lambda_2 C / \lambda_1 C_1}$$

E_2 is the temperature gradient at different depth, which is:

$$\frac{\partial\theta(z,t)}{\partial z}$$

from Eq. 5. Since the thermal conductivity of the Perspex is known, equations (3 and 6) make direct determination of the heat flux density at the surface in the porous medium to be possible as if it was under natural conditions before the block was placed on the sample.

KD2 Thermal properties analyzer: Measurements were made instantaneously with a KD2 digital meter (Decagon Devices Inc., Pullman, WA, USA) to compare with block measurements for the purpose of validation. The thermal probe was considered as an infinitely long heat source in an isotropic medium under a uniform initial temperature. During measurements, the 60 mm long probe was inserted into the samples and the in-built microprocessor ensures temperature stability within 90 sec before heating the probe for 30 sec. Thermal conductivity was thus calculated from the temperature rise before instantaneous display of results. KD2 was used to make measurement for the granite and clay with and without (Arctic Silver®) TIM.

Sample preparation: Samples used in this study were collected from south western Nigeria comprising rocks of the Precambrian basement (Fig. 1). This region of the country is very much affected by geological exploration activities due to well-logging and bore-hole construction. Nigeria lies between latitudes 50 and 140N and longitudes 30 and 140E and crystalline basement rocks of Precambrian age underlie about 50% of the country (Muotoh *et al.*, 1988). These are unconformably overlain by sedimentary rocks of Cretaceous to recent age. A block of granite of approximately 15×15×10 cm was cut to size and bored<1mm on one side to give space for the KD2 Thermal analyzer probe. For clay, a fine-ground sample (Table 1) was placed inside a Perspex

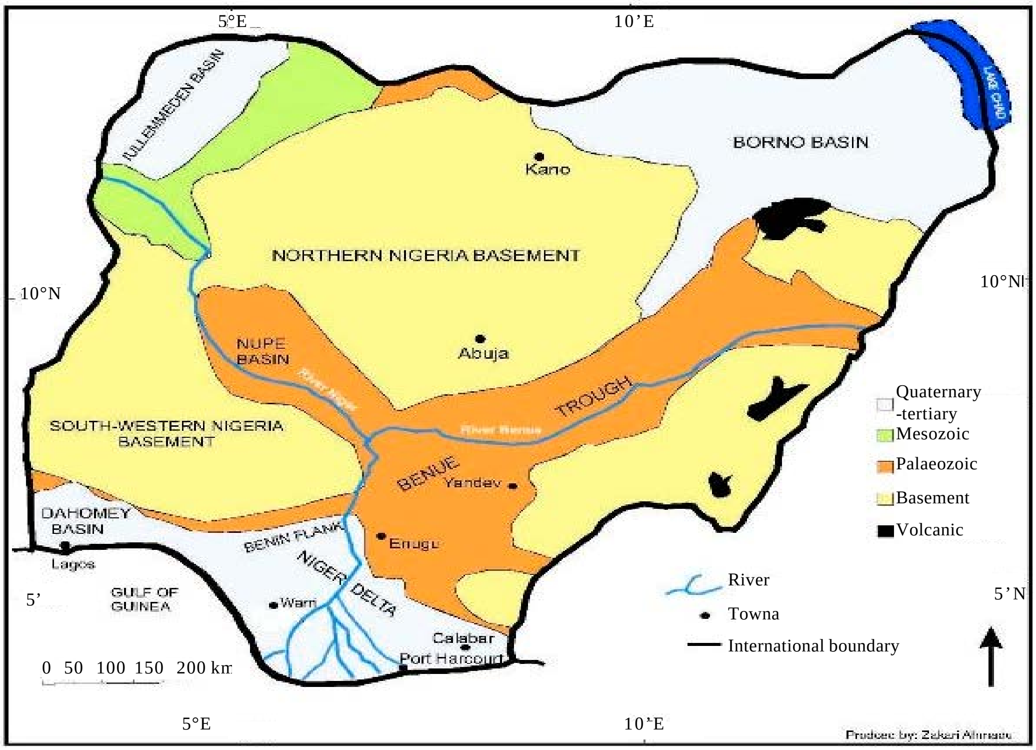

Fig. 1: Geological map of Nigeria

container of dimension 10×10×5 cm. Component analyses of the clay and granite using ASTM (2000, 2001) is shown in Table 1. A Picolog Data Logger (USB TC-08 Thermocouple (USA) was connected through temperature sensors connected to the contact/block apparatus made for the experiment. The data logger is connected to a converter, converting alternating (AC) current to a constant 15 V direct (DC) current, which was used for the experiment. The TIM used is applied in a thickness of 0.05 cm to close the contact surfaces of the block apparatus and the sample to reduce the thermal contact resistance.

A TIM used for this work is Arctic Silver® which is the current version of the company's eponymous thermal interface material. Arctic Silver is a high-density compound of silver, aluminum oxide, zinc oxide and boron nitride in a proprietary polysynthetic oil base. It is at least 88% thermally-conductive material by weight. Its thermal resistance is rated as less than 0.0045°C-in^2/W.

RESULTS AND DISCUSSIONS

Heat flux densities determined for granite and clay using thermal conductivities previously determined show increase with application of TIM as shown in Table 2. This was as expected since thermal conductivity initially obtained increased substantially following similar trend with TIM. The TIM-induced significantly increased values of HFD from Block agreed with ranges of values obtained from Weber (2006) and Sauer *et al.* (2008).

Experiments on dry clay and granite: Heat flux density of the granular clay sample was observed to increase from 9.99×10^{-2}-64.02×10^{-2} W m^{-2} for the block method upon the application of the Thermal Interface Material thus reducing the contact resistance error and from 26.28×10^{-2}-48.95×10^{-2} W m^{-2} for the solid granite. Increase in thermal conductivity values with TIM also impacts increase in heat flux density, which was significant as a result of the induced reduction in thermal contact resistance. Results from Block measurement and KD2 thermal properties analyzer compared very well upon TIM application, with both agreeing within the range of standard values existing in literature as shown in Table 3. Figure 2 illustrates the percentage underestimation by 541% for HFD without TIM for clay while Fig. 3 shows the percentage underestimation by 86% for HFD without TIM for granite sample. It also became very unmistakably clear that underestimations and uncertainties were substantially more pronounced, on measurements of heat flux density with no considerations for contact resistance, on granular

Table 1: Physical description and constituent analysis of experimented clay and granite samples

Samples	Colour	Grain size	Fabric	Mineral contents
Granite	Light grey	Block size 15×15×10 cm	Isotropic	Quartz (30%), microcline (35%), Plagioclase (30%) Others (5%)
Clay	Dark brown	Fine grained texture	Foliated	Clay minerals (63%) Quartz (25%) Feldspar (5%) Carbonates (5%) Organic matter (1%) Iron oxides (1%)

Table 2: Evaluation of heat flux densities from thermal conductivities of clay and granite with block method

	Clay		Granite	
	Without TIM	With TIM	Without TIM	With TIM
1st reading (λ)	0.6831	2.956	3.96	
2nd reading (λ)	0.6802	0.85	2.950	
Mean (λ)	0.6815	0.85	2.953	3.96

HFD ($\times10^{-2}$) 9.99-64.02-28.68-48.95 W m^{-2}

Table 3: Evaluation table of heat flux densities and thermal conductivities of the samples with and without TIM

Samples W m^{-2}	Block Exp. without TIM W/mK λ_{BO}	Block Exp with TIM W/mK λ_{BW}	Difference λ_{BW}. λ_{BO}	Difference (%)
Clay	0.68	0.85	0.17	20
HFD (×10^{-2})	9.99	64.02		
Granite	2.95	3.95	1.00	25
HFD (×10^{-2})	26.28	48.95		

Samples W m^{-2}	KD2 without TIM W/m K λ_{KO}	KD2 without TIM W/m K λ_{Kw}	Difference λ_{KW}.λ_{KO}	Difference (%)	Standard range values W/mK (Kappelmeyer and Haene, 1974)
Clay	0.66	0.84	0.18	21	0.25-1.8
HFD (×10^{-2})					
Granite	2.93	3.96	1.03	26	2.0-7.0
HFD (×10^{-2})					

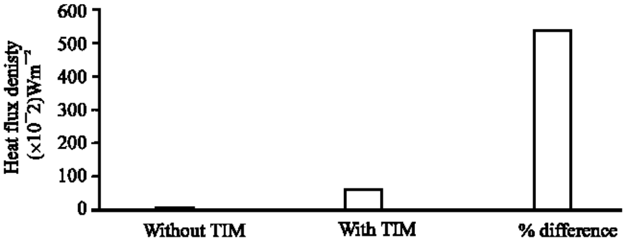

Fig. 2: Heat flux densities with/without TIM for Clay and %difference

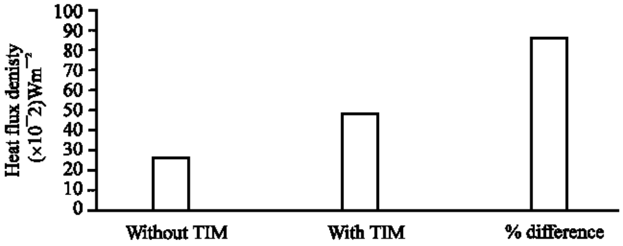

Fig. 3: Heat flux densities with/without TIM for Granite and %difference

geologic materials. This remarkable difference was not unexpected, given the fact that granular materials are more vulnerable to air infiltration on account of more prominent discontinuities associated with such materials arising from higher porosities.

CONCLUSION

Characterizing the ground thermal regime and estimation of water balance and mass exchange processes occurring across porous media often involve knowledge of heat flux through the surface layers, thereby making imperative its accurate measurement. However, the constant underestimation of ground heat flux has been traced to the presence of thermal contact resistance, the exact magnitude of which, is very difficult to estimate especially under field conditions and rather remains an area of persistent uncertainty. To this effect, Block method was therefore used to evaluate heat flux density of granular and solid porous geologic materials represented by granite and clay with a view to addressing accuracy concerns arising from contact errors. Thermal interface material successfully eliminated the underestimation of thermal properties in porous media. Thermal conductivity increased with the use of TIM for clay and granite at $p>0.05$. This confirms the effectiveness of thermal interface materials in addressing contact resistance errors and the associated uncertainties. Consequent upon this, heat flux densities determined was significantly different, thus increasing from 9.99×10^{-2}-64.02×10^{-2} W m^{-2} for clay and from 26.28×10^{-2}-48.95×10^{-2} W m^{-2} for granite. Hence, accuracy concern was therefore largely addressed with regards to contact measurements and the correction of the underestimation problem was validated with TIM. Reliability of the Block method to correctly evaluate heat flux density of both the granular and solid geologic materials was therefore established.

REFERENCES

ASTM, 2000. Standard test method for determination of thermal conductivity of soil and soft rock by thermal needle procedure. Designation: D 5334-00, American Society for Testing and Materials, ASTM Standards, 4, 8, 9.

ASTM, 2001. Standard test method for thermal conductivity of plastics by means of a transient line source technique. American Society for Testing and Materials, USA., pp: 1948-2059.

Akinyemi, O. D., T.J. Sauer and Y.S. Onifade, 2011. Revisiting the block method for evaluating thermal conductivities of clay and granite. Int. Commun. Heat Mass Transfer, 38: 1014-1018.

Akinyemi, O.D., Y.S. Onifade, B.S. Badmus and O.S. Awokola, 2012. Determination of thermal properties of rock samples using modified thermal block method. Earth Sci. India, 5: 38-50.

Bruijn, P.J., I.A. Haneghem and J. Schenk, 1983. An improved non steady-state probe method for measurements in granular materials, Part 1: Theory. High Temperatures-High Pressures, 15: 359-366.

Carslaw, H.S. and J.C. Jaeger, 1959. Conduction of Heat in Solids. 2nd Edn., Clarendon Press, Oxford, UK., pp: 426-428.

Falckenberg, G., 1930. Apparatur zur bestimmung des momentanen nachtlichen warmeaustausches zwischen erde und luft. Meteorol. Zeitschrift, 47: 154-156.

Hadas, A., 1974. Problems involved in measuring the soil thermal conductivity and diffusivity in a moist soil. Agric. Meteorol., 13: 105-113.

Hadas, A., 1977. Heat transfer in dry aggregated soil: Heat conduction. Soil Sci. Soc. Am. J., 4: 1055-1059.

Howell, T.A. and J.A. Tolk, 1990. Calibration of soil heat flux transducers. Theor. Appl. Climatol., 42: 263-272.

Kappelmeyer, O. and I.R. Haene, 1974. Geothermics with Special References to Application. Lubrecht Cramer Ltd., Belin, Stuttgart.

Muotoh, E.O.G., P.O. Oluyide, A.U. Okoro and O. Mogbo, 1988. The Muro Hills Banded Iron-Formation. In: Precambrian Geology of Nigeria, GSN, (Eds.). Geological Survey of Nigeria, Nigeria Pages: 219.

Philip, J.R., 1961. The theory of heat flux meters. J. Geophys. Res., 66: 571-579.

Robin, P., P. Cellier and G. Richard, 1997. Theoretical and field comparison of two types of soil heat flux meters. Soil Technol., 10: 185-206.

Sauer, T.J., D.W. Meek, T.E. Oschner, A.R. Harris and R. Horton, 2003. Errors in heat flux measurement by flux plates of contrasting design and thermal conductivity. Vadose Zone J., 2: 580-588.

Sauer, T.J., O.D. Akinyemi, P. Thery, J.L. Heitman, T.M. DeSutter and R. Horton, 2008. Evaluation of a new, perforated heat flux plate design. Int. Commun. Heat Mass Trans., 35: 800-804.

Sauer, T.J., T.E., Ochsner and R. Horton, 2007. Soil heat flux plates: Heat flow distortion and thermal contact resistance. Agron. J., 99: 304-310.

Schneider, T., 1969. The block-method for measuring heat flux density at the surface of soils and other solids. Agric. Meteorol., 6: 432-434.

Stigter, C.J., 1968. On the possibility of determining thermal properties from contact-surface temperatures. Physica, 39: 229-236.

Van Haneghem, I. A., J. Schenk and H.P.A. Boshoven, 1983. An improved nonsteady-state probe method for measurements in granular materials. Part 2: Experimental results. High Temp. High Pressures, 15: 367-374.

Van Wijk, W.R., 1964. Two new methods for the determination of the thermal properties of soils near the surface. Physica, 30: 387-388.

Van Wijk, W.R., 1967. New method for measuring heat flux density at the surface of soils or of other bodies. Nature, 213: 214-214.

Weber, S., 2006. Comparison of in-situ measured ground heat fluxes within a heteorogeneous urban ballast layer. Theor. Appl. Climatol., 83: 169-179.