International Journal of
Advances in Scientific Research and Engineering (ijasre)

E-ISSN : 2454-8006

DOI: 10.31695/IJASRE.2019.33403

Volume 5, Issue 7
July - 2019

Development of a Low-Cost Soil Heat Flux and Temperature Profile with Logger

M.O. Osinowo[1], **A.A. Willoughby**[1], **T. Ewetumo**[2] and **L.B. Kolawole**[1]

[1] Department of Physical Sciences, Redeemer's University, Ede, Nigeria

[2] Department of Physics, Federal University of Technology

Akure, Nigeria

ABSTRACT

Variation of soil temperature and soil heat flux measurements from a locally fabricated and calibrated device were analyzed and compared with a standard device. The soil heat flux consists of two-disc aluminum plates, dielectric material and two thermocouples such that each thermocouple was sandwiched between the aluminum plates and one side of the dielectric material. The sizes of the aluminum plates and the dielectric material were 32 mm in diameter and their thickness is 2.5 mm. Differential temperature between two thermocouples attached to two aluminum plates separated by a thermal insulator was used to measure the soil heat flux values. The thermocouples amplifier module AD8495 and then combined with a 16-bit Analog to Digital Converter (ADS1115) for a good measurement resolution was employed for the signal conditioning. A semiconductor sensor DS18B20 was used to measure the soil temperature. The microSD shield was included for storing data and DS3232, a Real Time Clock (RTC) module for timekeeping. Arduino mega 2560 microcontroller was used to coordinate the whole active and display the activities on LCD. The soil heat flux sensor was calibrated using the principle of thermal conduction over the surface area by heating with a known heat source. The thermal conductivity of heat flux is given by 3.3407 (WV-1m-1) from the empirical deduction. The temperature sensing unit was checked for accuracy by inserting it inside a calorimeter with the mercury-in-glass thermometer and the correlation obtained was 0.92. The soil heat flux and temperature sensing unit were compared with that of standard Campbell device. The correlation obtained for soil heat flux and temperature were 0.89 and 0.95 respectively. The result obtained when installed at the Redeemer's University, Ede, Nigeria, the variation of soil heat flux and temperature when placed at the same level of 10 cm into the soil gave the same value. The maximum peak of heat flux density usually occurs at about 13:00 pm to 15:00 pm with values around 260 W/m2 at 10 cm. The logging interval can be preset to any rate from 30 seconds and above.

Keywords: Soil Heat Flux, Temperature, Thermocouple, Aluminum Plate, Dielectric Material.

1. INTRODUCTION

Soil heat flux, *G*, or heat flux density is the amount of thermal energy flowing through an area of soil per unit time and the rate of change of soil temperature during the day or seasons is determined by the heat conductivity of the soil. Measurement of soil heat flux is an important consideration in several applications ranging from micro-meteorology, agronomy and land surface energy balance modelling to account for heat transfer into the soil, (Evett, Agam, Kustas, Colaizzi, & Schwartz, 2012; Heitman, Horton, Sauer, Ren, & Xiao, 2010a; Kustas, Prueger, Hatfield, Ramalingam, & Hipps, 2000a; Tyagi & Satyanarayana, 2010; Wang & Bras, 1999). Temperature, humidity, rainfall, soil heat flux and soil temperature are essential parameters required by the agronomist in order to be able to develop methods of improving soil productivity and crop yield prediction (Van Loon, Bastings, & Moors, 1998). One of several techniques of determining soil heat flux is the calculation of thermal conductivity of heat flux plates or disks and the temperature gradient across it. Most of the recent investigations of soil heat flux density have used this method because it is simple to implement. Heat flux plates have been fabricated and used to make direct measurements of soil heat flux from surface soil temperature (Evett et al., 2012; Fuchs & Tanner, 1968; Heitman, Horton, Sauer, Ren, & Xiao, 2010b; Kustas, Prueger, Hatfield, Ramalingam, & Hipps, 2000b; Ochsner, Sauer, & Horton, 2006; Sauer & Horton, 2005; Tyagi & Satyanarayana, 2010; Van Loon et al., 1998; Wang & Bras, 1999). Soil heat flux plates are small inflexible sensors shaped in the form of a wafer and embedded horizontally into the soil. In general, heat flux plates are based on the use of thermocouples attached to two metal plates with a thermal insulator sandwiched between the plates so that the thermal energy gradient over the plates can be measured. The measured heat flux density across the plates is proportional to the heat flux density in the soil.

Notable researchers contributed to the advancement of this approach in design and theories. (Deacon, 1950; Dunkle, 1940; Falckenberg, 1930; Fuchs & Tanner, 1968; Overgaard Mogensen, 1970; Philip, 1961; Portman, 1958). The heat flow in the soil and through the plates may be expressed, by the application of Fourier's law as:

$$\boldsymbol{G} = \frac{\boldsymbol{Q}}{\boldsymbol{A}} = -\boldsymbol{k}\frac{dT}{dz} \qquad (1)$$

where, $\boldsymbol{Q}$ is the heat transfer through the material, (J s^{-1} or Watt), $\boldsymbol{k}$ is the thermal conductivity of the soil (W m^{-1} K^{-1}), $\boldsymbol{A}$ is the surface area of the material and dT/dz is the vertical temperature gradient (Km^{-1}). In this work, dT in terms voltage that was developed at output of signal conditioning was measured with the aid of a by AD8495 thermocouple amplifier module. Also, temperature profiles at three levels were considered as well using DS18B20 temperature sensor.

2. MATERIAL AND METHOD

2.1 Basic Block Diagram of Heat Flux and Temperature Profile Measurement

The instrument consists of the developed heat flux sensors, temperature sensors, thermocouple amplifier, 16-bit analog to digital converter ADS1115, Arduino Mega 2560, microSD card shield and liquid crystal intelligent display unit (LCD). The basic block diagram of the instrument is shown in Figure 1.

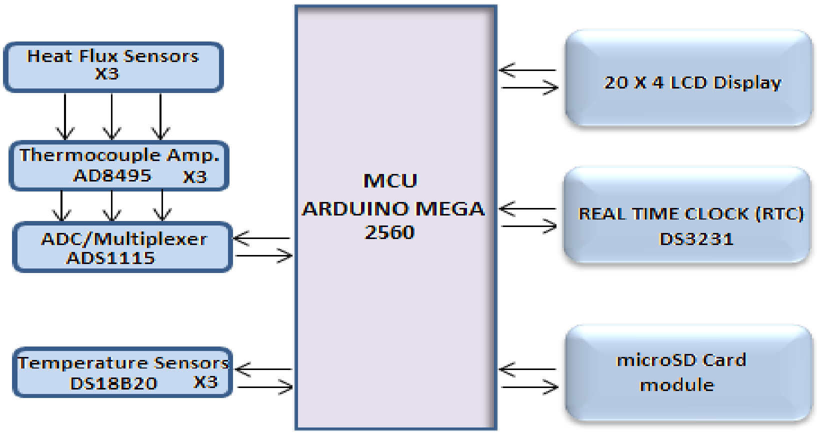

Figure 1: Block Diagram of Heat Flux Profile and Temperature Profile

2.2 Signal Conditioning for Heat Flux Sensor

An AD8495 thermocouple amplifier from Analog Devices was used to amplify signal from heat flux sensor. The board requires 3 V to 18 V dc and has free output voltage on the OUT pin. The output voltage from the AD8495 is given as the following:

$$\text{Output Voltage} = (V_{out} - 1.25) \qquad (2)$$

The output voltage range with 5 V power is from -1.125V to 1.625 V outputs (for 0 V to 5 VDC) and -1.125 V to 1.455 V (for 0 V to 3.3 VDC).

The output of the AD8495 is link to the ADS1115 which is a precision analog-to-digital converter (ADC) with 16 bits resolution. The ADS1115 is designed with precision and low power consumption. The ADS1115 features an onboard reference voltage and oscillator. Data are transferred via an I^2C-compatible serial interface; four I^2C slave addresses can be selected. The ADS1115 operate from a single power supply ranging from 3.3 V to 5.5V. The ADS1115 can perform conversions at rates to 860 samples per second (SPS). An onboard Programmable Gain Amplifier (PGA) is available on the ADS1115 that offers input ranges from the supply to as low as ±256mV, allowing both large and small signals to be measured with high resolution. The ADS1115 also features an input multiplexer (MUX) that provides two differential or four single-ended inputs. The output is connected to the microcontroller via SDA and SCL for further processing.

DOI: 10.31695/IJASRE.2019.33403

3. SOIL HEAT FLUX MEASUREMENT

3.1 The Heat Flux Sensor

The heat flux sensor consists of two circular aluminum discs of 32 mm in diameter and 2 mm in thickness and separated by Teflon thermal insulator of 2.5 mm thickness. Two thermocouples are sandwiched at both upper plate temperature (T1) and lower plate temperature (T2) of the developed sensor. It was insulated and protected from water by using silicate gum. Thermocouples can also be used to measure the difference of two temperatures by connecting the two thermocouples in series with reversed polarity such that their values subtract as in Figure 2, and the outputs can be connected to a thermocouple amplifier AD8495. If T_1 is at higher temperature than T_2, the heat flux value is positive or vice versa.

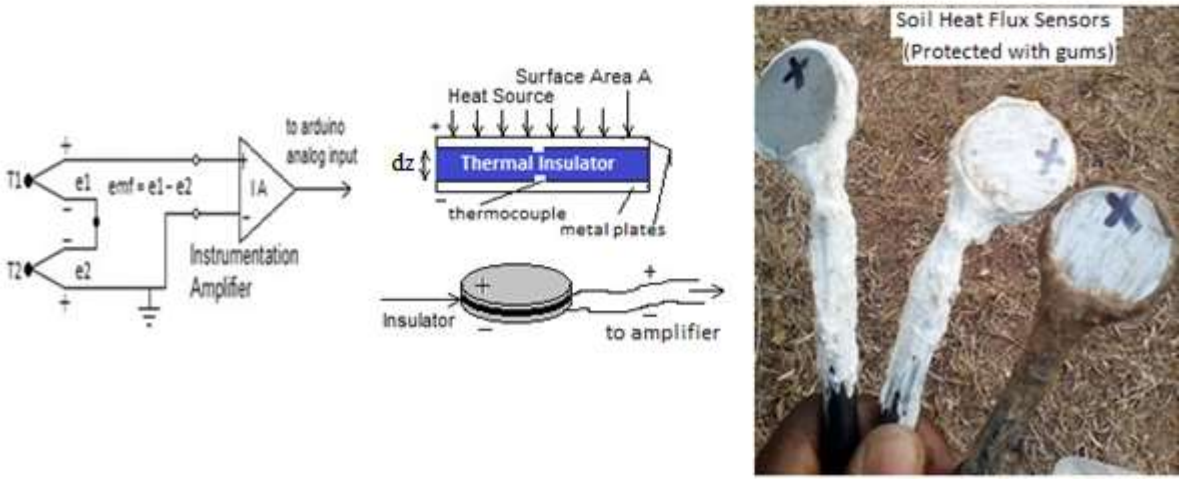

Figure 2: The Developed Soil Heat Flux Sensors

3.2 TEMPERATURE SENSORS FOR PROFILE MEASUREMENT

The DS18B20 temperature sensor is a 3-pin, 1-wire digital temperature sensor that requires only one data line or port pin (and ground) for communication with a microcontroller. The resolution is programmable from 9-bit to 12-bit Celsius temperature measurements. Additionally, it can derive (parasitic) power directly from the data line, eliminating the need for external power source. Each DS18B20 has a unique 64-bit serial code stored in on-board ROM, which allows multiple DS18B20s to function on the same 1-Wire bus. Therefore, it is simple to use one microprocessor to control many DS18B20s distributed over a large area. Temperature measurements range from -55 °C to +125 °C. Power supply range is from 3 V to 5.5 V. The digital (DO) was pulled-up with 4.7 kΩ resistor. Each temperature sensor was highly insulated to prevent damages due to moisture and water making it suitable for soil application.

4 DATA LOGGING SYSTEM WITH LIQUID CRYSTAL DISPLAY

The data logger with display consists of ardunio Mage 2560, memory card shield, and DS3232 timer board and 4 lines 20 characters liquid crystal display. On ardunio platform or complier a C program is written for proper communication and data acquisition. The output of each signal conditioning are connected appropriately depend on serial communication protocol requirement to communicate with arduino board and internally process the signal for logging and display data.

5 SOIL HEAT FLUX CALIBRATION FOR FLUX PLATE METHOD

This calibration process is essential in order to determine the calibration value (or the sensitivity), which is a constant that is required in the programming code to convert the heat flux sensor's output voltage to the appropriate heat flux density value that can be conveniently read by the Arduino at any instant. This was done with a one-dimensional heat flow method (Fuchs and Tanner, 1968), using a 12 V, 5 W plate dc electrical heater. The heater was placed on top of the fabricated soil heat flux sensor and a voltage applied across the heater was measured using a digital voltmeter and current passing through was also obtained with analog ammeter. A rheostat was used to vary the applied voltage as shown in Figure 3.

DOI: 10.31695/IJASRE.2019.33403

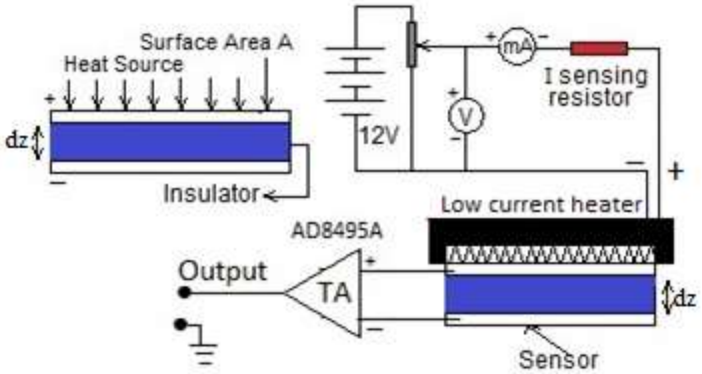

Figure 3: Calibration setup

The thermal conductivity of material (Fuchs *et. al.*, 1968; Evett *et. al.*, 2012) is given as

$$Q_{Conduction} = \frac{k(\Delta T)A}{z} \quad (3)$$

therefore the heat flux:

$$\frac{Q}{A} = \frac{k(\Delta T)}{z} \quad (4)$$

where, k is thermal conductivity in W m^{-1} K^{-1}, Q is amount of heat transfer through the material in Js^{-1} or W, A is the surface area of the material plate in m^2, ΔT is temperature change in Kelvin and z is the thickness of the thermal insulator between the parallel plates. The heat flux sensor that was developed with aluminum plate the thermal conductivity k can be by place heater and corresponding output voltage (V_{TC}) of the heat flux sensor can now be expressed as;

$$\frac{Q}{A} = k\frac{(\Delta V)}{z} \quad (5)$$

The heater and the heat flux sensor were placed inside an air-tight jacket to prevent air movement around the setup. The results are given in Table 1 and the P/A plotted against ΔV/z as shown in Figure 4. From the Figure 4, an empirical equation for calibration was obtained given as:

$$\frac{P}{A} = 3.3407\frac{V_{TC}}{z} + 49.796 \quad (6)$$

k will be equal to 3.3407 ($WV^{-1}m^{-1}$).

Table 1: Heat Flux Calibration (A = 8.04 x 10^{-4} m^2)

V_{dc} (V)	I_{dc} (A)	P_{dc} (W)	(P_{dc}/A) Wm^{-2}	ΔV_{TC} (V)	ΔV_{TC} /z
2.0	0.059	0.119	147.473	0.089	35.760
2.5	0.084	0.211	262.053	0.156	62.580
3.0	0.099	0.298	370.851	0.246	98.340
3.5	0.120	0.419	521.215	0.353	141.252
4.0	0.147	0.588	731.581	0.483	193.104
4.5	0.160	0.722	897.849	0.630	252.108
5.0	0.181	0.904	1124.119	0.796	322.264
5.5	0.201	1.103	1371.714	0.983	393.360
6.0	0.216	1.294	1609.188	1.189	475.608
6.5	0.241	1.565	1945.340	1.413	565.008

DOI: 10.31695/IJASRE.2019.33403

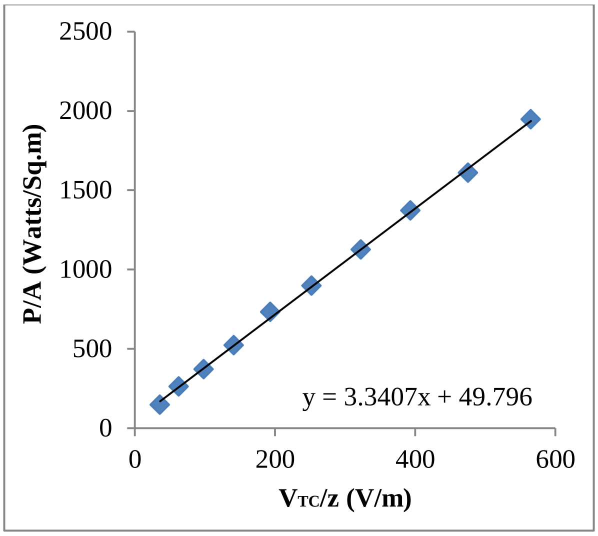

Figure 4: Soil Heat Flux Calibration

6. RESULT AND DISCUSSION

The developed heat flux sensor was examined for validation by comparing it with Campbell heat flux sensor by placing the developed sensor with that of Campbell at same level inside soil at 10 cm below the surface for two days in Ede, Nigeria. The graphs obtained from the data collected are shown in Figure 5 and 6. The Figure 5 and Figure 6 show the correlation and standardization. The correlation and slope from the graph is 0.97 and approximately 1 respectively. The display is a good response compared with the available heat flux sensor. The three temperatures and three heat fluxes were placed in the same level inside soil at 10 cm above the surface from 21 hour to 23 hour of local time. The data obtained for the period were plotted in Figure 7 and 8. The graph of Figure 7 shows the three temperature sensors at the same level for temperature 2 at around 22.04 hour, 22.17 hour and 22.00 hour; it also shows similar sparks (or spikes) on the temperature 3 at around 22.26 hour and temperature 1 at around 22.29 hour this may be due to time delay in sampling and inherent time response of temperature of device. For the heat flux sensors shown n Figure 8, there were slight variations which may be due to the response time of the sensors and sampling time in programme code. The result shows a good response and better variability.

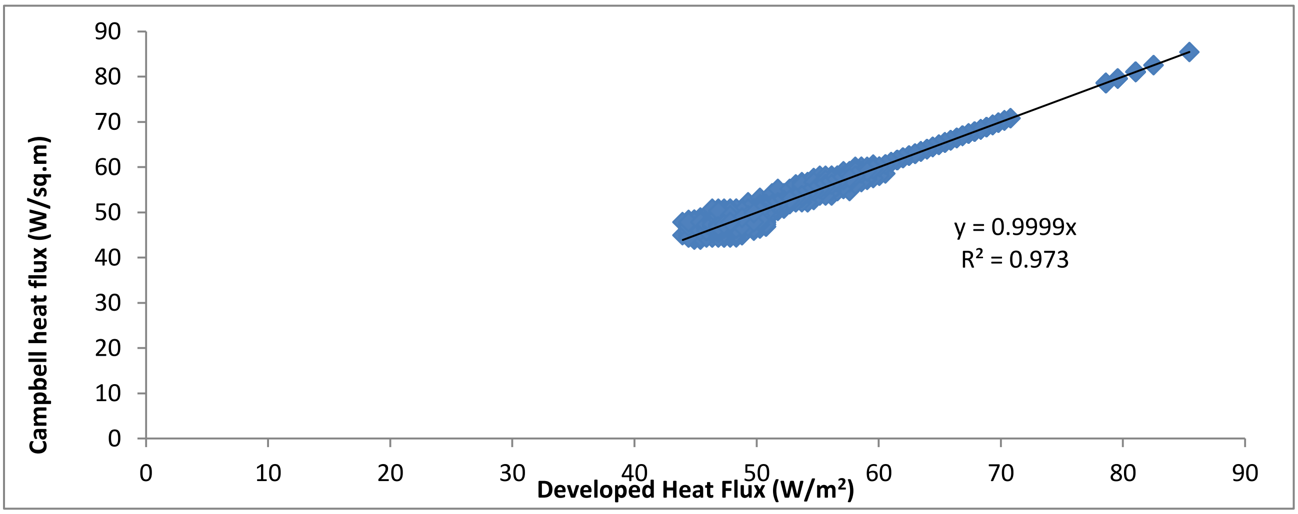

Figure 5: The two Heat Flux Sensors Measurement at Same Level in the Soil

DOI: 10.31695/IJASRE.2019.33403

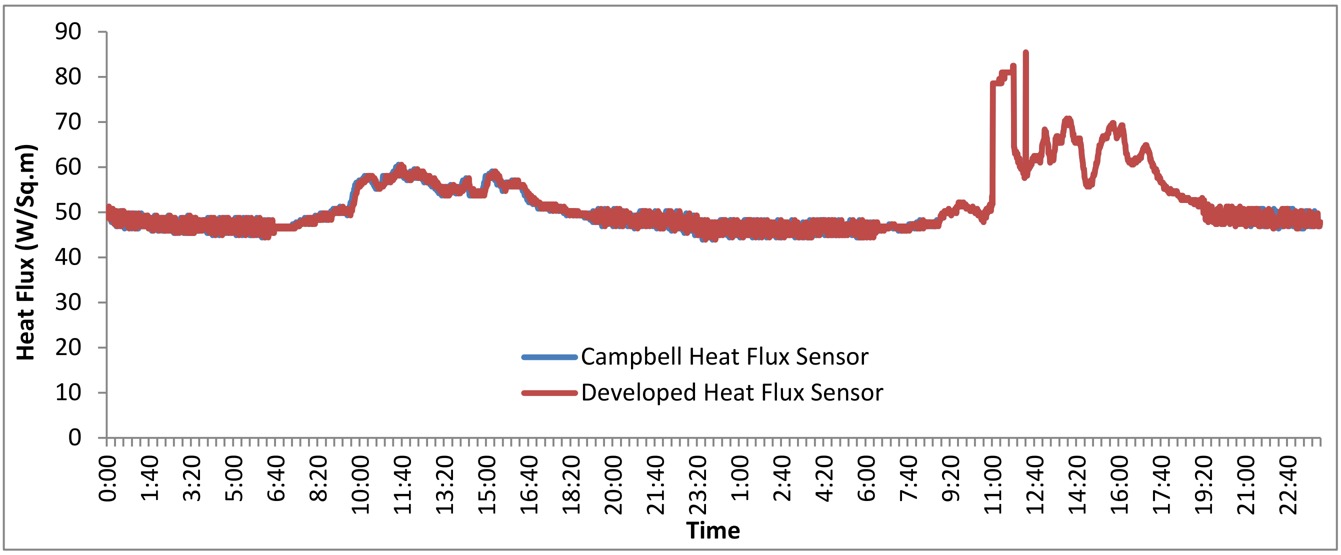

Figure 6: Comparison of Campbell and the Developed Heat Flux Sensors

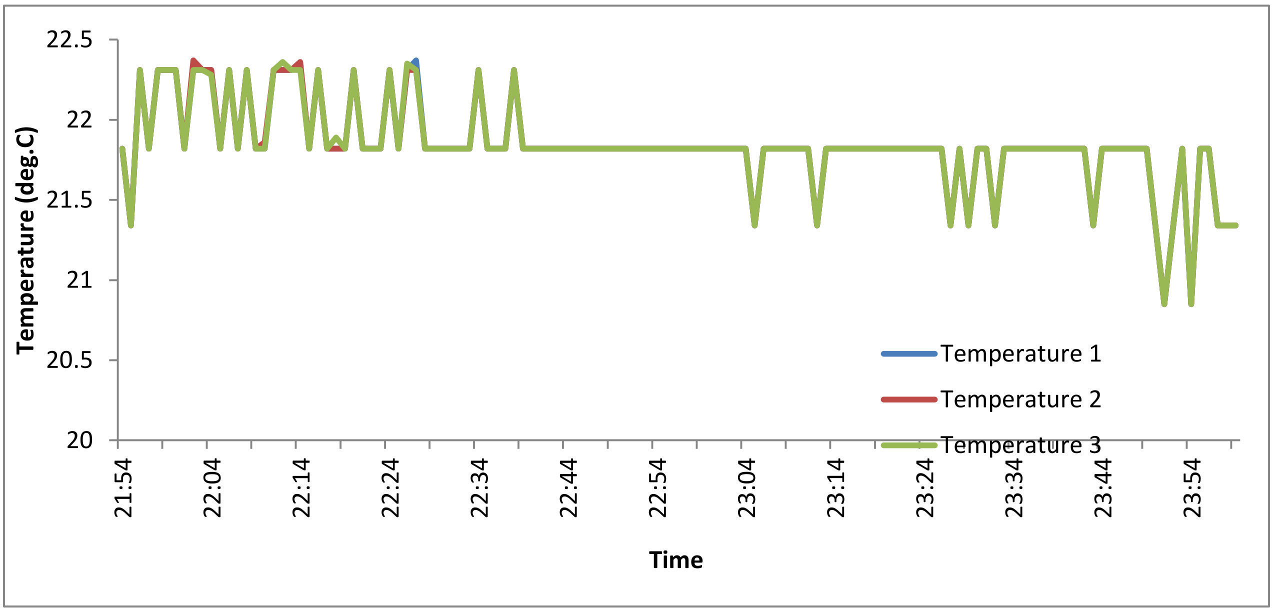

Figure 7: Three Temperature Sensors Measurement at Same Level in the Soil

DOI: 10.31695/IJASRE.2019.33403

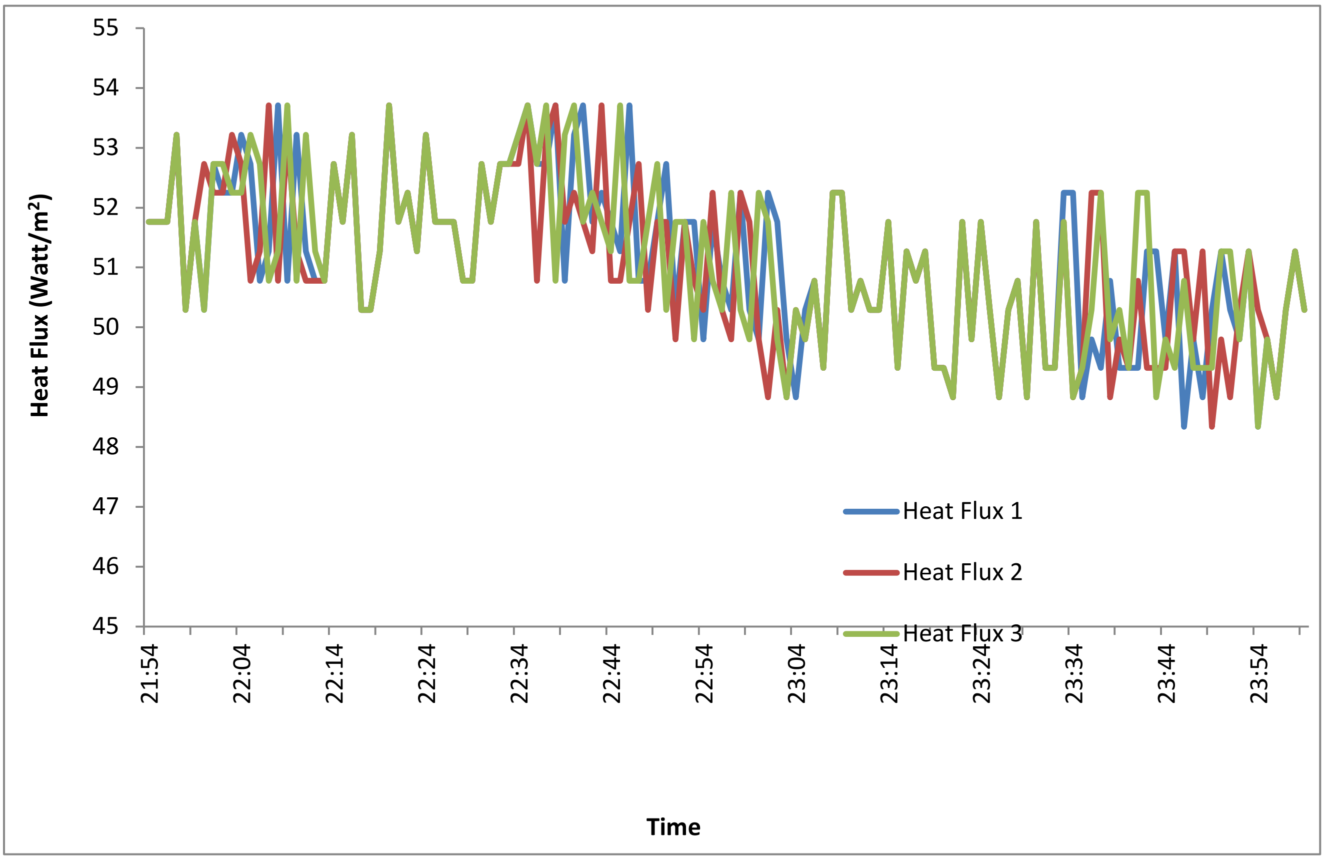

Figure 8: Three Heat Fluxes Sensor Measurement at Same Level in the Soil

7. CONCLUSION

Data logged can be easily opened in an Excel sheet for further analyses. The developed system performs as expected .The resolution of the device is 0.9561 W/m^2 and can measure up to a maximum of +1800 W/m^2. The thermal conductivity of heat flux is given by 3.3407 (WV^{-1}m^{-1}) from empirical deduction. The heat flux sensor was compared with the Campbell heat flux sensor; the correlation obtained was 0.973 and shows a good linear behaviour with a deviation of 1.1 Wm^{-2}. The developed and that of Campbell heat flux sensors were used to take measurements at the Redeemer's University, Ede, Nigeria on 28th June, 2018 from 21:50 to 00:01 midnight and from 29th August to 30th August 2018. The result obtained showed good variations of the soil heat flux and their graphs give the same trend and closed values at all measuring points. Time delay of about 12 ms was observed between the sensors which may be due to the accumulated microcontroller processing time and this can be solved through the software. The heat flux sensor can also be used in the study of thermal properties of buildings and materials.

REFERENCES

1. Kustas, W. P., Prueger, J. H., Hatfield, J. L., Ramalingam, K., and& Hipps, L. E. (2000a). Variability in soil heat flux from a mesquite dune site. *Agricultural and Forest Meteorology*, *103*(3), 249–264.
2. Ochsner, T. E., Sauer, T. J., & Horton, R. (2006). Field Tests of the Soil Heat Flux Plate Method and Some Alternatives. *Agronomy Journal*, *98*(4), 1005. https://doi.org/10.2134/agronj2005.0249
3. Overgaard Mogensen, V. (1970). The calibration factor of heat flux meters in relation to the thermal conductivity of the surrounding medium. *Agricultural Meteorology*, *7*, 401–410. https://doi.org/10.1016/0002-1571(70)90035-X
4. Philip, J. R. (1961). The theory of heat flux meters. *Journal of Geophysical Research*, *66*(2), 571. https://doi.org/10.1029/JZ066i002p00571
5. Portman, D. J. (1958). Conductivity and length relationships in heat-flow transducer performance. *Transactions, American Geophysical Union*, *39*(6), 1089. https://doi.org/10.1029/TR039i006p01089

DOI: 10.31695/IJASRE.2019.33403

6. Tyagi, B., & Satyanarayana, A. N. V. (2010). Modeling of soil surface temperature and heat flux during pre-monsoon season at two tropical stations. *Journal of Atmospheric and Solar-Terrestrial Physics*, *72*(2–3), 224–233.
7. Van Loon, W. K. P., Bastings, H. M. H., & Moors, E. J. (1998). Calibration of soil heat flux sensors. *Agricultural and Forest Meteorology*, *92*(1), 1–8.
8. Wang, J., & Bras, R. L. (1999). Ground heat flux estimated from surface soil temperature. *Journal of Hydrology*, *216*(3–4), 214–226. https://doi.org/10.1016/S0022-1694(99)00008-6

.

About the Authors:

M.O. Osinowo (B.Sc. (Hon.) Physics LASU, 1996; M.Tech. Physics (Electronic Measurements and Instrumentation Option), 2003, FUT, Akure Nigeria).
Lecturer I at Department of Physical Sciences, Redeemer's University, Ede, Nigeria.

A.A. Willoughby (B.Sc.(Hon) Physics Unilorin, M.Sc. Unilorin, Ph.D Physics (Ionospheric Physics) UI, Ibadan, Nigeria)
Associate Professor at Department of Physical Sciences, Redeemer's University, Ede, Nigeria

T. Ewetumo (B.Tech. (Hon.) Physics Electronics, 1994; M.Tech. Physics (Electronic Measurements and Instrumentation Option), 2001; and Ph.D Physics (Electronic Measurements and Instrumentation Option), 2011 from FUT, Akure Nigeria).
Senior Lecturer at Department of Physics, The Federal University of Technology, Akure, Nigeria.

L.B. Kolawole (B.Sc.(Hon), Ph.D Physics (Ionospheric Physics) UI, Ibadan, Nigeria
Professor Emeritus at Department of Physical Sciences, Redeemer's University, Ede, Nigeria

DOI: 10.31695/IJASRE.2019.33403