International Annals of Science
ISSN: 2456-7132
Volume 12, Issue 1, pp. 1-15, 2022
DOI: https://doi.org/10.21467/ias.12.1.1-15

RESEARCH ARTICLE

The Effects of Moisture Content on the Temperature of Some Selected Soil Samples in the Presence of Internal Heat

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Received: 20 March 2022 / Revised: 20 May 2022 / Accepted: 18 June 2022 / Published: 17 July 2022

ABSTRACT

The effect of moisture content on the temperature of some selected soil samples in the presence of internal heat was studied. The governing equation was modeled using Bosenneque's approximation base on some necessary assumptions by which the transfer occurred. These equations were non-dimensionalized by employing some standard dimensionless parameters and later reduced to ordinary differential equations using perturbation method. This was then solved analytically. The various effects of the physical parameters that materialized were examined on the unsaturated and saturated forms of some selected soil samples. With the aid of Matlab software, the numerical results were graphed for visual examination. It was observed that the presence of moisture content in these soils helped in boosting their temperatures as the solar radiation and internal heat increase.

Keywords: Internal heat, Prandtl number, solar radiation.

1 Introduction

Soil plays a very significant role in the earth's ecosystem. It is uniquely important to both plant and animal lives. Soils provide life and support for plants. They are home for myriad micro-organisms that fix nitrogen and decompose organic matter, and armies of microscopic animals as well as earthworms and termites [1]. Heat is however required in many of these biological processes which determine the availability of the necessary nutrients for the plants. Hence, the study of the soil/ground temperature as being affected by some physical factors is of a great importance.

Temperature generally is keenly important in the growth of crops. There is a minimum temperature, optimum temperature and the maximum temperature at which every crop can thrive. This is known as the cardinal temperature [2]. There is a minimum temperature at which a crop can germinate, at which respiration takes place and at which photosynthesis occurs, necessary for root growth and for water intake. And any temperature below this minimum value will hinder these processes. Meanwhile, temperature higher than the maximum will truncate the growth of the crop. In other words, crops develop at their best at the optimum temperature [2].

Usually, when planting seeds or seedlings, the soil temperature is more important than the air temperature. There are preferential temperatures for growing seeds or transplanting them. Suitable temperature should be determined for appropriate time of planting. Soil temperature affects the rate of entry of water in the seed. This affects the development of plumule and the radicle when plant grows which automatically controls the germination of seeds [3].

To understand the soil heat transfer, the surface temperature of the soil which matches up with the temperature at the top active layer of the ground is an important parameter. This measurement can be taken at the uppermost centimeters of the ground in order to avoid influences of solar radiation and focus on the seasonal changes of the ground temperature [4]. The temperature of ground surface varies with the type of canopy cover and moisture content. The thermal conductivity and porosity of soil type have minimal effect on the surface temperature of the soil and cause some more differences in the temperature in deep layers because they affect heat transfer with little effect on energy balance at the surface [5].

Solar radiation is one major factor that affects the temperature of the soils especially at the surface and still have a relatively good impact on it to a reasonable depth of the earth. Although, not all the energies emitted by the sun reaches the earth's surface; some percentages were reflected by the atmospheric particles, some by clouds and some from the surface of the earth by bright ground surfaces like snow, ice and sea [6]. In other words, the solar radiation that reaches the earth is always less than the one above the atmosphere and arrives the earth at an angle less than 90^{o} which varies with latitude, time of the day and day of the year [7].

Moreover, one main property that determines how much of this radiant heat a soil is capable of absorbing is the thermal conductivty. This however varies from soil to soil. In this study, amidst some other soil properties, the thermal conductivity makes it possible to be able to identify the soil type in consideration.

Generally, Thermal conductivity is the ability of a substance to transfer heat from one molecule to another. It is the exchange of heat energy between adjacent molecules and electrons in the conducting medium, and the higher the number of these molecules and electrons, the easier the heat is transferred. A substance which possesses a relatively large thermal conductivity is a good conductor of heat, while poor heat conductors or good thermal insulators are the substances which have small thermal conductivity [8]. Materials of higher thermal conductivity also possess higher heat transfer rate occurring across such materials while the rate is slower in materials with low thermal conductivity. Materials of high thermal conductivity are widely used for various purposes and in different fields such as in heat sink applications and electricity transportation, while materials with low thermal conductivity can be used as thermal insulation [9]. Thermal conductivity of materials in rear cases can be constant, but rather be temperature dependent, position (spatial) dependent, or time dependent [7]. It can also vary linearly [10], [11]), or be quadratic [12], or inversely linear [13], [14]. Its reciprocal is known as the thermal resistivity. Materials such as coppers, steels, aluminum, metals, silver, etc, that have high thermal conductivity also exhibit relatively high electrical conductivity. When a material with high thermal conductivity is heated, the heat generated is speedily conducted away from the section where it's being heated to the cooler part [9].

Meanwhile, [15] modeled mathematically, the effects of thermal conductivity of some substances on their temperature taking into consideration the magnetic field. They established the fact that when the thermal conductivities of these materials increased, their corresponding temperatures are also boosted.

Samara *et al* [16] compared the temperatures at different soil depths and atmospheric physical factors such as air temperature, humidity, precipitation, wind speed, and solar radiation in Keller Peninsula, located in King George Island, Antarctica Maritime. According to their work, there were series of local transformations which were caused by increase in ice-free areas in the Antarctic, as a result of climate change. This however has ability to affect the microclimate of the soil, causing greater melting of the permafrost and causing changes in the soil moisture.

In an investigation of temperature variation at soil depths in some parts of southern Nigeria, Nwankwo and Ogagarue [17] used a soil mercury-in-glass thermometer to measure temperature of soils at various depth of 15cm, 30cm, 45cm, 60cm, 75cm and 90cm. They took readings at intervals between 8am to 11am, 1pm to 4pm and 9pm to 11pm over the period of three weeks in November 2008. They observed that the temperature of the clay soil decreased as the depth increased and later increased. The temperature increased with increasing depth of the sandy soil. In the loamy soil, the temperature was discovered to increase to about 45cm depth, then later decreased as the depth increased. They drew conclusion based on the observations made that the temperature randomly varies from soil to soil as a result of different characteristics that the soils considered possessed. The mean temperature for clay soil ranges from 27.7 ^{o}C – 28.9 ^{o}C, 28.2 ^{o}C – 29.1 ^{o}C for sand and 28.3 ^{o}C – 29.0 ^{o}C for loam.

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Considering the internal heat generation to be negligible and using the Dirichet's boundary condition, Nwaigwe [18] modeled ground temperature with suction velocity and radiation. His results show that ground temperature decreased as the radiation parameter and the Prandtl number increased.

Meanwhile, Akinpelu *et al* [19] examined the combination of sandy soil with loamy soil and clay soil with loamy soil as being affected by solar radiation in order to attain a recommendation for maximum yield in some agricultural crops. They considered this at various wet/water levels of the soils combinations which ranges from about 1.4% to about 21.1 %. The results they got show that the solar radiation and the ground's internal heat increased the temperature of the soils as the intensities of these physical parameters rise. In addition, at the lower percentage of the water content, the rate together with the level at which the temperature of clay+loam soils increased is greater than that of the sandy+loam. But when the wet level is increased to a higher percentage up to about 21.2 %, the temperature of the combination of sandy+loam becomes greater than that of the clay+loam both in rate and in level.

Considering the above literature among host of others, this present study focuses on the effects of moisture content on some selected soil samples in the presence of internal heat. The use of variable boundary condition rather than a Dirichlet type makes the work more practicable.

2 Formulation of the Problem

The three (3) dimensional flow considered was reduced to two (2) dimensional by decomposing x and y which are on the same horizontal axis to become one ($y-axis$). This was further taken to be infinite. The vertical axis ($z-axis$) is taken to be in the soil and the solar radiation towards the surface of the soil in a direction due to gravity. Thermal conductivity of the soil is considered to be varying with time. The soil porosity and permeability are also put into consideration. Moreover, the ground is taken to be an optically-thin environment and the fluid is heat absorbing and electrically conducting.

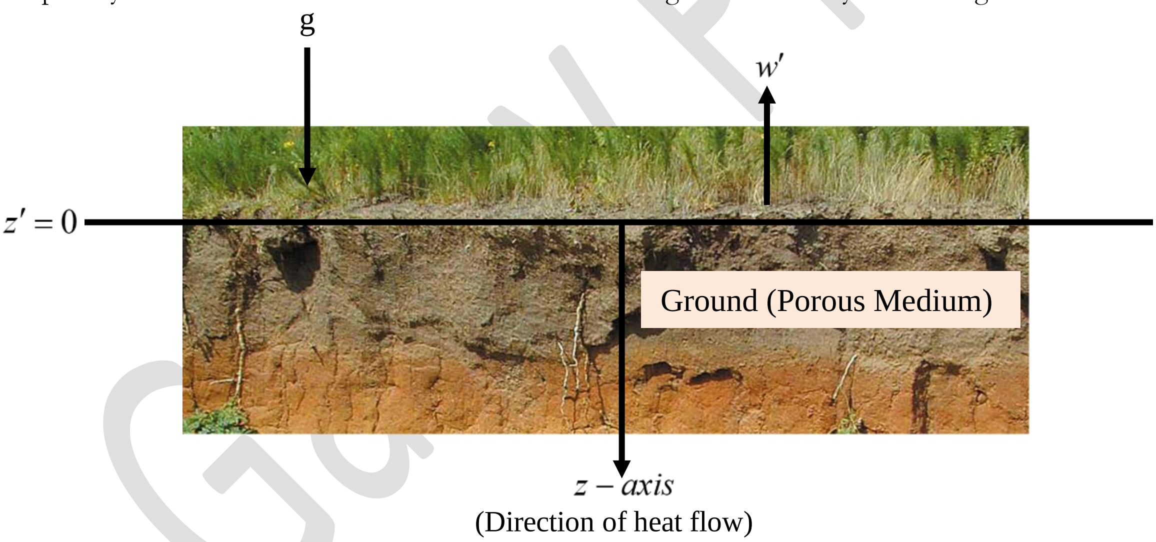

Figure 1: *The physical model and the coordinate of the problem ([18] with modifications)*

3 Mathematical Analysis

The work is modeled under the above conditions and governed by the following equations:

Continuity Equation

$$\frac{\partial w'}{\partial z'} = 0 \tag{1}$$

Energy Equation

$$\frac{\partial T'}{\partial t'} + \varphi w' \frac{\partial T'}{\partial z'} = \frac{1}{\rho C_p}\left\{\frac{\partial}{\partial z'}\left(k\frac{\partial T'}{\partial z'}\right)\right\} - \frac{\varphi}{\rho C_p}\frac{\partial q_r}{\partial z} + \frac{Q_0}{\rho C_p}(T' - T'_\infty) \tag{2}$$

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Subject to:

$$T' = T'_w + \lambda' \cos(\omega' t') \quad \text{at} \quad z = 0 \tag{3}$$

$$T' \to T'_\infty \quad \text{as} \quad z \to \infty \tag{4}$$

where,

z' is the dimensional depth of the ground (the distance perpendicular to y')

t' is the dimensional time, w' is the suction velocity

T' is the dimensional temperature

T'_∞ is the free stream dimensional temperature

T'_w is the dimensional wall temperature

φ is the soil porosity

ρ is the density

C_p is the specific heat capacity

k is the thermal conductivity

q'_r is the Radiative heat flux

Using the dimensionless parameters as used by [20], [21], [22] and [12]:

$$t = \frac{t' w_0^2}{w}, \quad z = \frac{w_0 z'}{w}, \quad \omega = \frac{w\omega'}{w_0^2}, \quad \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty} \quad \text{and} \quad \eta_0 = \frac{\lambda'}{T'_w - T'_\infty} \tag{5}$$

The varying suction velocity as used by [21] and [18] is given as

$$w' = -w_0(1 + \varepsilon A e^{i\omega' t'}) \tag{6}$$

where,

w_0 is the initial suction velocity,

A is the suction parameter and

ω the frequency of oscillation

The negative sign signifies that the suction is towards the surface of the ground. A and ε are very small such that $\varepsilon A << 1$.

Moreover, by [23], and [24] the heat flux which is from the external source is given as

$$\frac{\partial q'_r}{\partial z'} = 4\alpha^2 (T' - T'_\infty) \tag{7}$$

where,

α is the absorption coefficient.

The governing equation (2) then becomes:

$$\frac{1}{\varphi}\frac{\partial \theta}{\partial t} - (1 + \varepsilon A e^{i\omega t})\frac{\partial \theta}{\partial z} = \frac{1}{\varphi w \rho C_p}\left\{\frac{\partial}{\partial z}\left(k\frac{\partial \theta}{\partial z}\right)\right\} - R^2 + Q\theta \tag{8}$$

Following [25], [26] and [12], the thermal conductivity is taken to be time dependent and given as:

$$k = k_0(1 + st) \tag{9}$$

where,

s is the variable thermal conductivity parameter

t is time

k_0 is the thermal conductivity at temperature T_w

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Equation (8) then becomes:

$$\frac{1}{\varphi}\frac{\partial \theta}{\partial t} - (1+\varepsilon A e^{i\omega t})\frac{\partial \theta}{\partial z} = \frac{1}{P_r}\left\{\frac{\partial}{\partial z}\left((1+st)\frac{\partial \theta}{\partial z}\right)\right\} - R^2 + Q\theta \qquad (10)$$

Subject to:

$$\theta = 1 + \eta_0 \cos(\omega t) \quad \text{at} \quad z = 0 \qquad (11)$$

$$\theta \to 0 \quad \text{as} \quad z \to \infty \qquad (12)$$

where,

$$R = \sqrt{\frac{4\alpha^2 \theta w}{\rho C_p w_0^2}} \quad \text{(the radiation parameter)}$$

$$Q = \frac{Q_0 w}{\rho C_p \varphi w_0^2} \quad \text{(the internal heat generation parameter)}$$

$$P_r = \frac{\varphi w \rho C_p}{k_0} \quad \text{(the Prandtl number)}$$

A_0 is the amplitude of variation

4 Method of Solution

Using perturbation method to reduce equation (10) alongside the boundary conditions (3) – (4) to ordinary differential equation, the assumed solution takes the form:

$$\theta(z,t) = \theta_0(z) + \varepsilon e^{i\omega t}\theta_1(z) + o(\varepsilon^2) \qquad (13)$$

Differentiating (13) with respect to t and z while neglecting the higher order term $o(\varepsilon^2)$, and substituting it into (10), the governing energy equation becomes:

$$(1+st)\frac{d^2\theta_0}{dz^2} + P_r\frac{d\theta_0}{dz} + P_r Q\theta_0 = P_r R^2 \qquad (14)$$

$$(1+st)\frac{d^2\theta_1}{dz^2} + P_r\frac{d\theta_1}{dz} + \left(P_r Q - \frac{P_r i\omega}{\varphi}\right)\theta_1 = -P_r A\left(m_1 C_1 e^{m_1 z} + m_2 C_2 e^{m_2 z}\right) \qquad (15)$$

Solving equations (14) – (15) subject to the following,

$$\theta_0 = 1 + \eta_0 \cos(\omega t),\ \ \theta_1 = 0 \quad \text{at} \quad z = 0 \qquad (16)$$

$$\theta_0 \to 0\ ,\ \theta_1 \to 0 \quad \text{as} \quad z \to \infty \qquad (17)$$

The ambient soil distribution then becomes:

$$\theta = \xi_a + \varepsilon e^{i\omega t}\xi_b \qquad (18)$$

Where,

$$\xi_a = C_1 e^{m_1 z} + C_2 e^{m_2 z} + C_3$$

$$\xi_b = C_4 e^{m_3 z} + C_5 e^{m_4 z} + C_6 e^{m_1 z} + C_7 e^{m_2 z}$$

$$m_1 = -\frac{P_r}{2(1+st)} + \sqrt{\frac{P_r^2}{4(1+st)^2} - \frac{P_r Q}{1+st}}$$

$$m_2 = -\left(\frac{P_r}{2(1+st)} + \sqrt{\frac{P_r^2}{4(1+st)^2} - \frac{P_r Q}{1+st}}\right)$$

$$m_3 = -\frac{P_r}{2(1+st)} + \sqrt{\frac{P_r^2}{4(1+st)^2} - \frac{P_r Q}{1+st} + \frac{P_r i\omega}{\varphi(1+st)}}$$

$$m_4 = -\left(\frac{P_r}{2(1+st)} + \sqrt{\frac{P_r^2}{4(1+st)^2} - \frac{P_r Q}{1+st} + \frac{P_r i\omega}{\varphi(1+st)}}\right)$$

$$C_1 = -C_3 e^{-m_1 z}$$

$$C_2 = 1 + A_0 \cos(\omega t) + C_3\left(e^{-m_1 z} - 1\right)$$

$$C_3 = R^2 / Q$$

$$C_4 = \frac{-C_6 e^{m_1 z}}{e^{m_3 z}}$$

$$C_5 = -(C_4 + C_6 + C_7)$$

$$C_6 = \frac{-P_r A m_1 C_1}{m_1^2 + st m_1^2 + P_r m_1 + P_r Q - \left(\frac{P_r i\omega}{\varphi}\right)}$$

$$C_7 = \frac{-P_r A m_2 C_2}{m_2^2 + st m_2^2 + P_r m_2 + P_r Q - \left(\frac{P_r i\omega}{\varphi}\right)}$$

In order to be able to examine the emerged physical parameters on the temperature of the soils in consideration, the adopted numerical values of the thermal conductivities and porosities of the soils were displayed on tables 1 and 2 below.

Table 1: *Thermal conductivity of different soil types [27]*

Texture Class	Thermal Conductivity (Btu/ft hr ^{0}F)	
	Unsaturated	**Saturated**
Sand	0.440	1.440
Clay	0.640	0.960
Silt	0.960	0.960

Table 2: *Typical porosity values for various soil types [28] and [29]*

Description	Porosity (min – max)	Average Porosity
Sand; Coarse	0.26 – 0.43	0.345
Sand; Fine	0.29 – 0.46	0.375
Clay	0.29 – 0.41	0.350
Silt (organic)	0.42 – 0.68	0.550

In line with some existing literature like [22], [19], and [24] among host of others, other parametric values adopted include:

$P_r = 0.71$, $Q = 0.01$, $\omega = \pi/2$, $\varepsilon = 0.01$, $t = 1.0$, $A = 0.5$, $R = 0.1$, $A_0 = 1.0$, $h_0 = 1.0$, $S_C = 0.6$, $S_r = 0.2$, $Gr = 2.0$, $Gc = 2.0$, $M = 5.0$

All the figures thus correspond to these values except otherwise stated.

5 Results

The temperature profile obtained was presented numerically and displayed on graphs to better illustrate the effects of the resulted physical quantities on the temperature of the soils while dry and when they are moist at increasing depth. In the study, variations in the radiation parameter, the internal heat generation and the Prandtl number were examined on temperature of three (3) soil types, namely: sand, clay and silt both in their unsaturated forms and when the soils were saturated with water.Discussions

Figures 2, 6 and 10 represent an average ground temperature with increasing depth at constant values of the physical parameters for unsaturated and saturated sandy soil, unsaturated and saturated clay, and unsaturated and saturated silt respectively. On an average, that is, when all the physical parameters involved are constant, the temperature decreased as the depth extended and converged at 1. This convergence takes place at a depth of about 9.144 to 15.240 meters (30 to 50 feet) depending on place/location, known as the “mean earth temperature” [27].

Meanwhile, as the electromagnetic waves from solar energy through process of radiation increases according to Figures 3, 7 and 11, all the soils involved (as listed above) absorbed the energy [6] and their temperatures are gradually raised; yet, converged at 1 (a depth of about 30 to 50 feet).

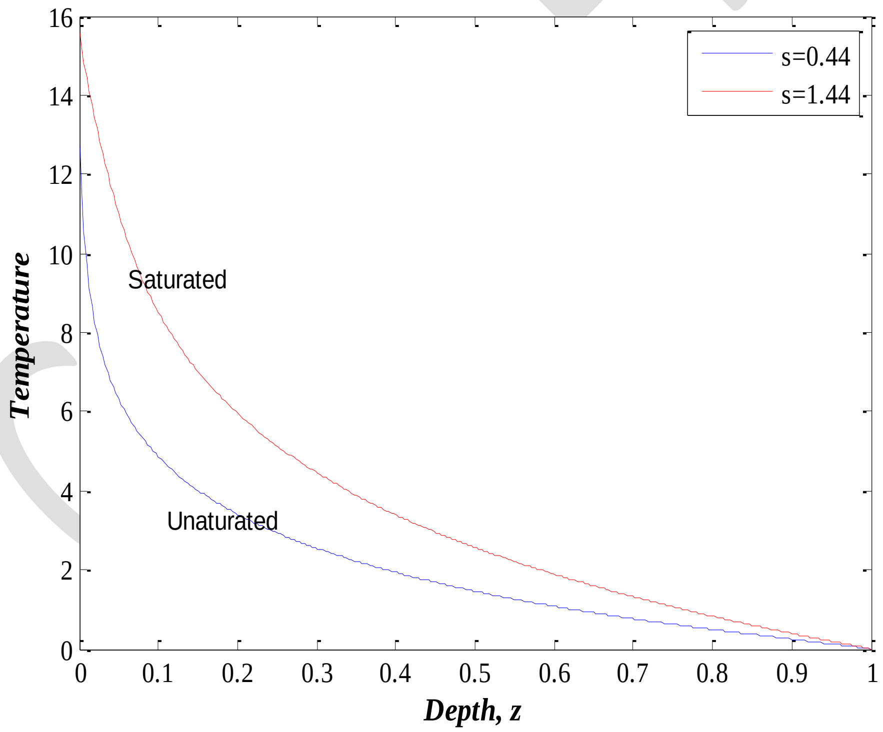

Figure 2: *Average ground temperature at increasing depth with constant values of the physical parameters for saturated and unsaturated sandy soil.*

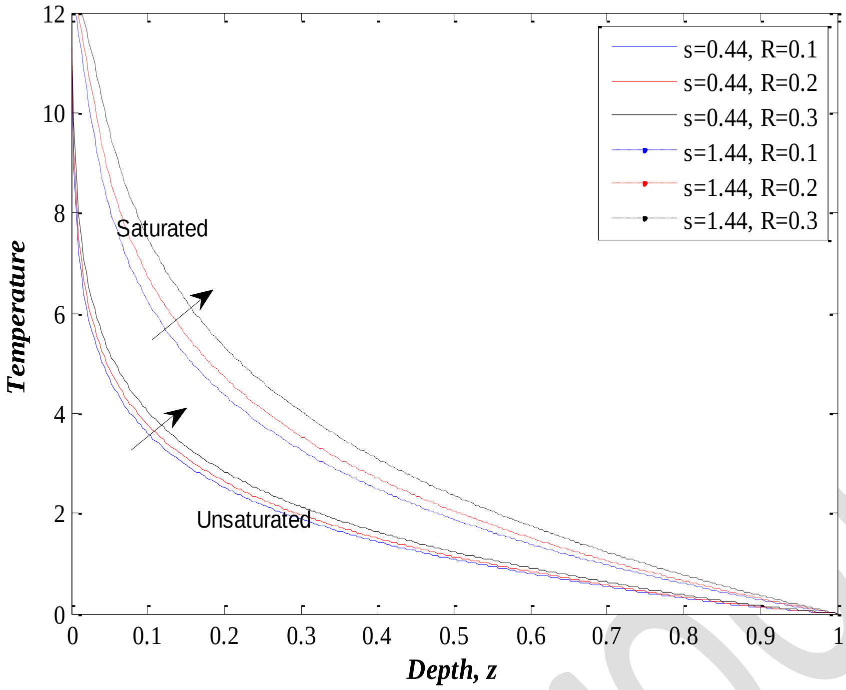

Figure 3: *Comparison of effects of mounting solar radiation (R) on ground temperature between ground containing saturated sandy soil and ground with unsaturated sandy soil content at increasing depth.*

Moreover, in Figures 4, 8 and 12, at any increase in the **radiogenic heat** produced by decay of naturally radioactive elements or isotopes in the earth crust and left over of the **primordial heat** from the formation of the earth [30], referred to as the internal heat generation, there are relative increments in the temperature of the soils considered. The soils absorb this internal heat because of their ability to conduct heat (the thermal conductivity) which added to their initial heat status and thereby raised it. Nevertheless, they all converged also at 1.

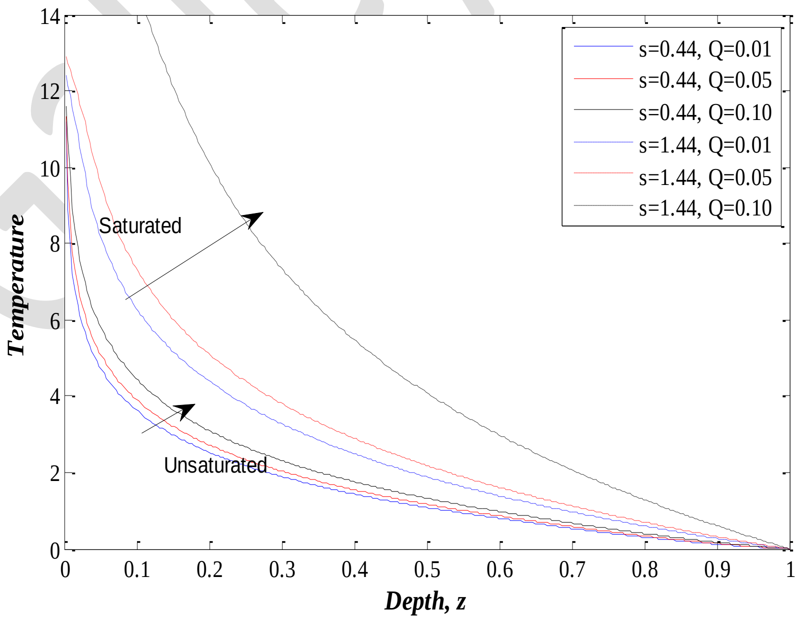

Figure 4: *Comparison of effects of growing internal heat generation (Q) on ground temperature between ground containing saturated sandy soil and ground with unsaturated sandy soil content at increasing depth.*

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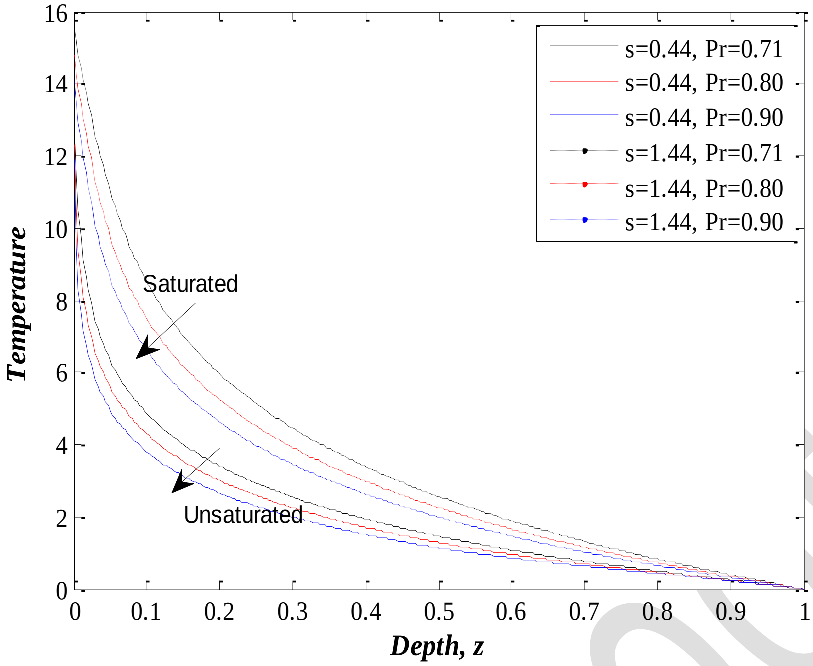

Figure 5: *Temperature profile for various values of Prandtl number for both saturated and unsaturated sandy soil at increasing depth.*

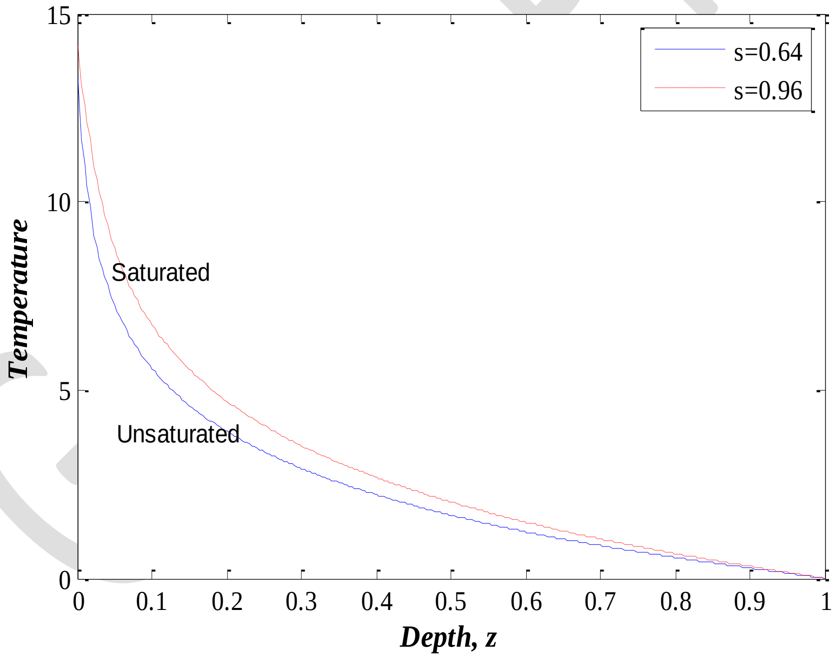

Figure 6: *Average ground temperature at increasing depth with constant values of the physical parameters for saturated and unsaturated clay.*

Figures 5, 9 and 13 depict the temperature profiles for various values of Prandtl number for sandy soil, clay soil and silt respectively. It is observed that increase in the Prandtl number leads to the decrease of thermal boundary layer of all the soil types. This is because the smaller values of Prandtl number correspond to increase in the thermal conductivity at the boundary layer which speeds up the rate of heat diffusion [22]. In other word, the thermal diffusivity dominates at the boundary layer. As the heat diffuses away from the boundary layer to give room for higher Prandtl number, the temperature at the boundary layer reduced.

More explicitly, Figure 3 compares the effects of rising solar radiation (R) on ground temperature between ground containing saturated sandy soil and ground with unsaturated sandy soil at increasing depth. It is discovered that the temperature of the saturated sand is greater than that of the unsaturated sand. Besides, the rate of increase of this temperature as the radiation increases is more than that of the unsaturated sandy soil. Since the thermal conductivity of the saturated sandy soil (1.44 Btu/ft hr ^{o}F) is greater than that of the unsaturated (0.44 Btu/ft hr ^{o}F), which is as a result of the thermal conductivity of the water, the saturated sand absorbs heat faster and more than the unsaturated which in turn increases its temperature further.

This case is similar when comparing effects of growing internal heat generation (Q) on ground temperature, between ground containing saturated sandy soil and ground with unsaturated sandy soil at increasing depth which Figure 4 also represents. The temperature of the saturated sand increased more, and at a quicker rate than that of the unsaturated sand. The heat energy rising from the earth crust are conducted more rapidly by the saturated sandy soil because of the moisture content which enhances its temperature more than that of the unsaturated sand.

Figure 5 also represents the temperature profile while evaluating the influence of various values of Prandtl number on both saturated and unsaturated sandy soil at increasing depth. On the average, temperature of the saturated soil is greater than that of the unsaturated. However, as the Prandtl number increases, there is decrease in temperature of both soil states. The saturated sand has a slight greater rate of decline in temperature than the unsaturated. This is as a result of the rate of diffusion of heat at the boundary layer of the saturated sandy soil (having moisture) being more than that of the unsaturated. And the rate at which this heat diffuses away from the boundary layer to give room for higher Prandtl number resulted to its faster rate of cooling.

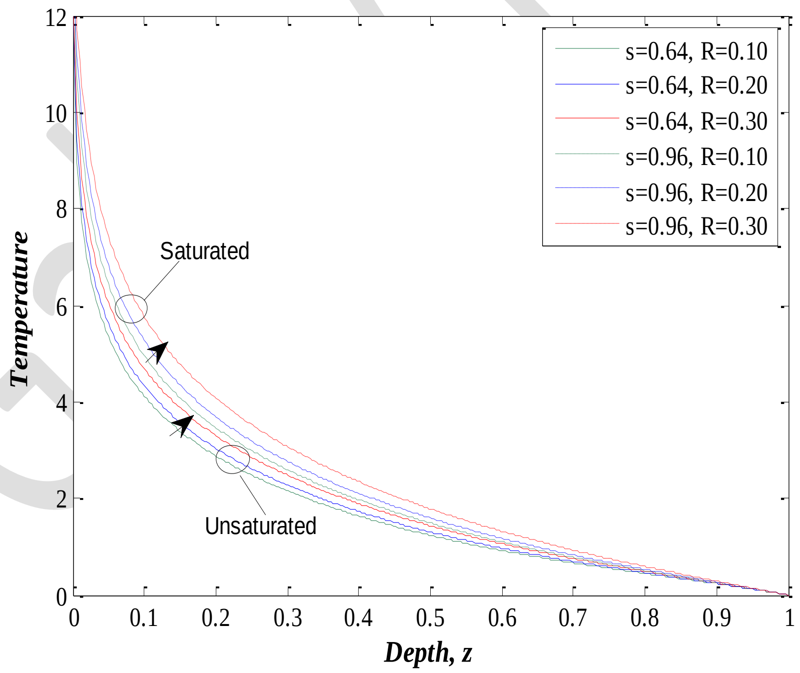

Figure 7: *Comparison of effects of mounting solar radiation (R) on ground temperature between ground containing saturated clay soil and ground with unsaturated clay soil content at increasing depth.*

Figure 7 as well represents a comparison effect of growing solar radiation (R) on ground temperature between ground containing saturated clay soil and ground with unsaturated clay soil at increasing depth. It is observed that the temperature of the saturated clay is higher than that of the unsaturated, but the rate of increase in temperature for both state of soil are almost the same; though that of the saturated is slightly greater. The thermal conductivity of the saturated clay which is more than that of the unsaturated is the factor responsible for this disparity in their temperature. The moisture content present in the saturated clay enhances its capacity for conducting more heat than the dry clay. However, since the difference between their thermal conductivities (which is 0.32 Btu/ft hr ºF) is not much put side by side that of saturated and unsaturated sandy soil (which is 1.0 Btu/ft hr ºF), the difference in the rate of increase in their temperature is not too significant.

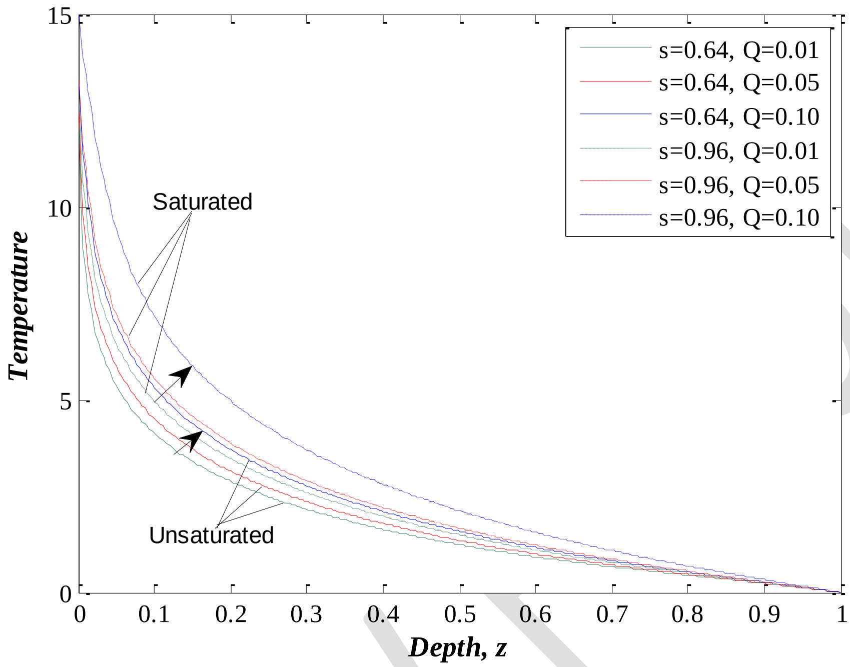

Figure 8: *Comparison of effects of growing internal heat generation (Q) on ground temperature between ground containing saturated clay soil and ground with unsaturated clay soil content at increasing depth.*

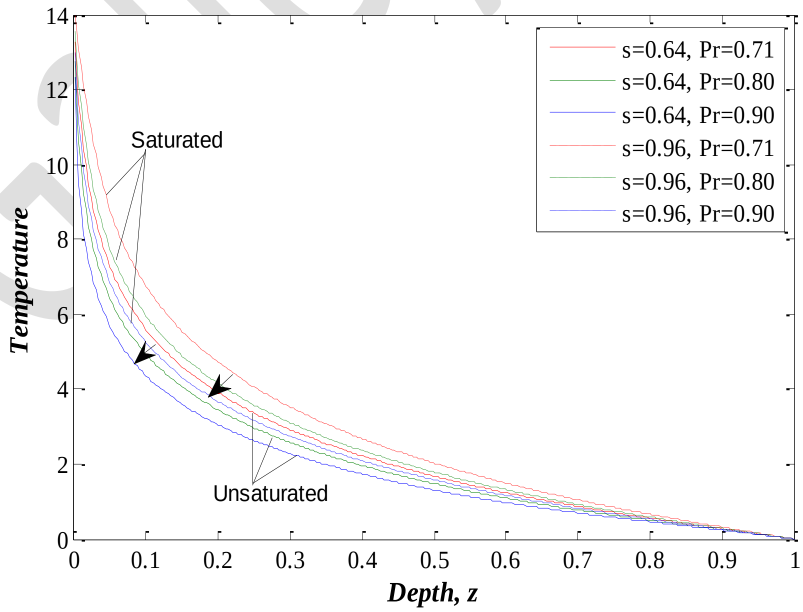

Figure 9: *Temperature profile for various values of Prandtl number for both saturated and unsaturated clay soil at increasing depth.*

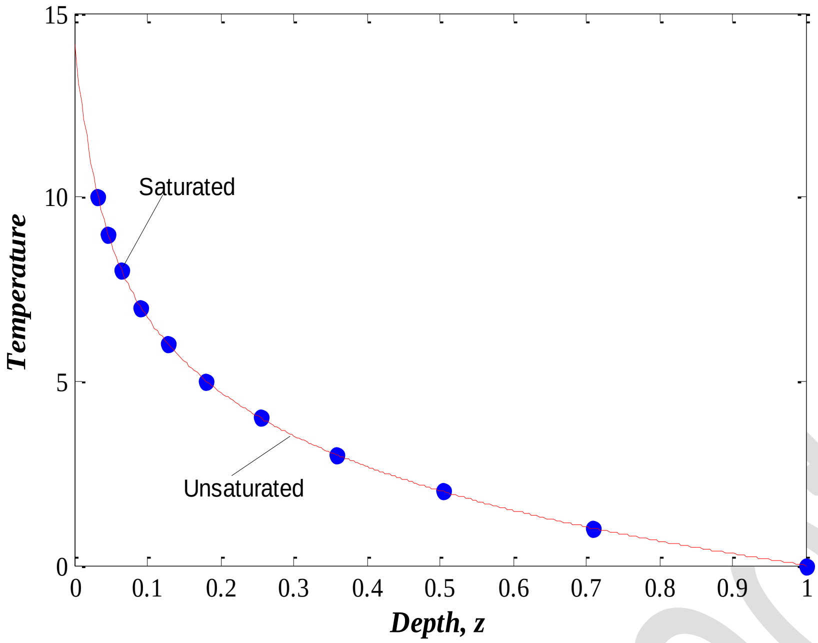

Figure 10: *Average ground temperature at increasing depth with constant values of the physical parameters for saturated and unsaturated silt.*

Similarly, comparing the effects of rising internal heat generation (Q) on ground temperature between ground containing saturated clay soil and ground with unsaturated clay soil at increasing depth, as shown in Figure 8, it is discovered that the average temperature of the saturated clay is greater than that of the unsaturated. It is also noted that the rate of increase in temperature of both states of clay are almost the same, but becomes more obvious when the heat generation rises the more. This result follows as above.

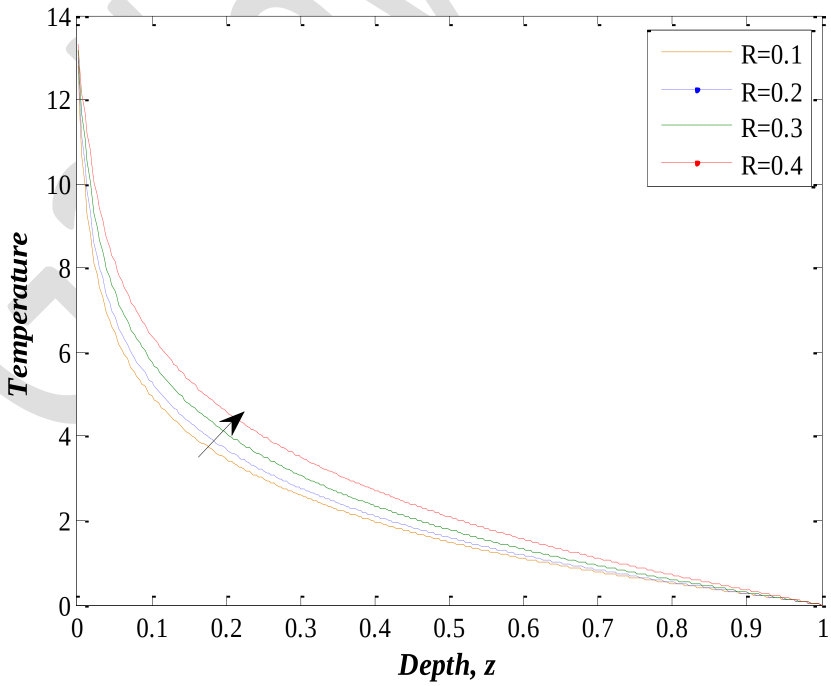

Figure 11: *Effects of mounting solar radiation (R) on ground temperature for saturated and unsaturated silt at increasing depth.*

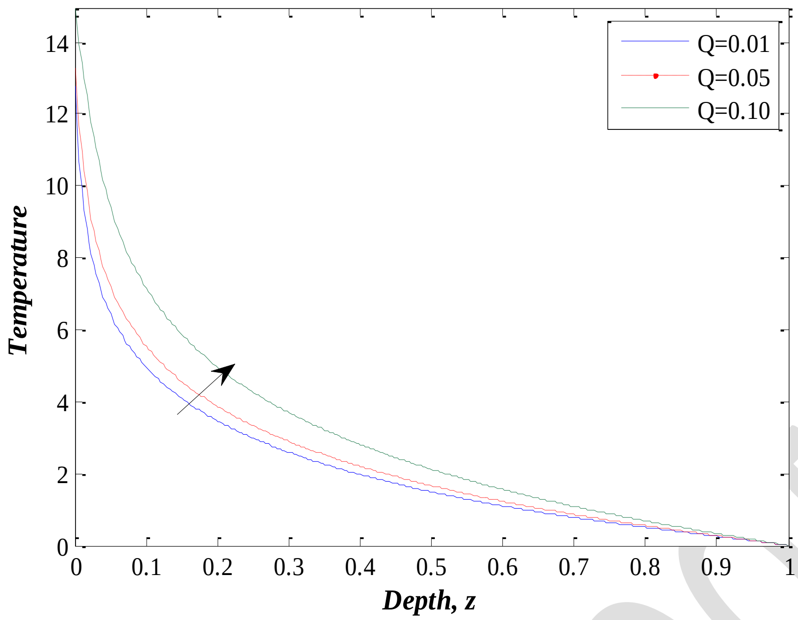

Figure 12: *Effects of growing internal heat generation (Q) on ground temperature for saturated and unsaturated silt at increasing depth*

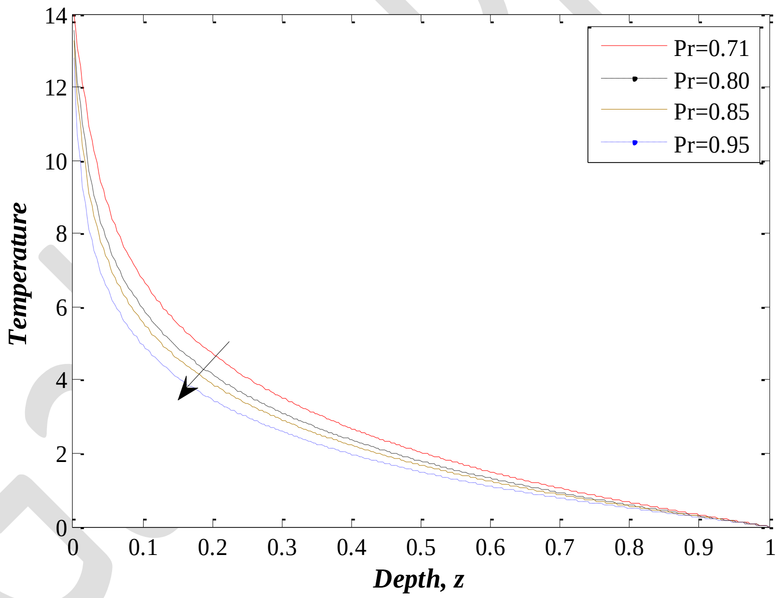

Figure 13: *Temperature profile for various values of Prandtl number for saturated and unsaturated silt.*

Figure 9 shows the temperature profile for various values of Prandtl number (P_r) for both saturated and unsaturated clay soil at increasing depth. The temperature of the saturated soil is still greater than the dry clay on an average. Since the difference in the thermal conductivities of both states of clay is not much pronounced (unlike that of sandy soil), variation in the rate at which heat diffuses away from the boundary layer between the two states of the clay is not also very significant.

As regard the silt, there is no significant difference between the dry soil and when the soil is saturated with water (Figures 10). Therefore, it is at the same level and rate that these physical factors (solar radiation, internal heat and Prandtl number) affected the soil both when its dry, and when it is saturated with water (Figures 11, 12 and 13).

6 Conclusion

This work has been focused on the effects of moisture content on the temperature of some selected soil samples, which includes sand, clay and silt, in the presence of internal heat. The results of the study show that saturated form of all these soils which enhances the rate of heat conduction will be more preferable especially for crops like okro which requires warmer temperatures of about 32 ^{o}C for the seedling and later transplanted into soils with about 24 ^{o}C for healthy growth, compare to plants like tomatoes, cucumbers and snap peas which require soil's temperature of about 16 ^{o}C. Also, since the rate and level at which moisture content affects the temperature of these soil, mixture of some of the soil types will be more appropriate in growing some crops. Meanwhile, thermal conductivity and the porosity are the only soil properties that were considered in the work. Since soil properties are not limited to the main three that were used in this present work, future work can then incorporate more of these properties which include; colour, mulch, pH and texture among others were not considered.

7 Declarations

7.1 Competing Interests

The authors thereby declare that there is no any conflict of interest in whatever way concerning the work.

7.2 Publisher's Note

AIJR remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

How to Cite this Article:

Will be updated in the final version.

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