Archives of Environmental Sciences and Environmental Toxicology

GAVIN PUBLISHERS

OPEN ACCESS

Du ZY, et al. Arch Environ Sci Environ Toxicol: AESET-108.
DOI: 10.29011/AESET-108. 100008.

Research Article

An Experimental Study of Soil Temperature Field of Earth-to-Air Heat Exchanger In Greenhouse

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Citation: Du Z Y, Cui S, Liu QG, Liu S, Tian H (2019) An Experimental Study of Soil Temperature Field of Earth-to-Air Heat Exchanger In Greenhouse. Arch Environ Sci Environ Toxicol: AESET-108. DOI: 10.29011/AESET-108.100008.

Received Date: 28 December, 2018; **Accepted Date:** 09 January, 2019; **Published Date:** 18 January, 2019

Abstract

This paper presents an experimental investigation into the temperature of the soil field around an earth-to-air heat exchanger and associated heat transfer between the soil and exchanger, which is regarded as a novel apparatus used for heating a greenhouse in an economic and energy efficient measure. Experimental testing was undertaken throughout a whole year at 2017 based on a sunlight greenhouse in Taiyuan city, Shanxi Province, China. The results show that when the inlet air velocity varied from 0.5 to 4.5 m/s, soil temperature around the Soil-To-Air heat exchanger and associated heat transfer rate between the passing air and the surrounding soil increased with the increase of air velocity, which led to the increased fluctuation scale of the soil temperature. Change in the inlet air temperature, based on the ambient temperature variation, led to the same form of variation in soil temperature. Temperature of the soil varied adversely against its distance to the central line of the pipe, with the inflectional radius distance of around 0.5m. This research has delivered a range of fundamental data applicable to analysis of the dynamic performance of the Earth-To-Air Heat Exchanger (EAHE) for solar greenhouse, thus contributing to the accelerated green agriculture development in China and worldwide, and further, to achieving the global targets in fossil fuel saving and carbon emission.

Keywords: Earth-To-Air Heat Exchanger; Experimental Investigation; Greenhouse; Soil Temperature Field

Introduction

Since the mid-1980s, in the district of 32°N ～43°N of north part of China, the solar greenhouse has been developed rapidly. According to the statistics, the area of this type of greenhouse reached $8.8×10^5 hm^2$, which makes up approximately a quarter of the agricultural facilities in China in 2010 [1]. The solar greenhouse was developed from the Chinese traditional greenhouse in Anshan, Liao ning Province. It is composed of (1) Back wall and east-west gable against the cool wind and prevent the heat exchange between inside and outside of greenhouse.(2) Front house roof for lighting. During the night, the outside of front house roof is covered by several heat preservation materials. In the morning after the air temperature inside greenhouse rises, the covering materials should be rolled up. In the afternoon, when the air temperature inside greenhouse down to 17℃～18℃ ,the covering materials should be put down to prevent loss of heat.(3) Back roof is connected with the front roof and back wall.(4) Cold-Proof Ditch to prevent the loss of heat through soil. However, the air temperature and humidity inside greenhouse with no heating devices cannot meet the production needs of the agriculture in cold areas. Therefore, we need to seek an energy saving through to regulate the air temperature and humidity in the solar greenhouse. Due to the delay effect of thermal response of soil, the sub-soil temperature is nearly constant throughout the year. Therefore, at a sufficient depth, the soil temperature is higher than ambie temperature in winter and lower in summer. In the solar greenhouse, the EAHE system uses underground soil as a heat source or sink and air as the heat transfer medium of heat exchange. The air is transported to the shallow surface and exchange heat, derived by the temperature difference between the soil and air. Then the air is transported to greenhouse, to lower indoor air temperature at daytime or sunny days and increase air temperature at night or cloudy day. By this way, we can save energy in daytime or sunny and use it in night or cloudy day. In addition, the ambient air is pre-heated in winter and Pre-Cooled in summer.The main advantages of this system are its simplicity and high cooling and heating potential. As a result, the use of the EAHE for cooling and heating agricultural greenhouses, public buildings and residences has gained much effort in the past several years [2-4].

Zeng and Wu, et al. [5,6] applied the EAHE to fresh air system. They concluded that, in northern China, cooling of fresh air by using EAHE was an effective approach to improve indoor air quality and to save energy in summer. Leyla Ozgener and Onder Ozgener [7] monitored thermodynamic and economic parameters of EAHE system for three heating seasons in greenhouse, applied this system in Turkey, and provided references for evaluating geothermal resources. Cui [8] proposed a transient and three-dimensional model to simulate heat transfer in an EAHE. He found that EAHE system had significant effects on cooling and dehumidification of greenhouse in north China during summer. Arif Hepbasli [9] investigated the EAHE system for greenhouse heating in Turkey during winter, and analyzed its performance at the aspects of both function and energy efficiency for the first time. Mongkon, et al. [10] applied EAHE system for cooling in an agricultural greenhouse under the tropical climate in Thailand. It was found that the implementation of the EAHE in a tropical climate was practical potentially, especially during summer. A fully transient three-dimensional numerical model was developed and described by Gauthier, et al. [11] for the thermal behavior of Soil Heat Exchanger-Storage Systems (SHESSs) associated with greenhouse. The model based on the coupled conservation equations of energy was validated against experimental data collected from an EAHE installed in an agricultural greenhouse. The results of the parametric study indicated that an air blowing velocity of 4 m/s was nearly optimal. Wu and Jiang, et al. [12,13] analyzed the effects of pipe depth, pipe length, pipe diameter, and duration of operation on air outlet temperature by using numerical simulation method. Taking the horizontal buried pipe of Ground-Source Heat Pump (GSHP) as the research object, Na, et al. [14-16] proposed a bi-dimensional dynamic mathematical model, and modeled and simulated the temperature field and the heat flow distribution for the horizontally buried pipes of the GSHP. Wu, et al. [17] utilized a commercial ANSYS to predict the soil temperature field around the horizontally buried pipe of GSHP both in winter and summer. Furthermore, the soil temperature field around the single pipe were compared with that around the double pipes in the same condition, and the effective thermal radius were gained, respectively. Cui, et al. [18] simulated the soil temperature profile around the horizontally buried pipe by using the MATLAB software. The results revealed that the soil temperature gradient was not equal in all direction.

However, most of modeling research focuses only on thermal performance and feasibility of EAHE system in buildings and greenhouses.Few efforts were taken to the soil temperature field of EAHE system. As the largest mass part of the greenhouse system, soil plays an important role for the growth of the crops. And soil temperature is one of the key factors impacting the thermal performance of EAHE [19]. In this paper, the soil temperature field was analyzed based on the continuous testing of soil temperature around the EAHE with different air-in velocity. The research can be utilized for providing the basis for the optimization design of pipe distance and pipe depth, and reliable experimental data support for the application of EAHE in the north of China.

Experimental Greenhouse

The experimental greenhouse is located in Xiaodian District in the city of Taiyuan (112˚33E, 37˚54N), Shanxi Province, China. The experimental greenhouse faces to the south with the size of 63 m (from east wall to west wall) by 9.7m (from south wall to north wall). The back wall (thickness of 1m) and side walls (0.65m) were built of hollow brick and red brick. The experimental greenhouse is covered by polyethylene membrane of 0.2 mm thick with steel stricter as the support. It is equipped with a thermal curtain and a standard ventilation equipment. However, it is not equipped with any heating equipment. The EAHE system is made of 16 PVC (polyvinylchloride) pipes. Two rows of 8 pipes, 20m long, are buried at 1m and 2m depths, respectively. The pipes are parallel to the longitudinal axis of the greenhouse and are spaced 1m apart. The section diagram of EAHE system is shown in (Figure 1).

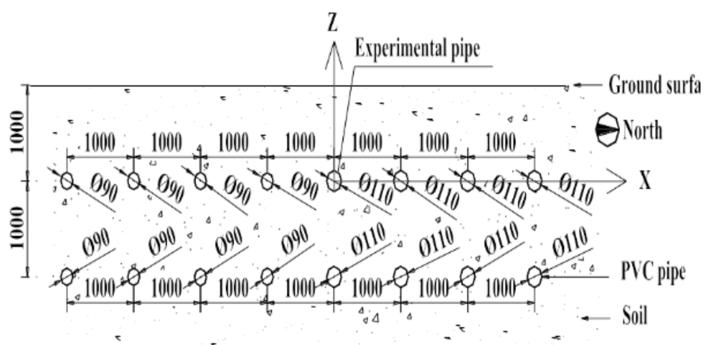


Figure 1: The section diagram of EAHE system.

Experimental Equipment and Measured Points

Measured Points

In order to determine soil temperature change around the buried pipes in EAHE, we select the pipe with the diameter of 110 mm at the depth of 1 m as investigated pipe. In this paper, 3D Cartesian coordinates system was set up by taking the north as X-axis, air flow direction as Y-axis, and vertical direction as Z-axis. The measured points of soil temperature on Y=1.3 m cross section are shown in (Figure 2).

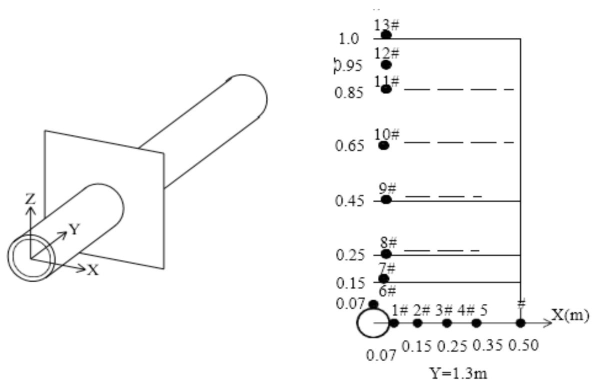


Figure 2: The measured points of soil temperature on Y=1.3 m cross section.

Experimental Equipment

The inlet of EAHE was connected by an elbow with a 0.73kW, single phase, variable speed motorized blower (GXF-II-4A, maximum flow rate of 1.06 m^3/s, and maximum speed of 1450 rpm). Ambient air was blown intoand through the buried pipes. Twelve air temperature and humidity sensors (LTM8901,±0.5℃, ±3% RH, resolution of 0.0625 ℃, and 0.5% RH) were inserted at the center of the experimental pipe along the length at a horizontal distance of 0m, 1.05m, 1.35m, 2.1m, 2.9m, 4.1m, 5.5m, 7.2m, 9.15m, 11.15m, 14.2m and 17.2m, respectively, from the upstream end to measure air temperature and humidity. Eight resistance temperature detector temperature sensors (DS18B20, accuracy of ±0.2℃ and resolution of 0.033℃) were mounted at a depth of 0.07m, 0.15m, 0.25m, 0.45m, 0.65m, 0.85m, 0.95m and 1.0m, respectively, to measure soil temperature at different depths. One additional temperature sensor was inserted at a distance of 15 m away from the EAHE system at a depth of 3m in the ground to measure the undisturbed soil temperature. Five resistance temperature detector temperature sensors at axial distance of 1.3m from the inlet of EAHE were also installed to measure the temperature of soil at a distance of 0.07m, 0.015m, 0.25m, 0.35m, and 0.5m from the pipe surface, respectively. Air flow velocity was measured with the help of a digital anemometer (QDF-6, range of 0-30 m/s, accuracy of 3 % and resolution of 0.1 m/s). The data logging system was programmed to record and store the testing data at every 2 min interval during the whole testing period.

Results and Analysis

Variation of The Soil Temperature Around The Buried Pipe With The Time of Operation

(Figure 3) shows the changing of soil temperature with the duration of operation in X and Z directions. The soil temperature in X direction had different changing trend from the soil temperature in Z direction during EAHE operation.

In this section, experimental data from January 21 to January 24 in 2017 were adopted. The EAHE inlet air flow velocity was 4.5 m/s during the operation time. As shown in (Figure 3(a)), during daytime the air temperature was high, soil temperature increased continuously providing cooling effect. Although the soil

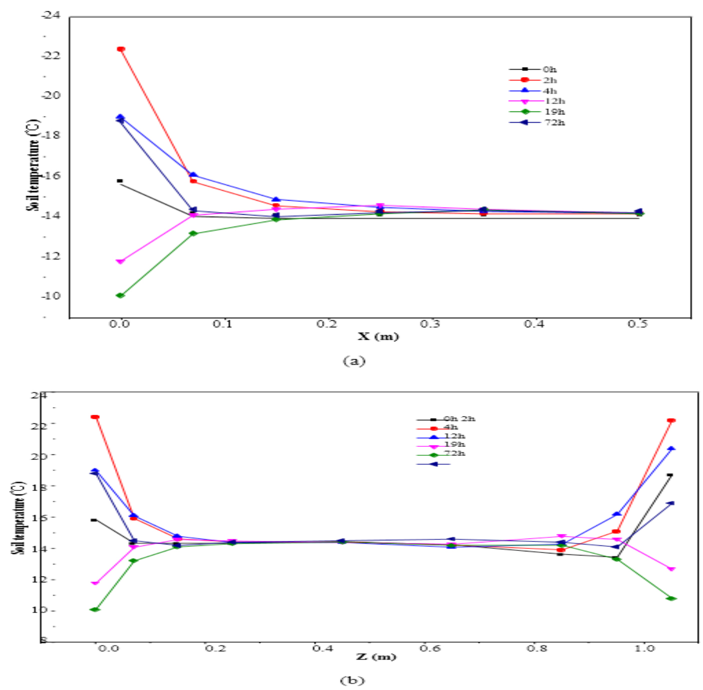


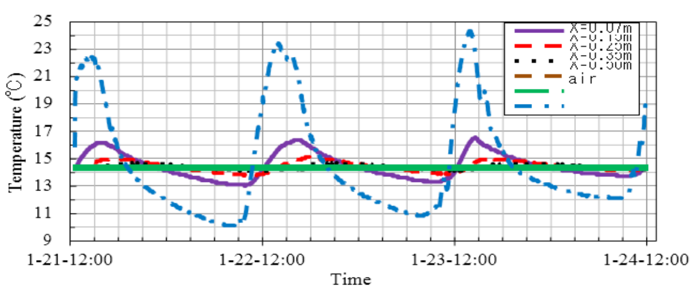
Figure 3: The temperature profiles of soil in **(a)** X direction **(b)** Z direction.

temperature decreased gradually along the radial direction, the decreasing rates dropped with the increase of the distance away from the pipe surface.During nighttime air temperature went down and cooled the sub-soil. Therefore, the soil temperature during the nighttime had different changing trend from the soil temperature during the daytime. It was observed that the soil temperature decreased gradually along the radial direction. When the distance was far enough, the soil temperature was equal to the soil initial temperature.The soil temperature in X direction away from the pipe surface 0.07m and 0.15m dropped to 14.1℃ and 14.6℃ after 12 h, respectively. The temperature of soil 0.25m and 0.35m away from the pipe surface remained unchanged after 12 h. The soil temperature rise decreased when the distance from the EAHE surface increased after 72 h, the soil temperature of soil 0.5 m away from the pipe surface increased just 0.1℃.

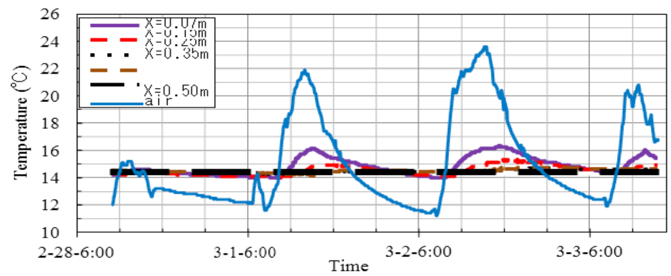
It can be seen from (Figure 3(b)) that the soil temperature near the pipe surface and ground surface had higher amplitude than that far away from the pipe surface and ground surface, respectively. The soil temperature changing rate decreased, and then increased with increase of the distance away from pipe surface in Z direction. However, the soil temperature changing rate close to the ground surface was faster than that near the pipe surface. The influence of EAHE system on soil temperature was predominant in the first 0.25m in Z direction away from the pipe surface. The soil temperature had the same changing trend as the inlet air temperature in this region. The effect of solar radiation, indoor air temperature, air velocity and air relative humidity on soil temperature was predominant in the last 0.55m in Z direction. The soil temperature of the other region was less affected by outside, which remained unchanged.

The Soil Temperature Profiles in X Direction Under Different Air Velocity

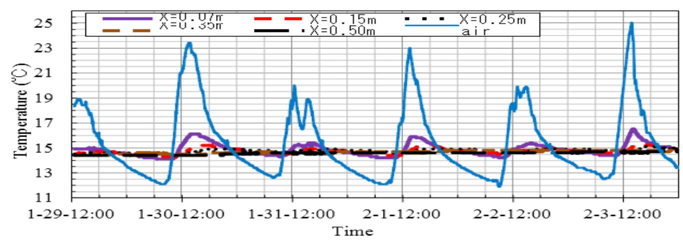
Influence of air velocity on the soil temperature in X direction is illustrated in (Figure 4). It has been observed that the soil temperature in the immediate vicinity of buried pipe changed more rapidly than that far away from the pipe surface. Furthermore, the amplitude of soil temperature decreased gradually along the X direction from the pipe surface. As shown in (Figure 4), the soil temperature at 0.5m in X direction away from the pipe surface was not affected by EAHE with a constant value. The reason is that the ability of heat transfer in the immediate vicinity of buried pipe was strong due to the large temperature difference between air and soil. The heat capacity in the soil dissipated gradually and the dissipation propagated towards away from the pipe surface. When the air velocity was 1.5 m/s, the soil temperature at 0.3m in X direction away from the pipe surface was not affected by EAHE. When the air velocity was 0.5m/s, the soil temperature in X direction away from the pipe surface 0.25m was not affected by EAHE with a constant value of 14.4 ℃. The affected soil thickness under low air velocity was greater than under high air velocity. Thermal influencing radius under the air velocity of 0.5, 1.5, 3.5, and 4.5m/s were 0.25m, 03.5m, 0. m and 0.25m within 72 h in X direction, respectively.



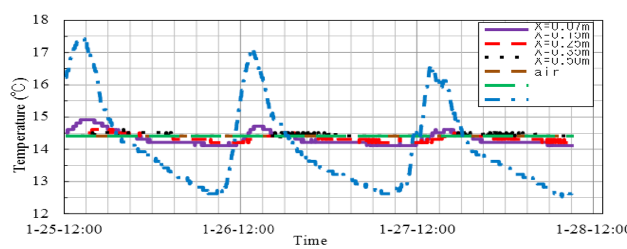
(a)



(b)



(c)



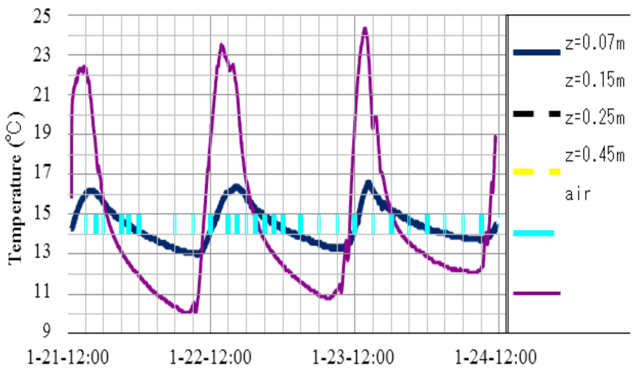
(d)

Figure 4: The soil temperature profiles in X direction under different air velocity **(a)** 4.5 m/s **(b)** 3.5 m/s **(c)** 1.5 m/s and **(d)** 0.5 m/s.

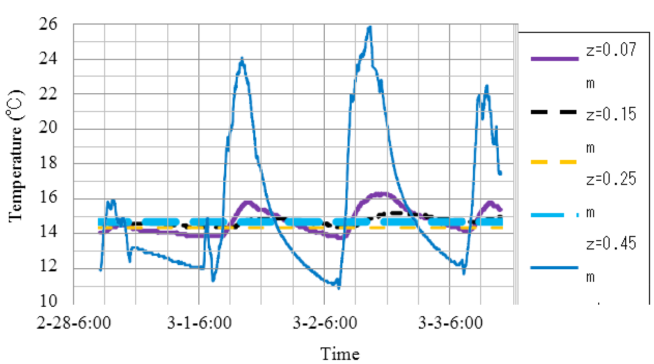
The Soil Temperature Profiles in Z Direction Under Different Air Velocity

The soil temperature profiles at the different distance from 0.07m to 0.45m away from the pipe surface in Z direction are plotted in (Figure 5). It can be seen from (Figure 5) that the effect of air on the soil temperature close to the pipe surface was greater than that far away from the pipe surface in Z direction in terms of magnitude and variation. The soil temperature had the maximum amplitude, and the temperature response of soil was most notable at 0.07m in Z direction away from the pipe surface.The soil temperature changing rate decreased gradually with the increasing distance in Z direction. As the radial distance increased, however, the delayed thermal response of soil increased rapidly.When the distance was far enough, the soil temperature was equal to the soil initial temperature. When the air velocity was low, the time of air staying in the pipe was long. Hence, the amount of heat transfer by the air was more than that of high air velocity. As seen in (Figure 5), when the air velocity was 1.5 m/s, the soil temperature in Z direction away from the pipe surface at 0.15m depth was not affected by EAHE. When the air velocity was 0.5 m/s, the soil temperature at 0.07 m depth in Z direction from the pipe surface kept a constant value of 14.3℃. As a result, the affected soil thickness under the air velocity of 0.5 m/s, 1.5 m/s, 3.5 m/s, and 4.5 m/s were 0.25 m, 0.25 m, 0.5 m, and 0.5 m within 72 h in Z direction, respectively.

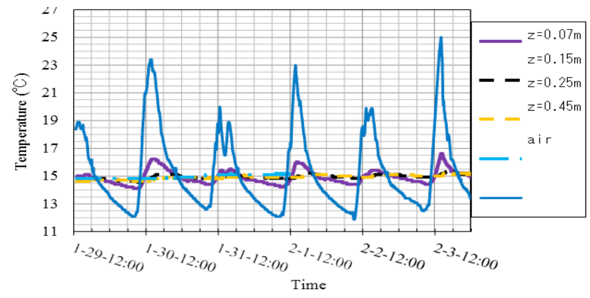
Furthermore, the influence of solar radiation, indoor air temperature, air velocity and air relative humidity on soil temperature was predominant in the last 0.55 m in Z direction. The soil temperature had obvious relation to the velocity of air in this region.



(a)



(b)



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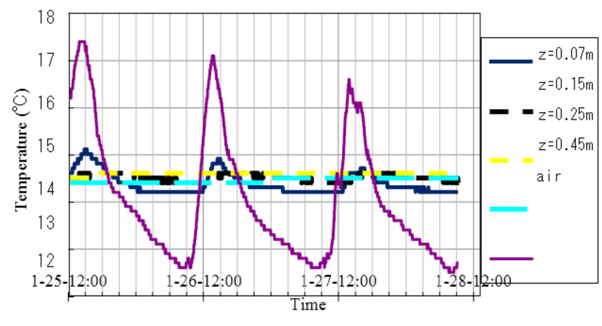

(d)

Figure 5: The soil temperature profiles in Z direction under different air velocity **(a)** 4.5m/s **(b)** 3.5m/s **(c)** 1.5m/s and **(d)** 0.5m/s.

Comparison of the soil temperature in X and Z Directions

By analyzing the soil temperature in X and Z directions, it is found that the decay and delay degrees of soil temperature wave were different despite that the soil temperature had the similar changing trend in two directions. (Figure 6) shows the soil temperatures in X and Z directions under the air velocity of 4.5 m/s. As seen from (Figure 6), it is found that curves for soil temperature at 0.07 m in X and Z directions away from the pipe surface were complete overlapped. However, there were distinct difference in soil temperature between X and Z directions at 0.15 m away from the pipe surface. First, the amplitude of soil temperature at two positions were different. The soil temperature at 0.15m in X direction from the pipe surface fluctuated in the range of 13.6 to 15.1℃. The amplitude of the temperature was about 0.75℃. However, the soil temperature at 0.15m in Z direction from the pipe surface fluctuated in the range of 14 to 14.9℃. The amplitude of the temperature was about 0.5 ℃. In addition, the highest difference (positive) was noticed between X and Z directions away from the pipe surface at 0.15m, which reached at the value of 0.2℃ during daytime.

However, the soil temperature at 0.15m in X direction from the pipe surface was lower than that in Z direction, which was lower than 2℃. The soil temperature at 0.15m in X direction from the pipe surface lagged behind that in Z direction.

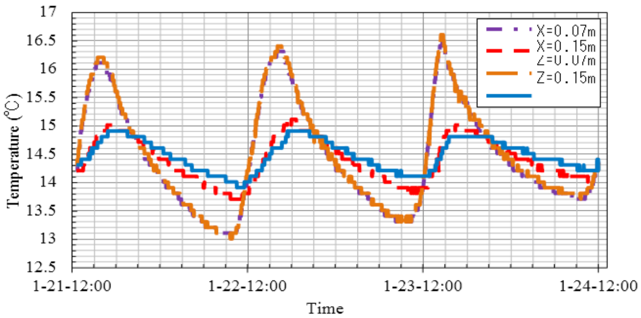

Figure 6: Comparison of the soil temperature in X and Z directions.

Conclusion

The heat transfer process between air and surrounding soil was simplified in the study by just considering the heat transfer by convection. The soil temperature increases during the daytime in winter when the indoor air temperature is higher taking advantage of forced convection between air and surrounding soil. On the one hand, the air inside the EAHE is cooled down along the length reducing the heat transfer and consequently loosing lesser thermal energy to the soil, on the other hand, the soil temperature increases with the time of operation and consequently the temperature difference between the air and soil temperature is smaller. Furthermore, the moisture movement in the soil is driven by the temperature gradient. Simultaneously, the moisture trend to redistribute itself under the created moisture gradient. After the use in days, the soil temperature close to the pipe surface is higher than that of away from the pipe surface. Accordingly, soil moisture migrates under temperature gradient from the higher temperature regions to the lower temperature regions. The soil thermal conductivity decreases along with the decrease of soil moisture content. Therefore, the heat transfer dissipates gradually. As a result, the heat transfer process air and surrounding soil is a dynamic process, which is neither subjected to Dirichlet boundary condition nor subjected to Neumann boundary condition [20].

The experimental study of soil temperature was conducted for an EAHE system installed in an agricultural greenhouse. The main conclusions are summarized as below:

- The soil temperature close to the pipe surface was more sharply than that far away from the pipe surface in X direction. In addition, the amplitude of soil temperature was also much larger. The soil temperature near the pipe surface and ground surface had higher temperature changing rate than that far away from the pipe surface and ground surface in Z direction. However, the soil temperature gradient was much larger near the ground surface that affected a wider range.
- The penetration of heat in radial direction was not beyond 0.5m. Therefore, the pipe centers were separated by one m, and 110mm diameter tubing was reasonable.

Acknowledgement

This study was supported by the National Nature Science Foundation of China (NO.51476108).

Conflicts of Interest

The authors declare no conflict of interest.

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