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ANALYSIS, DESIGN AND TESTING OF AN EARTH CONTACT COOLING TUBE FOR FRESH AIR CONDITIONING

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ABSTRACT

Based on a theoretical analysis of small-scale experiments, a 57 m earth contact cooling tube was designed, constructed, and tested to provide cooling for residential buildings and related applications. Warm outside air is drawn through the tube and its heat is absorbed through the tube walls into the surrounding soil. The cooled air then enters the building. Our study investigated cooling performances at different air velocities and soil saturation in test run durations up to 30 days. Experiment results demonstrated that this system could provide up to 1.5 tons of cooling at a flow rate of 1600 cubic meter/hour during hot summer days. This study concluded that earth-cooling tubes are a feasible air-conditioning option for cooling demands in the Midwest, U.S.A. This system requires very little energy. Thus its use is especially interesting in areas where energy generation or supply is problematic. This paper presents the earth contact tube system, structure details of the system, and experiments.

INTRODUCTION

Cooling and heating are major energy sinks for residential and commercial properties. Common cooling systems use heat pumps or air-conditioner to chill air that will be distributed throughout a building. These systems with high-energy usage often cannot provide cooling during times of power failure. Low-energy consumption solutions could make residential and commercial systems more independent. With appropriate photovoltaic support and battery backup, these systems could be entirely self-sufficient.

Reports on cooling tube performances suggest there is a great potential for using cooling tubes for air conditioning. Systems like this are commonly referred to as “cooling pipes”, “earth pipes”, “earth tubes”, and “earth contact cooling tubes”. In such systems, the initial air supply enters a building through an underground pipe. With the average ground temperature being 12-15°C (55-60°F) at a depth > about 1.2 meter / 4 feet (depending on the geographical location), this initial air is cooled passively via heat loss into the surrounding soil without the need for energy. The culvert-cooling tube, due to its unusually high-energy efficiency, is highly recommended for low-energy use air conditioning.

The potential cooling ability of cooling tubes has been documented. Viera et al. (1984) have simulated the performance of earth tube cooling systems with fan cycling in four southeastern cities. They concluded that earth tube cooling could meet the entire sensible load in moderately hot climates [1]. Francis (1981) describes a case study of a system of two 400-foot long cooling pipes with a COP of 18.5 [2]. In this study it was concluded “most of the cooling takes place in the first 200 feet of the tubes”.

A theoretical model by Wang et al. estimated a cooling potential of about 12,000 BTU/h for a 200 ft cooling tube with a diameter of 1.5 ft placed between 8 to 12 feet underground [3]. Newman performed several tests on different types of cool tubes with variable airflow rates (for more detailed description of Newman’s methods see Chen et al. [4]). The attained cooling performances of each tube were matched with its theoretical model. The results predicted that a 200 ft. tube with a diameter of 1.5 ft. buried in a depth of 10 ft. could have a cooling capacity of about one ton of cooling (12,000 BTU/h; 3.5 kW).

To verify the predictions of Newman’s study and examine the potential cooling effect, a 188 ft cooling tube was designed and installed at the University of Nebraska’s Passive Solar Energy Research Test Facility. The objective of this study was to explore the cooling effects of a cooling tube on a residential building for possible application to other residential/commercial buildings.

NOMENCLATURE

CE cooling effect, W
CE_{ct} cooling effect for cooling tube, W
CE_r cooling effect for room, W
FR air flow rate, m³/h
T temperature, °C
T_a ambient temperature, °C
T_{ci} temperature cooling tube inlet, °C
T_{co} temperature cooling tube outlet, °C
T_r room temperature (inside house), °C
c_p specific heat energy, J/kg °C
m mass, kg
ΔT temperature difference, °C
ΔT_{ct} temperature difference between cooling tube in- and outlet, °C
ΔT_r temperature difference between cooling tube outlet and room temperature, °C

Material and Methods

In 1990, the University of Nebraska installed a 57 m (188 ft.) long cooling tube at the Passive Solar Research Test Facility (Solar Site; Figure 1). The Solar Site is a one-story house (16 by 64 feet) designed to investigate alternative heating and cooling experiments and their potential for commercial and residential use. Besides the modified Cool-Storage Roof and the Ground-Source-Heat-Pump system, a cooling tube has been installed. The room's large south window front and the concrete slab create a high cooling load for the summer season.

The cooling tube enters the Solar Site through its concrete slap from the south side and runs southeast to northwest. The 0.45 m (18 inch) diameter culvert tube made of 1/32-inch corrugated steel was installed at a depth of about 3 meter (10 foot). Holes were drilled into the bottom of the tube over the entire length to allow moisture to trickle out. Before the cooling tube was lowered into its position, a sand bed was situated at the bottom of the construction trench to hinder moisture build-up beneath the tube. The soil surrounding the cooling tube was characterized as loess and its thermal conductivity determined as being 2.3258*10-3 W/m°C by Magdanz [5]. The air enters into its slanted inlet, flows through the horizontal part until it's directly underneath the building (Figure 1). A right angle directs the air straight upwards for the 3.6 m (12 ft) tall exit that ends 0.45 m (2 ft) above the floor inside the building. A fan and a damper are mounted on top of the tube exit. The fans power amounts to approx. 560 W (3/4 HP). The damper was calibrated for several flow rates using the same fan speed. During the experiments, the flow rate was set at a certain position with a continuously running fan for the entire test. The flow rate was measured using a FlowHOOD. The fan installed at the return end draws air through the pipe, thus setting the room space under positive pressure and therefore minimizing the effect of infiltration of ambient air [6]. Unfortunately, even with a set damper position the air flow will still vary according to the outside wind conditions. Tube-internal air flow meters are planned to be installed as the experiments continue.

Temperature sensors were installed internally throughout the entire tube at 10 ft intervals. Ground temperature sensors were installed at three locations above the pipe to study the influence of the cooling pipe to the surrounding soil. The cooling tube ground temperature sensors (also known as Culvert Pipe Ground Temp. Sensors) were installed at three different locations along the buried pipe directly above it. The first is found 2m away from the house towards the pipe inlet, the second 23 m toward the pipe inlet, and the third is situated about 12 m away from the pipe inlet toward the house.

The ground temperature reference sensors were installed at the west side of the Solar Site (3 m away from the house), isolated from all ground heat energy exchangers (SLINKYS and Cooling Tube). This sensor group is located north of a large bush, thus is almost shaded all day long. As a result its temperatures are consistent lower than the temperatures of the cooling tube, which are situated in the open field.

All temperature sensors are type-T thermocouples.

The temperature sensors and various ambient sensors were integrated in the on-site system-control and data-logger unit. The National Instruments LabVIEW software was used to create a custom program that can record and control the various systems housed at the Solar Site.

Following figure demonstrates the test sites and cooling tubes properties.

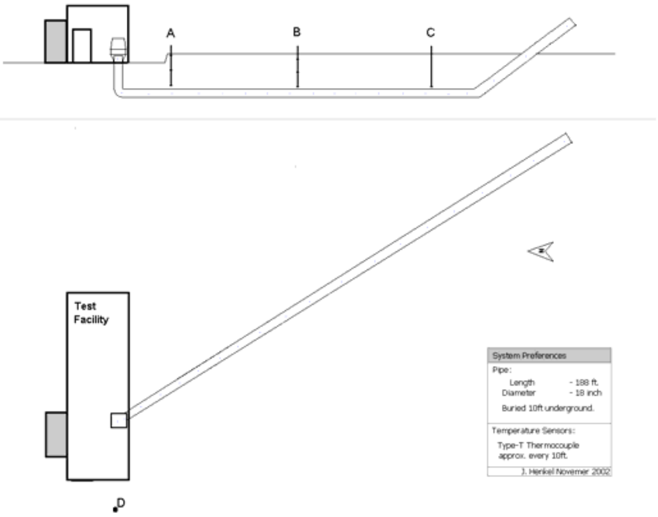

Figure 1 Solar Site Plan

Following temperature sensors were recorded during the tests:

Name	Location	Depth in m (ft)
Ambient 1	Ambient	n/a
SE 4’	Inside	n/a
#CP1-T	A	0.15 (0.5)
#CP1-M	A	1.4 (4.5)
#CP1-B	A	2.7 (9)
#CP2-T	B	0.6 (2)
#CP2-M	B	1.5 (5)
#CP2-B	B	2.9 (9.5)
#CP3-B	C	2.9 (9.5)
#Ground Ref.-T	D	0.6 (2)
#Ground Ref.-M	D	1.5 (5)
#Ground Ref.-B	D	2.9 (9.5)
#0 Pipe TC_(°F)	Cooling Tube Inlet	
…	…	
#19 Pipe TC_(°F)	Cooling Tube Return	

Table 1 Installed Sensors

The Locations A, B, C, and D according to Figure 1.

The Cooling Pipe temperature sensors *#0 Pipe TC_ (°F)* to *#19 Pipe TC_ (°F)* are installed at 10-foot intervals throughout the entire pipe.

The cooling performances were calculated using standard heat energy formulas that were incorporated for this application [7].

We also have to differentiate between the cooling effect on the air drawn through the cooling pipe and the effective cooling effect on the room space. The cooling effect on the air drawn through the cooling pipe describes the heat energy being extracted from the outside air as it passes through the conduit.

$$CE_{ct} = FR * c_p * \Delta T_{ct} \qquad (1)$$

With, the assumption that T_a equals T_{cti}: $\Delta T_{ct} = T_a - T_{cto}$

The cooling effect on the inside air of the building can be illustrated as:

$$CE_r = FR * c_p * \Delta T_r \quad (2)$$

With: $\Delta T_r = T_r - T_{cto}$

Experiments

Two long-term experiments were conducted.

Test ONE ran from 12 July to 12 August 2002 (30 days) at a flow rate of 1320 m^3/h (800 cfm; velocity: 2.3 m/s). The ambient temperatures varied between 15.5°C (60°F) at night to 37.8°C (100°F) during day hours. The test will be addressed as Test ONE below. The flow rate was measured as 797.2 cfm (SD 18.22).

Test TWO ran from 30 August to 9 September 2002 (ten days). The flow rate was set to 1680 m^3/h (1000 cfm; velocity: 2.9 m/s). Ambient Temperatures varied between 18°C (65°F) and 35°C (95°F). This test will be addressed as Fall TWO below. The flow rate was measured prior the test as 1003.17 cfm (SD 9.15).

Results

The results of test ONE will be discussed below.

The flow rate during the entire test was 1320m^3/h (800 cfm). The ambient temperature ranged between 12 °C (55 °F) and 39°C (102 °F) (Figure 2).

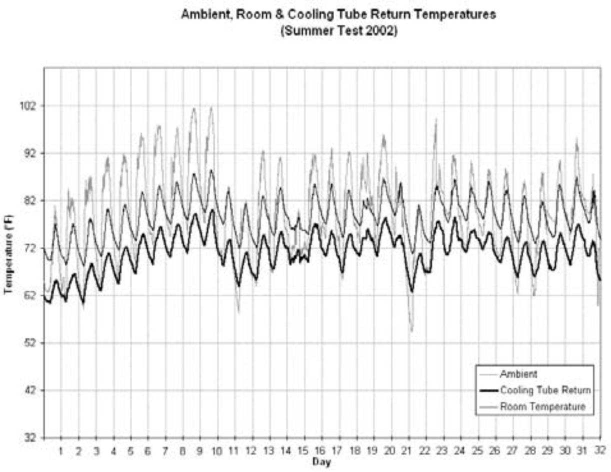

Figure 2 Ambient, Room and Cooling Tube Return Temperatures (Summer Test)

For most of the test the ambient temperature reached its maximum of above 32°C (90 °F). The daily temperature cycle covered a range of 12 °C (approx. 20 °F).

The cooling effect for the time was between 1.7 to 3 kW (5000 to 10,000 BTU/h) (Figure 3). After an initial decrease from 3 kW it reaches its maximum of 3 kW every day during the warmest hours of the day. The cooling effect of the cooling tube (between cooling tube inlet and outlet) surpasses 3.5 kW (12,000 BTU/h) almost every day. A negative cooling occurs if the ambient temperature drops below the temperature inside the cooling tube.

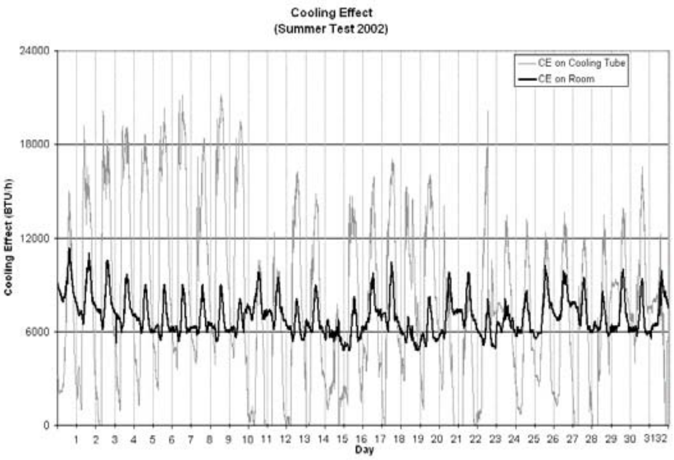

Figure 3 Cooling Effects (Summer Test)

Following figure will illustrate the ground temperatures at the undisturbed location (Figure 4). You will notice a slight increase of there values due to the warming of the soil through sun radiation during the summer. The increase amounts to about 2.2 °C (4 °F). Again, the location of the ground reference temperatures is shaded most of the day due its placement on the north side of a large brush.

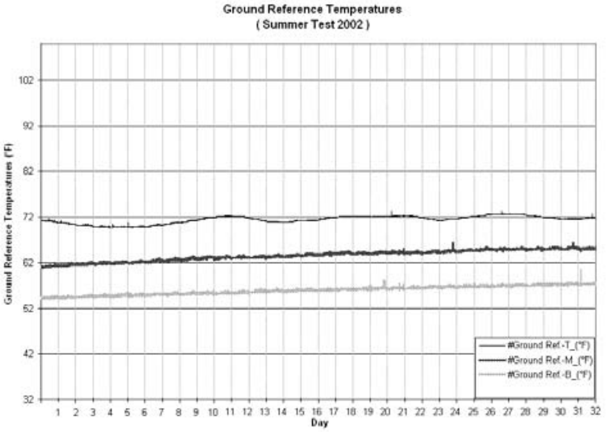

Figure 4 Ground Reference Temperatures (Summer Test 2002)

When looking at Figure 5, the ground temperature near the top of the soil follows the daily cycles closely. This can be ascribed to its low buried depth of only 6 inches. The sensor location near the cooling tube indicates a close following of the temperature of the cooling tube temperature cycle. The sensor at the location in the middle (CP1_M, installed depth 4.5 ft) shows no obvious relation to the daily temperature cycles of its neighboring sensors. It can be concluded that the heat influence of soil surface or the cooling tube the at this point is marginal. The temperature at CP1_M increases only by 1.4 °C (2.5 °F) throughout the entire test.

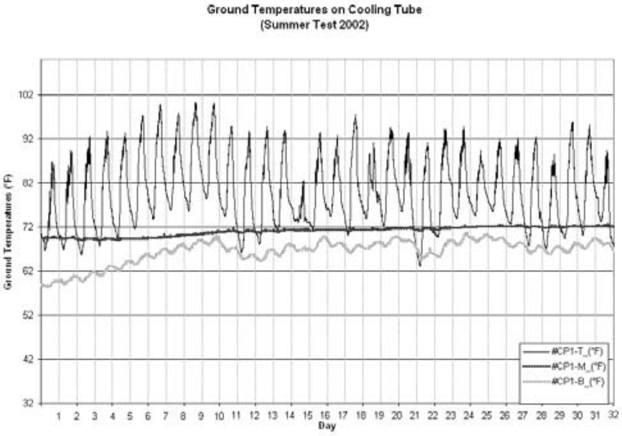

Figure 5 Ground Temperatures on Cooling Tube (Location CP1 - Summer Test)

The temperature near the cooling tube (CP1_B) fluctuates but establishes a semi-stable state after the first third of the test trial. Even after a warm-up of 5 °C (9 °F), the cooling tube is still able to supply sufficient cooling (see Figure 3). The average COP for the entire cooling time of test ONE is 4.4. The maximum COP reached eleven.

To illustrate a daily cycle of temperatures as well as the cooling please refer to Figure 6.

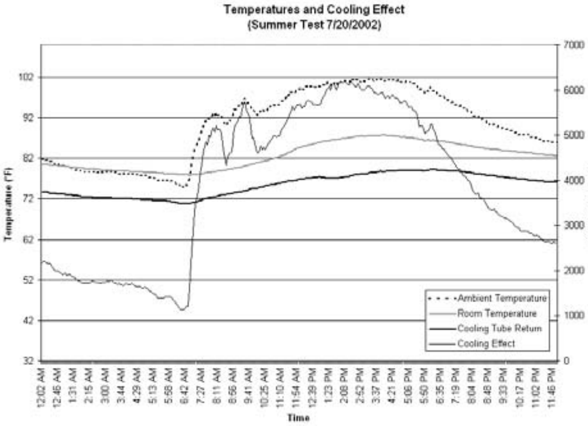

Figure 6 Temperatures and Cooling Effect (7/20/2002)

Following chapter will discuss the results of test TWO.

The flow rate being used was 1680m^3/h (1000 cfm).

The ambient temperature was moderate between 35 °C (95 °F) during the day and 18 °C (65 °F) at night, except on cold night with temperatures down to 11 °C (52 °F) (Figure 7).

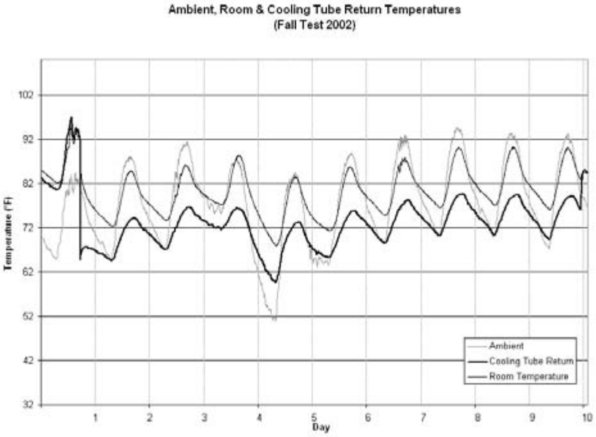

Figure 7 Ambient, Room and Cooling Tube Temperatures (Fall Test 2002)

The cooling effect (CE_r) amounted to values between 2.3 and 3.5 kW (8,000 and 12,000 BTU/hr) (Figure 8). The highest values were recorded during the hottest hours of the day, 2 pm to 5 pm. During these times – when chilling is needed the most- the cooling effect reached its maximum of 3.5 kW almost every day. The CE_{ct} averages in its maximum between 3.8 – 5 kW (13,000 – 17,000 BTU/h) .

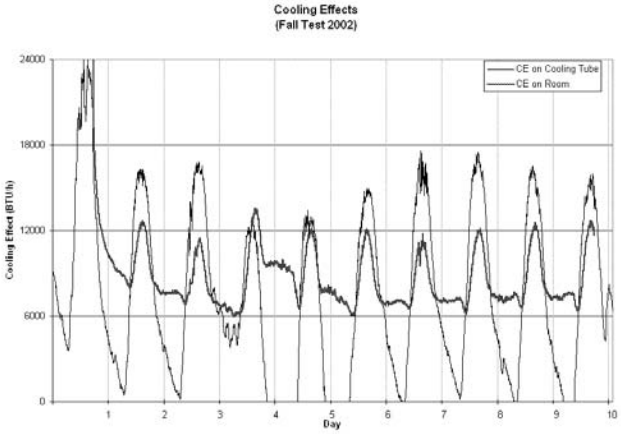

Figure 8 Cooling Effect Fall Test 2002

The ground temperatures (Ground Reference temperatures) in undisturbed soil were almost entirely steady throughout the test duration. The deeper the sensor was installed the lower the indicated temperature (Figure 9).

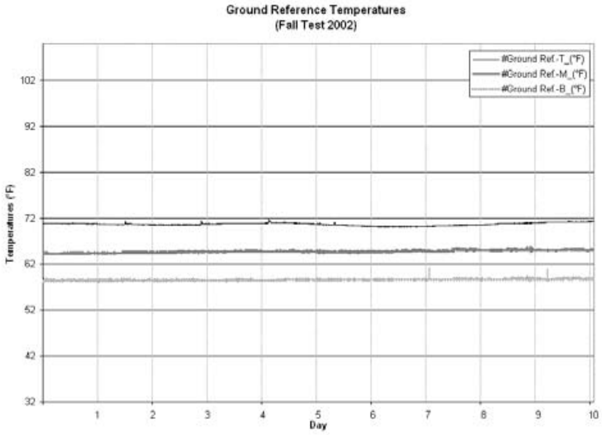

Figure 9 Ground Reference Temperatures (Fall Test 2002)

Ground temperatures at the cooling tube close to the surface followed the daily temperature cycles closely. Sensor CP1_T follows the ambient temperature more rapidly due to its low buried depth of only 6 inches (Table 1). The ground temperatures close to the cooling tube did follow the daily cycles of the air temperature passing through. However ground temperatures situated more than 4 feet away from the pipe weren't much effected (Figure 10). Soil temperature saturation has been observed but the cooling tubes performance did not drop considerately throughout the test. Soil temperature saturation could be characterized as the soil reaching the temperature of the air passing through the cooling tube. If there is no difference between the temperatures of the passing air and the tube no cooling can be achieved. The sensor installed directly above the cooling tube (CP1_B) indicated saturation throughout the test. It follows the diurnal temperature cycles and increases in its average throughout the test. Sensor CP1_M, installed at a depth of 4.5 feet (half way down to the tube), does not show a fast reaction to the heat being absorbed by the soil surrounding the cooling tube. It does increase but only be 1 °C (2°F).

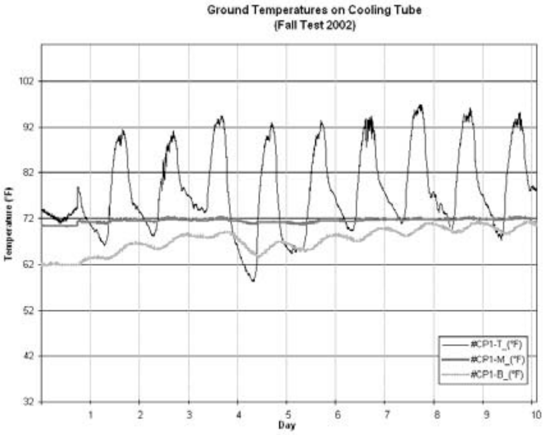

Figure 10 Ground Temperatures on Cooling Tube
(Location CP1)

The COP of test ONE averages at 4.2 with its maximum at 8.6.

Conclusions

It has been shown that a cooling tube of that length (approx. 200 ft) can provide a cooling effect of 12,000 BTU/h as predicted by T.C. Wang. A 560 W fan coupled with this system can supply a cooling of up to 6 kW. An average COP of 4 makes it a promising alternative to less efficient air conditioning systems. Even after a continuous run of a month the system is able to contribute to the cooling of the house. Although the soil around the tube did warm up, the systems cooling performance did not drop essentially - during test ONE the cooling effect of the last days always reached 3 kW. Continuously seasonal testing could provide more test data of ground temperatures around the cooling tube and their saturation characteristics. Also, the system was tested under continuous running conditions that are probably unrealistic. The usual running cycle would allow the system to be shut down during the night and give the soil time to regain its initial condition.

However no measurements of humidity were taken during these test trials. It has to be mentioned that air humidity control is of importance for venting outside air straight into commercial as well as residential spaces. Further studies are needed to investigate its relevance for this system.

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