ARE EARTH TUBE HEAT EXCHANGERS OF INTEREST WHEN HEATING BUILDINGS?

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Abstract

It is a well known fact that the temperature of the soil, some meters below the surface, is relatively stable. If this heat could be utilized by use of an earth tube heat exchanger, significant benefits could occur when space heating for buildings is considered. The inlet ventilation air is then led through a long earth tube and when the air passes the pipe it will take up, or leave, heat to the surrounding soil depending on their relative temperatures. In this paper two case studies are presented. The buildings of concern are sited in the vicinity of Linköping, about 200 km south of Stockholm, Sweden. One of the cases utilizes heat from the earth tube in an air-to-water heat pump, while the other uses an air-to-air heat exchanger. The studies show that the earth tubes only to a very low degree contribute to the need of added heat in order to achieve a desirable indoor climate. Hence, the extra cost for the tube will not be balanced by the decreased cost for space heating. This discouraging result might depend on too short heat pipes or the fact that the difference in temperature between the passing air stream and the surrounding soil was too small.

INTRODUCTION

A few meters below the earth surface the temperature of the soil is rather stable. Even during hard winters the temperature will be well above zero °C and water pipes et c. will not freeze. However, a colder climate indicates that the amount of soil above the pipes must be increased in order to achieve permanent non-freezing conditions. For the site Linköping, which is dealt with here, the soil depth must be about 1.5 meters to ascertain that freezing does not occur. If this heat could be utilized, and used for e. g. space heating of buildings, the need for purchased energy would be reduced. One way to do this is to bury a long tube in the soil and then let the needed ventilation air for the building pass through this pipe. The cold air stream will then collect some of the heat from the surrounding soil on its way into the building. In Reference [1] there is a description of a test equipment used in the U.S.A. where the author shows how much heat that is collected. The pipe was not connected to a building but instead used only for experiments. The winter when the tests where made was very cold and thus there was a significant difference between the inlet air temperature and the temperature of the soil, at least during some periods of monitoring. The author also showed that the cold air made the moistened soil freeze, at least around the beginning of the tube. From this freezing, extra heat could be utilized because of the latent heat transferred when the phase change occurred between water and ice. During other conditions there is also a possibility to use the earth tube as a cooling device, for instance in the summer. The author to Reference [1] also gives some references where earth tubes have been the main interest and it seems that the use, hitherto, has been emphasized for livestock housing in the U.S.A. In Reference [2], with about 30 references, there is a more extensive survey made for a building in Boden, about 1000 km north of Stockholm, Sweden. Due to the location up in the north, the site has a very cold climate and thus it was possible to study conditions where the surrounding soil both was in a frozen and an unfrozen state. The author has also tried to elaborate a method for calculating the resulting temperatures in the air stream flowing through the pipe. He does this by use of a superposition technique where it is assumed that the varying inlet temperature of the air can be divided into pulses with piece wise constant temperatures. The reason for this can be found in e. g. Reference [3], p. 109, where such cases can be handled analytically in a strict mathematical way.

CASE STUDY 1

The first case studied here describes an electrically heated building where the heat is transported using the ventilation system. During cold periods, when the heating device must be used, the ventilation air is warmed by use of an ordinary resistance heater implemented in one of the ventilation ducts. There are no extra radiators in the building except for one in the bathroom. The inlet air is also coupled to an air-to-air heat exchanger where the outlet air will warm the incoming air. The earth tube is constructed of a PVC-pipe, 25 meters long, with a diameter of 0.16 meter, buried into the soil consisting of fine sand or silt. The pipe is then coupled to the heat exchanger. There is also a defroster implemented in front of the heat exchanger which ascertains that the device will not be choked with ice from condensed water, see Figure 1.

See Reference [4] for more details about this heating system. In the case studied, several measurements have been made of temperatures, solar irradiation, electricity use and ventilation air flows, as well as domestic water use. The main interest here is, however, only to study the performance of the earth tube and thus the temperatures of the incoming and outgoing air from this device is of interest. The air flow through the pipe was 39 liters per second or about 130 m^3/h when the equipment was installed in 1987. The value was also checked up in 1989 and the flow was then 162 m^3/h, i. e. an increase has occurred but, unfortunately, the reason for this is not known. All the temperatures are monitored by use of a computerized system, where average values are stored on the hard disk each ten minutes, which therefore is the finest resolution available. In Table 1 1 an example of the temperatures of interest is shown.

Starting with the inlet temperature ten minutes past midnight the first day of January 1988, the average air temperature for the passed ten minutes was 1.8 °C. The outlet temperature was monitored for the same period to 2.3 °C,

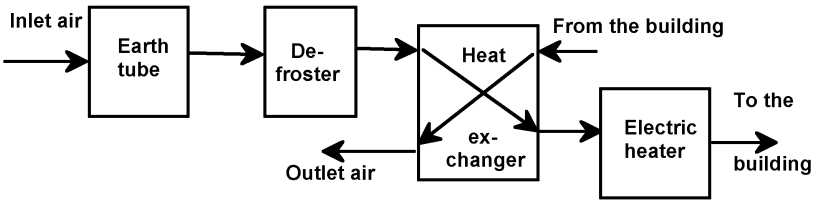

Figure 1: Principal view of the heating system, first case

Time	Inlet	Outlet	Time	Inlet	Outlet	Time	Inlet	Outlet
00.10	1.8	2.3	01.10	1.8	2.2	02.10	2.6	2.5
00.20	1.8	2.2	01.20	1.8	2.3	02.20	2.6	2.5
00.30	1.8	2.2	01.30	1.8	2.3	02.30	2.6	2.6
00.40	1.8	2.3	01.40	2.0	2.3	02.40	2.7	2.6
00.50	1.8	2.2	01.50	2.1	2.4	02.50	2.8	2.6
01.00	1.8	2.3	02.00	2.4	2.4	03.00	2.8	2.6

Table 1: Inlet and outlet air temperatures in °C for three hours starting at midnight 1988-01-01

i. e. a very small increase of temperature by 0.5 degrees. Examining the other values in Table 1 show that the other differences are still smaller and for some values they are even negative, i. e. the inlet air has been cooled by the earth tube. The reason for this discouraging result might be that there has been a rather stable period of the climate before this monitoring period and the soil surrounding the tube has almost the same temperature as the inlet air. The differences are also so small that the significance of the monitoring devices, PT100 elements, might influence the result.

There is therefore a need for examining a longer period of time, e. g. one week. Because of the fact that there are over 2000 temperature values, a table is not convenient and the values are instead plotted in a graph, Figure 2.

Each ten minute period has then been assigned a value of 0.1 and then the periods are added to each other which explains the scale in Figure 2. In Figure 2 it is obvious that the earth tube will result in a more leveled temperature curve of the outlet air temperature. It is also clear that the air stream sometimes, in the beginning of the week, collects heat from the surrounding soil while in other periods, in the end of the week, the soil is warmed by the air. Further, if the peeks and valleys of the two temperature curves are examined it is shown that there are no time gaps between e. g. the peaks. The moment where there is a

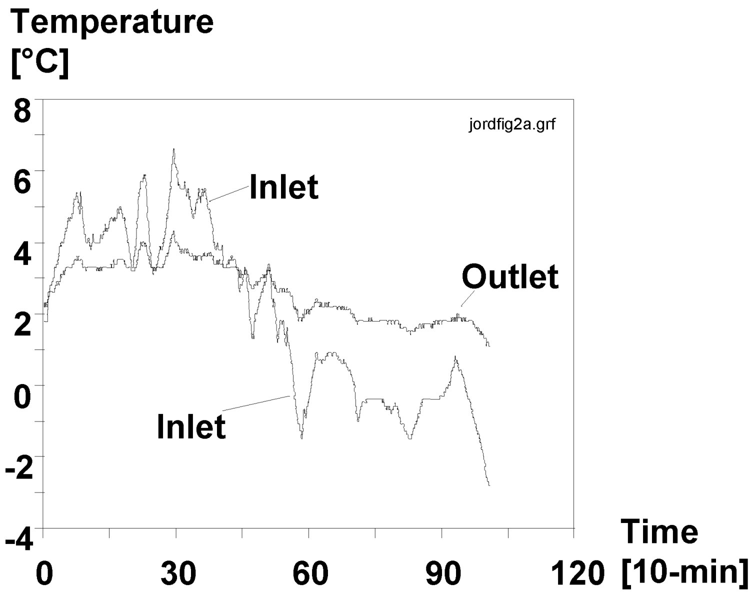

Figure 2: Inlet and outlet air temperatures in the earth tube for the first week in January 1988

peak in the inlet temperature there is also a peak in the outlet temperature even if it is much smaller in magnitude. During the week, the maximum difference between the two temperatures was only about 4 °C which implies that only a very small amount of heat has been transferred between the soil and the air stream. The heat capacity of air is about 1.006 kJ/kg×°C while the density is about 1.177 kg/m^3, see Reference [3], Table A-5. This implies that each m^3 of air will store approximately 0.33 Wh/°C. The flow of the air stream was measured to about 150 m^3/h as an average value, and hence, approximately 48 Wh/°C per hour is accumulated in the considered air stream. The first ten minutes of the examined week, see Table 1, the difference in temperatures was 0.5 °C. During these ten minutes, five degree minutes have been utilized which equals about 0.08 degree hours. Adding values for the other five periods during the first hour, shows that 0.45 degree hours were generated. For the whole week, i. e. 168 hours, this sum has been calculated to 106.4 degree hours, and multiplying this value with the heat accumulated in the air stream, yields that 5.1 kWh have been transferred from the soil to the ventilation air. It should be noticed that the energy transferred from the air stream to the soil have been subtracted, and thus 5.1 kWh is the net result for the first week. In Sweden this amount of energy costs about 3 SEK to buy from the electricity utility and it is clear that, for the performance of the earth tube, this is a very discouraging result. (Seven SEK equal about one US dollar.) Mentioned above was the fact that the maximum difference in temperature between the inlet and outlet air stream was only 4 °C. With such a small difference it is obvious that the examined earth tube contribution to space heating in the building, only is of academic interest. There is therefore a need for examining a still longer period of time. In Figure 3, the first four months of 1988 are shown.

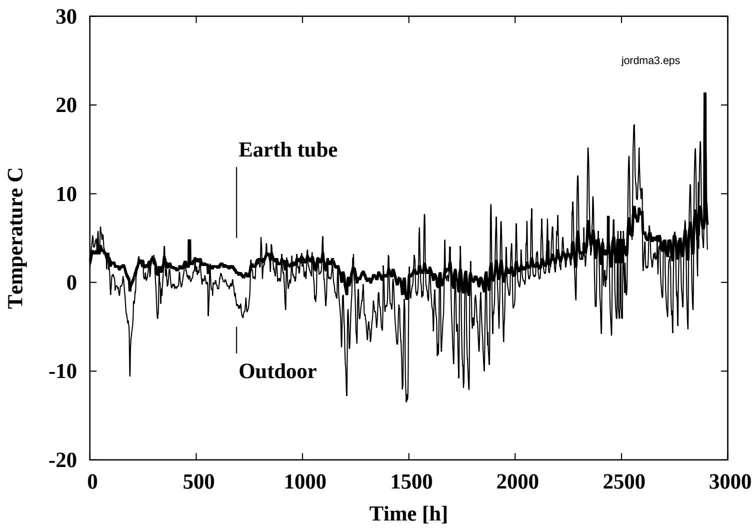

Figure 3: Earth tube, and outdoor air temperatures for January to April, 1988

Because of the vast amount of values involved we have shown average temperatures during each hour instead of each ten minutes. From this figure it is likewise obvious that the earth tube has a leveling influence on the air temperature. While the outdoor temperature fluctuates heavily, the air temperature inside and at the end of the tube is more constant. The tube thus works as expected but the problem is that under certain periods much heat is transferred from the air stream to the surrounding soil which results in very low overall energy gains. In Table 2 this is shown in more detail.

The heat flow from the soil to the air, and vice versa, have been calculated for each month of the examined period. The table also shows the net result of these flows and it is apparent that the gains are rather small.

In Table 2 it is shown that the maximum heat gains occur during week no 8,9 and 11, i. e. about hours 13.00 - 18.00 in Figure 3, with about 35 kWh each week. However, there are also weeks with negative gains, see weeks no 13, 14, 16 and 18. During the 18 weeks shown in Table 2 about 244 kWh were utilized, or about 14 kWh each week. If it is assumed that there are about 24 weeks per year, November - April, where the earth pipe is of interest for heat gains, this would imply that about 325 kWh each year could be utilized. In Sweden each kWh of electricity costs about 0.5 SEK and thus approximately 160 SEK each year is saved. Further, assuming that the life-cycle for an earth tube is about 25 years and the real interest rate is 5 %, will result in an net present value factor of 14.09. The cost for the earth tube must therefore be lower than 2 500 SEK if it will be profitable. The real cost, however, is probably at least 5 times higher, and hence this earth tube is not of any economic interest.

Week no	From air to soil	From soil to air	Net flow
1	-3.5	8.6	5.1
2	-0.3	17.5	17.2
3	-0.2	11.9	11.6
4	-0.0	14.8	14.8
5	-0.9	15.5	14.6
6	-0.5	9.2	8.7
7	-0.6	12.9	12.3
8	-0.3	36.5	36.2
9	-0.5	35.6	35.1
10	-3.5	18.4	14.9
11	-0.9	35.2	34.3
12	-6.6	20.5	13.8
13	-7.2	4.6	-2.6
14	-9.9	3.3	-6.6
15	-2.2	23.3	21.1
16	-13.1	11.0	-2.1
17	-4.7	24.2	19.5
18	-5.3	2.2	-3.2
Sum	-60.41	305.01	244.60

Table 2: Transferred heat between the earth tube and the surrounding soil in kWh

CASE STUDY 2

The second case study also describes a building outside of Linköping, Sweden. The heating system operates here by use of an exhaust air heat pump where heat from the outgoing ventilation air heat domestic hot water and water used for space heating. Under periods when this heat is not sufficient, electric resistors are used for peak heating. The resistors are built into the hot water supply, inside the heat pump apparatus, and hence they are also used for heating the domestic hot water used in the building. The hot water is then led into a heat exchanger located in the ventilation system. The heat captured in the water is therefore transferred over to the passing air stream and led out into different rooms in the house. The water to air heat exchanger has a limited ability to transfer heat. Therefore, for the sake of very cold winter days, an electrical heater has been implemented as well. However, before the ventilation air passes the heat exchanger, it has already been led through a solar panel device and after this through an earth pipe made of PVC, diameter 0.15 m, and about 15 metres long. Figure 4 will explain the situation.

The solar panels are located vertically at an external wall and the air is supposed to collect some heat by passing this device. During the summer this heat is of no use and hence it is possible to by-pass the solar panels and instead transfer the air directly through the earth pipe. The discouraging result from the case study number 1 above, implies that a colder winter period should be studied. Therefore, we have chosen the first months of 1987 instead of 1988. The air temperatures before and after the earth tube are shown in Figure 5.

Unfortunately, it is hard to distinguish the two temperature curves from

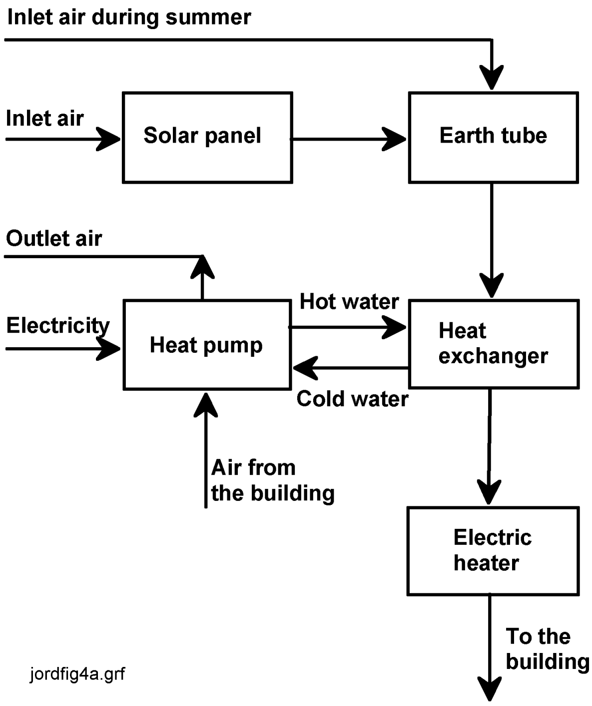

Figure 4: Schematic view of the heating system, case 2

each other because of the black and white graphics. The temperatures after the earth tube are covered by the temperature curve after the pipe. However, the first items can be identified by the somewhat thicker line in the middle of the graph. As in the first case, it is obvious from Figure 5, that the earth pipe has a significant leveling effect on the air stream temperatures.

It is also obvious that the temperatures before the earth tube varies much more than in Figure 3 because of the solar panel system. The climate has also been much colder because the inlet temperatures are far below -10 °C during long periods of time. In Table 3 the situation is clarified for one day in March, 1987.

Starting at midnight, the outdoor temperature was about -14 °C. Almost the same temperature appeared after the solar panels and before the earth tube. This is so, of course, because there was no sun to heat the solar collectors at that time of the day. After the earth tube, the temperature was significantly increased, about - 2 °C . Both the outdoor temperature and the temperature after the solar panels dropped until about 8 a.m., when the outdoor temperature slowly got higher again. The temperature after the solar panels , however, increased more rapidly because the sun started to shine on the solar collector. At 14 p.m. the outdoor temperature was about - 7 °C while the temperature

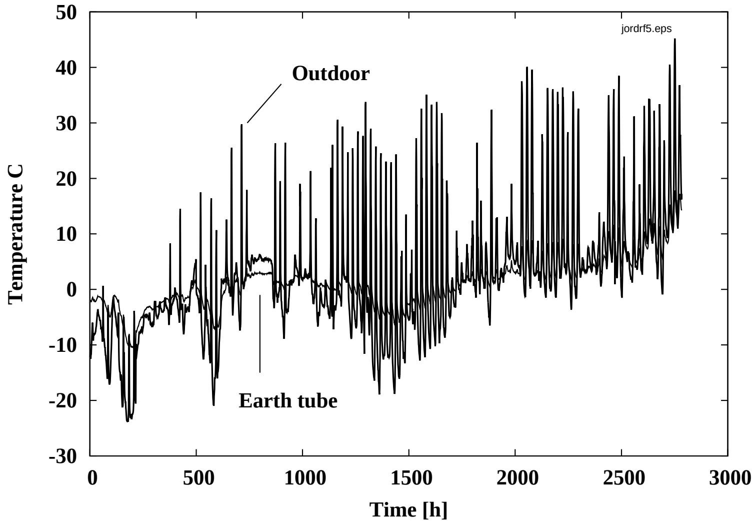

Figure 5: Temperatures before and after the earth tube, January to April 1987, case 2

after the solar device had increased to about + 26 °C. After this hour the temperatures decreased again. The air temperature after the earth pipe shows a much more leveled behavior. The lowest temperature during the day was about - 4 °C while the highest was about + 2 °C.

The air flow trough this case 2 earth tube has been monitored to 136 m^3/h, which implies that about 45 kWh/°C per hour was captured in the air. In Table 4 the calculated heat flows are shown based on the monitored temperatures from January 1 to April 30.

The total calculated heat flow from the air stream to the surrounding soil was about 374 kWh, while the heat flow from the soil to the air was about 309 kWh. The earth tube in this case resulted in a total negative heat flow of 65 kWh, i. e. heat was transferred from the air stream to the soil which was not suggested from the beginning. In Table 4 it is obvious that the earth tube worked as expected the first four weeks in 1987. About 130 kWh was transferred from the soil to the earth tube. From week no. 5, however, the heat flow was negative almost all of the weeks and from week no. 11 no positive net flow occurred at all. This is, at least to some extent, the result of the solar panels which heated the inlet ventilation air substantially, see Table 2 where in increase of 30 °C occurred for the hours around noon. However, it could be expected that the air heated the soil during these hours and that this heat was recovered during subsequent hours when the air stream was colder. This is noticeable in Figure 6 where the temperatures in Table 3 have been shown in a graph.

Starting at midnight, the outdoor and the air stream temperatures were very closely related. When the solar rays hits the solar collector the air stream temperature rises very quickly and results also in an increase of the air temperature after the earth tube. When the sun disappears again the air stream temperature will decrease but not as fast as the increase earlier observed. Further, the air temperature after the solar collector was a few degrees higher than the outdoor

Time	Outdoor	Before	After	Time	Outdoor	Before	After
00.00	-13.91	-13.81	-2.22	13.00	-7.21	23.13	1.62
01.00	-13.91	-14.32	-2.63	14.00	-7.11	25.74	2.23
02.00	-14.81	-14.62	-2.83	15.00	-7.21	12.08	1.12
03.00	-15.01	-15.22	-3.13	16.00	-7.81	10.48	0.91
04.00	-15.41	-15.62	-3.34	17.00	-8.81	-0.76	-0.3
05.00	-15.51	-15.92	-3.54	18.00	-9.91	-7.09	-1.31
06.00	-15.61	-16.02	-3.74	19.00	-11.01	-8.9	-1.92
07.00	-15.51	-16.42	-4.05	20.00	-11.81	-10	-2.22
08.00	-15.01	-15.02	-4.05	21.00	-13.11	-11.51	-2.63
09.00	-12.51	-10.8	-3.64	22.00	-14.21	-12.51	-2.93
10.00	-10.01	-7.49	-3.13	23.00	-15.11	-13.41	-3.24
11.00	-8.71	-0.96	-2.02	00.00	-15.71	-14.52	-3.54
12.00	-7.71	16.8	0.51				

Table 3: Air temperatures in °C before and after the earth tube, March 1, 1987, case 2

Week no	Air to soil	Soil to air	Net	Week no	Air to soil	Soil to air	Net
1	0.1	50.8	50.7	10	26.8	29.9	2.9
2	0.3	54.6	54.2	11	25.6	18.2	-7.4
3	0.9	11.2	10.3	12	19.8	6.4	-13.4
4	7.5	25.0	17.5	13	39.2	1.9	-37.3
5	18.5	13.4	-5.1	14	41.2	4.8	-36.4
6	17.4	11.2	-6.3	15	23.8	4.2	-19.6
7	13.3	13.8	0.5	16	32.0	5.9	-26.0
8	28.7	18.1	-10.6	17	48.3	4.6	-43.7
9	24.4	34.7	10.3	18	7.0	0.1	-6.9

Table 4: Calculated heat flows in kWh from and to the earth tube air stream for 18 consecutive weeks, January 1 - April 30, 1987

temperature during the rest of the day, which probably is a result of the heat capacity of the solar panels. This will also influence on the temperature after the earth tube but still there was a small temperature increase, of two or three degrees, that must emanate from the earlier warm-up of the surrounding soil. From Figure 6 it is clear that the heat in the solar warmed air stream is not perfectly recovered and subsequently there is a loss of heat to the soil around the tube. In Table 2 it is shown that the overall performance of the earth tube not was the one expected. For the studied period of time the resulting energy gains were negative and more heat was transferred from the air stream to the soil than vice versa. Subsequently, there were no savings to emerge from a lower degree of space heating in the building.

In Figure 6 it is shown that there is a significant amount of heat emanating from the solar panels. Most of this heat is transferred through the earth tube walls and out into the soil layers and it seems that only a very small amount of heat is recovered during subsequent hours. This is probably an effect of a high thermal conductivity in the soil layers around the tube. In Reference [2] p. 14 it is shown that the moisture content of the soil has a vital influence and

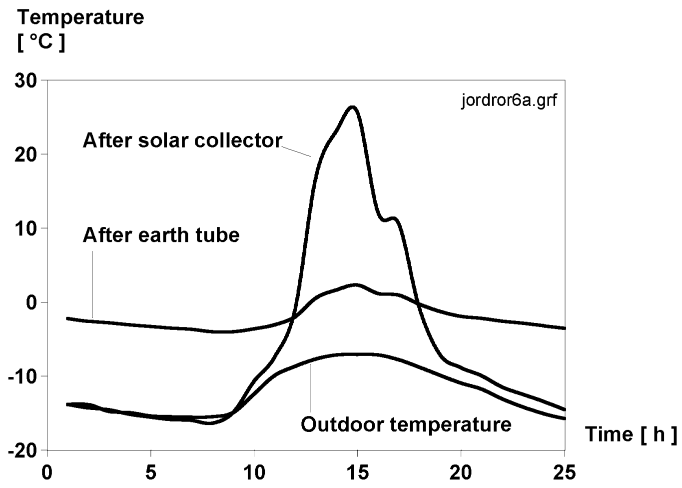

Figure 6: Outdoor temperature and temperatures of the air stream before and after earth tube

the conductivity varies from about 0.2 for dry moraine up to 2.2 W/m×°C for a 100 % saturation degree. When the soil is in a frozen state the conductivity has a maximum value of about 2.6 W/m×°C. It is shown that the climate was very cold during the monitoring period and therefore it may be assumed that the saturated soil around the earth tube is in a frozen state. Hence, heat from the solar panels will rapidly be transferred from the vicinity of the tube out to more distant soil layers. The heat pulse will not be sufficient to increase the soil temperature in a noticeable amount and therefore no heat recovery will occur.

CONCLUSIONS AND DISCUSSION

From the two studies above it is clear that the earth tubes are not of any economic interest as they are implemented today. The reason for this is that during some periods of time the earth tube acts like a cooling device. If the inlet of the air stream could be switched at times when the outdoor temperature is higher than the temperature in the earth tube things would be better. The inlet air to the building should in such a case only be led through the earth pipe when significant gains are to be expected. However, such a solution will also lead to longer periods of cold soil temperatures because there is no warm air flowing through the pipe which enables the soil to increase its temperature. The only heat source will thus be the heat flowing in from soil layers farther away. The maximum temperature difference in the air stream was found to be about 31 °C. This implies that approximately 1.4 kWh per hour was transferred from the soil to the air stream or vice versa. The length of the earth tube was in case two

15 m, and hence about 100 W/m was the heat flux through the pipe wall. This is an average value and, of course, the heat transfer in reality has its highest value in the beginning of the pipe, this because the temperature difference has its maximum there. In Reference [2] p. 117 the heat transfer through an earth tube of exactly the same length was calculated to 220 W/m in the beginning of the pipe while it was 110 W/m in the end of it. The pipe in Reference [2] thus had a better thermal performance but the values correspond surprisingly well, especially when the northerly site, and hence the colder climate, is considered.

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