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ARE EARTH TUBE HEAT EXCHANGERS OF INTEREST WHEN HEATING BUILDINGS?

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SUMMARY

It is a well-known fact that the temperature of the soil, some metres 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 in which it will, depending on their relative temperatures, take up heat from, or leave heat to, the surrounding soil. 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 may have depended on heat pipes that were too short or the fact that the difference in temperature between the passing air stream and the surrounding soil was too small.

KEY WORDS Heat exchanger Earth tube Heating Ventilation Heat recovery Electricity heating

INTRODUCTION

A few metres below the earth's surface the temperature of the soil is fairly stable. Even during hard winters the temperature will be well above zero Celsius and water pipes etc. 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 at Linköping, which is dealt with here, the soil depth must be about 1·5 metres to ensure that freezing does not occur. If this heat could be utilized, and used, for example, for 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 ventilation air needed 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 Baxter (1992) there is a description of test equipment used in the USA where the author shows how much heat 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 therefore 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. Baxter (1992) also gives some references where earth tubes have been the main interest, and it seems that their use, hitherto, has been emphasized for livestock housing in the USA.

In Nilsson (1991), which has about thirty references, a more extensive survey is reported of a building in Boden, about 1000 km north of Stockholm, Sweden. Because of the location up in the north, the site has a very cold climate and so it was possible to study conditions when the surrounding soil was in both 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 piecewise

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constant temperatures. The reason for this can be found in, for example, Holman (1965, 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 metres long, with a diameter of 0·16 m, buried in the soil, which consists 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 ensures that the device will not be choked with ice from condensed water (see Figure 1). See Gustafsson (1992) 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 so the temperatures of the incoming and outgoing air from this device is of interest. The air flow through the pipe was 39 litres per second or about 130 m^3/h when the equipment was installed in 1987. The value was also checked 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 every ten minutes, which therefore is the finest resolution available. In Table 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 past ten minutes was 1·8 °C. The outlet temperature was monitored for the same period at 2·3 °C, i.e. a very small increase in temperature of 0·5 degrees. Examining the other values in Table 1 shows 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

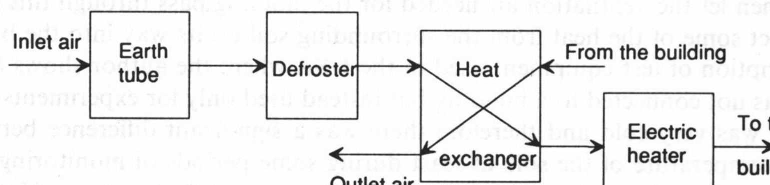

Figure 1. Schematic view of the heating system—Case Study 1

Table 1. Inlet and outlet air temperatures in degree Celsius for three hours starting at midnight 01.01.1988

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

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 over 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 (see 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 levelled temperature curve of the outlet air temperature. It is also clear that the air stream sometimes, at the very beginning of the week, collects heat from the surrounding soil, while in other periods the soil is warmed by the air. Further, if the peaks and valleys of the two temperature curves are examined it can be seen that there are no time gaps between, for example, the peaks. Whenever there is a 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, (Holman 1985, Table A-5). This implies that each cubic metre of air will store approximately 0·33 W h/°C. The flow of the air stream was measured to be about 150 m^3/h as an average value, and hence, approximately 48 W h/°C per hour is accumulated in the air stream considered. In the first ten minutes of the week examined (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 kW h 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 kW h 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 (7 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 is only 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. Because of the great number of values involved we have shown avearge temperatures for each hour instead of each ten minutes. From this figure it is likewise obvious that the earth tube has a levelling influence on the air temperature. While the outdoor

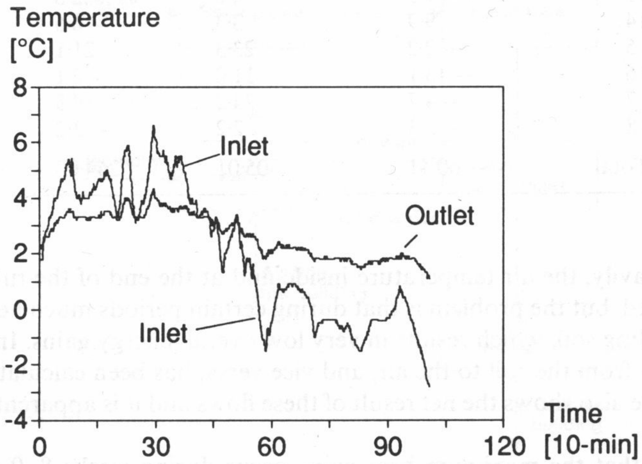

Figure 2. Inlet and outlet air temperatures in the earth tube for the first week in January 1988

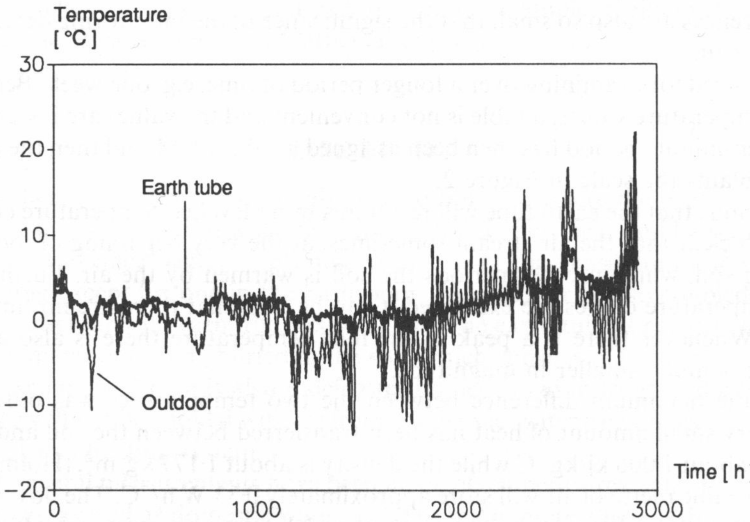

Figure 3. Earth tube and outdoor air temperatures for January to April 1988

Table 2. Transferred heat between the earth tube and the surrounding soil in kW h

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
Total	− 60·41	305·01	244·60

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 during 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, has 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 weeks 8, 9 and 11, i.e. about hours 1300–1800 in Figure 3, with about 35 kW h each week. However, there are also weeks with negative gains, see weeks 13, 14, 16 and 18. During the 18 weeks shown in Table 2 about 244 kW h were utilized, or about 14 kW h 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 kW h each year could be utilized. In Sweden each kilowatt-hour 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%, it will result in a net present value factor of 14·09. The cost for the earth tube must therefore be lower than 2500 SEK if it is to be profitable. The real cost, however, is probably at least five times higher, and hence this earth tube is not of any economic interest.

CASE STUDY 2

The second case study also describes a building outside Linköping, Sweden. The heating system operates here by use of an exhaust air heat pump where heat from the outgoing ventilation air heats domestic hot water and water used for space heating. During 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 Case Study 1 above implies that a colder winter period should be studied. Therefore, we have chosen the first few 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 each other in black and white graphics. The temperatures after the earth tube are covered by the temperature curve before the pipe. However, the first items can be identified by the somewhat thicker line in the middle of

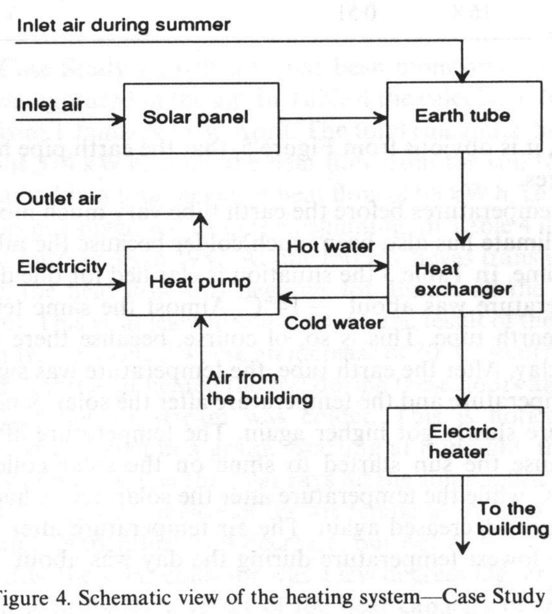

Figure 4. Schematic view of the heating system—Case Study 2

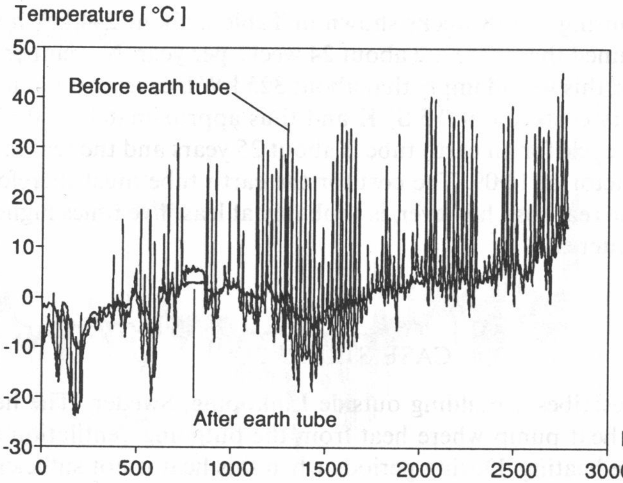

Figure 5. Temperatures before and after the earth tube, January to April 1987—Case Study 2

Table 3. Air temperatures in degrees Celsius before and after the earth tube, 1 March 1987—Case Study 2

Time	Outdoor	Before	After	Time	Outdoor	Before	After
00·00	− 13·91	− 13·81	− 2·22	1300	− 7·21	23·13	1·62
01·00	− 13·91	− 14·32	− 2·63	1400	− 7·11	25·74	2·23
02·00	− 14·81	− 14·62	− 2·83	1500	− 7·21	12·08	1·12
03·00	− 15·01	− 15·22	− 3·13	1600	− 7·81	10·48	0·91
04·00	− 15·41	− 15·62	− 3·34	1700	− 8·81	− 0·76	0·3
05·00	− 15·51	− 15·92	− 3·54	1800	− 9·91	− 7·09	− 1·31
06·00	− 15·61	− 16·02	− 3·74	1900	− 11·01	− 8·9	− 1·92
07·00	− 15·51	− 16·42	− 4·05	2000	− 11·81	− 10	− 2·22
08·00	− 15·01	− 15·02	− 4·05	2100	− 13·11	− 11·51	− 2·63
09·00	− 12·51	− 10·8	− 3·64	2200	− 14·21	− 12·51	− 2·93
10·00	− 10·01	− 7·49	− 3·13	2300	− 15·11	− 13·41	− 3·24
11·00	− 8·71	− 0·96	− 2·02	0000	− 15·71	− 14·52	− 3·54
12·00	− 7·71	16·8	0·51				

the graph. As in the first case, it is obvious from Figure 5, that the earth pipe has a significant levelling effect on the air stream temperatures.

It is also obvious that the temperatures before the earth tube vary 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 for 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, to 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 2 p.m. the outdoor temperature was about − 7°C while the temperature after the solar device had increased to about + 26°C. After this hour the temperatures decreased again. The air temperature after the earth tube shows a much more levelled behaviour. The lowest temperature during the day was about − 4°C while the highest was about + 2°C.

Table 4. Calculated heat flows in kW h from and to the earth tube air stream for 18 consecutive weeks 1 January–30 April 1987

Week no	Air to soil	Soil to air	Net flow	Week no	Air to soil	Soil to air	Net flow
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

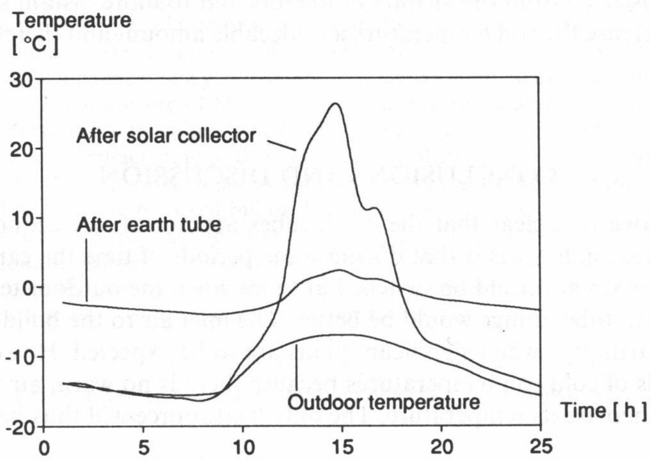

Figure 6. Outdoor temperature and temperatures of the air stream before and after earth tube

The air flow through this Case Study 2 earth tube has been monitored to 136 m^3/h, which implies that about 45 kW h/°C per hour was captured in the air. In Table 4 the calculated heat flows are shown, based on the monitored temperatures from 1 January to 30 April. The total calculated heat flow from the air stream to the surrounding soil was about 374 kW h, while the heat flow from the soil to the air was about 309 kW h. The earth tube in this case resulted in a total negative heat flow of 65 kW h, 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 in the first four weeks in 1987. About 130 kW h was transferred from the soil to the earth tube. From week 5, however, the heat flow was negative for almost all the weeks, and from week 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 an 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 hit the solar collector the air stream tempertature 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 temperature for the rest of the day, which is probably a result of the heat capacity of the solar panels. This will also influence 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 4 it is shown that the overall performance of the earth tube was not the one expected. For the period of time studied 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 Nilsson (1991, p. 14) it is shown that the moisture content of the soil has a vital influence and the conductivity varies from about 0·2 for dry moraine up to 2·2 W/m °C for a 100% degree of saturation. 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 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 as 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 kW h per hour was transferred from the soil to the air stream or vice versa. The length of the earth tube was 15 m in Case Study 2, 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 at the beginning of the pipe, this because the temperature difference has its maximum there. In Nilsson (1991 p.117) the heat transfer through an earth tube of exactly the same length was calculated to be 220 W/m at the beginning of the pipe, while it was 110 W/m in the end of it. The pipe in Nilsson (1991) 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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