GROUND COOLING OF VENTILATION AIR FOR ENERGY EFFICIENT HOUSE IN MALAYSIA: A CASE STUDY OF THE COOLTEK HOUSE

G. REIMANN
IEN Consultants, Kuala Lumpur, Malaysia. www.ien.com.my

H. BOSWELL, S. BACON
CoolTek Building, 350 Jalan Woodland, Tiara Melaka Golf & Country Club, Ayer Kerah, 75450 Melaka, Malaysia

Abstract

The paper presents an analysis of on-site measurements of the ground cooling air duct system of the energy efficient CoolTek house in Melaka, Malaysia. Measurements of temperature, humidity and CO_2 were undertaken indoors, outdoors and inside the ground cooling air duct system during two modes of operation. The first mode of operation was a fully passive mode where the ventilation was driven only by the thermal pull of the solar chimney. The second mode of operation was a hybrid mode where a small fan assisted the solar chimney in ventilating the building. Some improvements of the ground cooled air duct system are suggested on the basis of the analysis.

Keywords: Ground cooling of air, energy efficient tropic housing, CoolTek, solar chimney.

1. Introduction

Year 2004 saw the completion of the energy efficient CoolTek house in Melaka, Malaysia. The 200 m² house is air-conditioned 24-hours, yet, the daily air-conditioning consumption is only 8 kWh – or RM 1.8 in local currency. The five aspects of the CoolTek house design are orientation, protection, insulation, ventilation and investigation. Energy efficient measures include insulation of entire building envelope, high performance glazing, complete shading from direct sunlight and air-tightness. The focus of this paper, however, is on the workings of the ground cooled air duct system for ventilation purposes. Ground cooling of inlet air is known from other climates – in particular in hot and dry climates with high diurnal temperature swings – but is not common in the hot and humid tropical Malaysia. Vernacular Malaysian architecture has high naturally ventilated pitched roof ceilings and big well shaded window openings to harness any breeze while not allowing entry of direct sunlight. In contrast, the CoolTek house has a flat (15° picth) roof with low ceiling and is built very air tight. The only common design element is the wide eves. The design strategy of the CoolTek house is possible due to the emergence of the air-conditioning technology and is intended to minimise its use. The paper investigates whether the ground cooling system of inlet air helps to increase the energy efficiency of the house.

2. Ground Cooled Ventilation System

The CoolTek house does not have any openable windows in the air-conditioned zone and all doors to the outside have double-seals to ensure air tightness of the building envelope. The darkest outdoor surface of the white coloured house is the red brick chimney functioning as a solar heat retaining sink, so as to act as a thermal chimney. The air sucked out of the house by the solar chimney (4.55 m above floor level) is to be replaced by air from the ground cooled ducts with two floor level inlet openings. Each of the two ground cooled air ducts are connected to a sub-soil chamber constructed from 50 mm thick 1000 mm diameter concrete culvert, containing five concrete filled ceramic pipes standing on a concrete plinth of 300 mm depth with heavy concrete, surface insulated lid. This chamber is again connected with an approximately 10 meter sub-soil duct with an air intake opening (4.55 m below floor level) shaded by a tree; see Figure 1. It is worth mentioning that the solar chimney is connected to the non-air-conditioned garage via the roof space. The garage, which is fitted with an automatic roller door with rubber seals, is not as air-tight at the remained of the house and will therefore reduce the solar chimney pull on the air-conditioned spaces. The original design of the ventilation system relied solely on passive measure, i.e. the thermal suction of the solar chimney. It is fair to assume that the ground temperature equals the annual average ambient temperature, which in case of outdoor temperatures measured at the CoolTek house would be about 26.4°C.

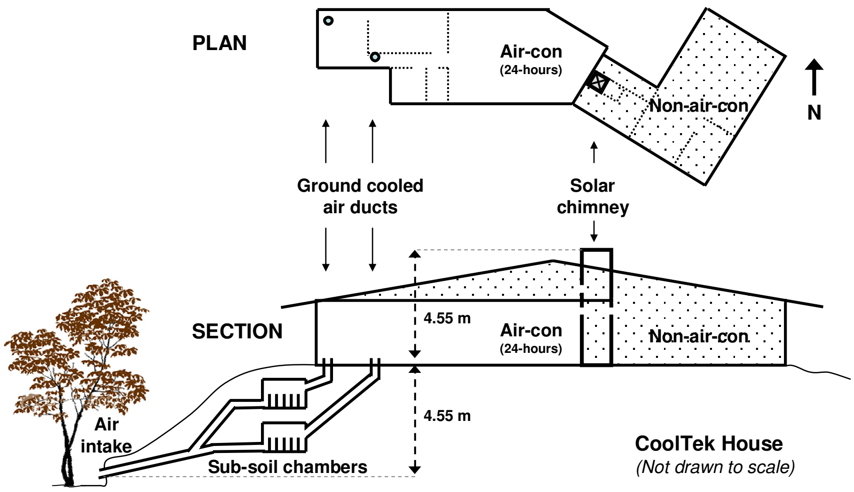


Fig.1 The ground cooled fresh air system of the CoolTek house

Apart from conditioning the air, the ground cooled air ducts were also intended to give a sound proof entry of fresh air to the house. Moreover, the under ground ducting system would also increase the air quality of the inlet air because dust and other particles would be able to settle out of the air before entering the house. Only the energy aspects of the ground cooled fresh air system will be investigated here.

3. Measurements

The performance of the ground cooled ventilation system was monitored with the use of several dataloggers measuring temperature, humidity and CO_2 levels. Only one CO_2 sensor was available, so it was shifted between the measurement locations. The instrumentation used was HOBO dataloggers that were set to log at 15-30 minute intervals; see Table 1 below.

Table 1. Measuring equipment

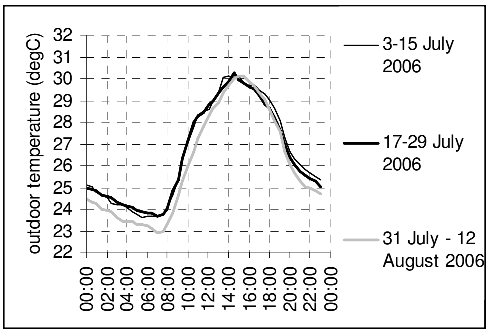
Instrument	Measurements	Accuracy	Logging interval
HOBO H08-004-02	a) Temperature b) Relative humidity	± 0.5°C ± 2.5%	15-30 min
HOBO U12-012	a) Temperature b) Relative humidity	± 0.35°C ± 2.5%	15-30 min
Telaire 7001	a) CO_2	± 50 ppm	15-30 min

The measuring equipment was placed at three locations to monitor the temperature, humidity and CO_2 levels inside the house, outside the house and inside the ground cooled air ducts connecting the two. Since the CoolTek house is air-conditioned 24-hours the absolute humidity level of the air will be lower indoors than outdoors at all times. Similarly, the CO_2 level will be higher indoors than outdoors because of human occupation of the house. Continuous measurements of these values inside the cooled air duct would therefore give a good indication of the flow direction in the ground cooled air duct across the day. Some of the measurements were repeated one year later after the installation of a 35W auxiliary fan to the solar chimney had been installed at the exhaust from the living room to the solar chimney. The schedule of measurements is shown in Table 2 below.

Table 2. Schedule of measurements

Location	Measurements	Period	Logging interval	Fan	Electric bill	Avr. outdoor temp.
A: Outdoors	Temp., humidity	3 July – 12 August 2006	30 min	No	19.9 kWh / day	26.4°C
B: Inside the house (bedroom)	Temp., humidity, CO_2	3–15 July 2006	30 min	No	20.4 kWh / day	26.6°C
C: Inside the house (computer room)	Temp., humidity, CO_2	17–29 July 2006	30 min	No	20.1 kWh / day	26.5°C
D: Inside the ground cooled air duct (0.5 m below the floor)	Temp., humidity, CO_2	31 July – 12 August 2006	30 min	No	19.1 kWh / day	26.0°C
E: Inside the ground cooled air duct (0.5 m below the floor)	Temp., humidity, CO_2	19 May – 2 June 2007	15 min	No	-	-
F: Inside the ground cooled air duct (0.5 m below the floor)	Temp., humidity, CO_2	3–6 June 2007	15 min	Yes	-	-

Table 2 shows that during the first batch of measurements in year 2006 the electricity consumption was virtually the same during each of the three 2-week periods (B – D) that the measuring equipment was shifted between the three locations. This indicates that the usage of the house was similar during these three periods, which the couple living in the house also could attest to. Figure 2 below shows that the slight variation in air-con consumption seems to match the slight variation in average outdoor temperature.



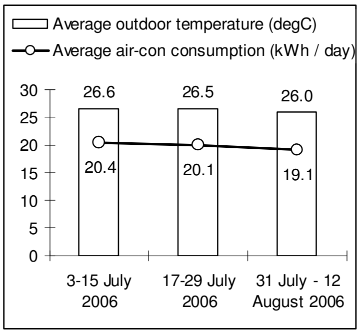


Fig.2 Mimimal variation in average temperature and air-con usage over three measuring periods

Figure 2 shows that the variation in climate and house usage is minimal of the measurement periods B-D (Table 2), so it is fair to assume that the measured data for each of the periods can be compared to one another, as will be done in the following section.

4. Results of passively ventilated ground cooled air ducts

The measured variation in temperature, humidity and CO_2 level will now be analysed to evaluate the performance of the ground cooled air duct system when it is passively ventilated by the solar chimney.

4.1 Temperature measurements

The typical temperature profiles were measured to investigate at what hour of the day it will be advantageous to draw air through the ground cooled air duct in order to pre-cool inlet air to the CoolTek house. The average temperature curves are found in Figure 3 below.

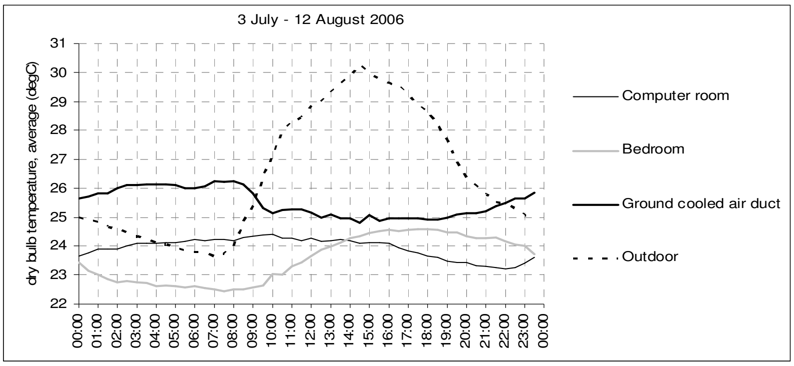


Fig.3 Average daily temperature measurements (period A – D)

Figure 3 shows that the indoor temperature, which is air-conditioned 24 hours with a set point of 24°C, is cooler than the outdoor temperature most of the time. The average outdoor temperature shoots up to about 30°C in the afternoon during which time it would be advantageous to draw air through the ground cooled air duct, which theoretically should have an air temperature of 26.4°C (i.e. the average ambient temperature). The average temperature measured in the ground cooled air duct is seen to vary between 25°C (day time) and 26°C (night time). If there was a steady flow of air through the ground cooled air duct to the indoor environment, one would expect the temperatures to be stable or to reflect the outdoor temperature variation, i.e. higher day time values than night time values. However, the opposite seems to be the case indicating either a smaller air flow or a reversed air flow in the ground cooled air duct during the day time.

4.2 CO_2 measurements

In order to determine the flow direction of air in the ground cooled air duct system it is useful to analyse the measured CO2 levels, as they will differ from outdoor to indoors. The outdoor CO2 level is expected to be more or less constant around 350 ppm whereas the indoor CO2 level is expected to be higher indoor the house due to human respiration.

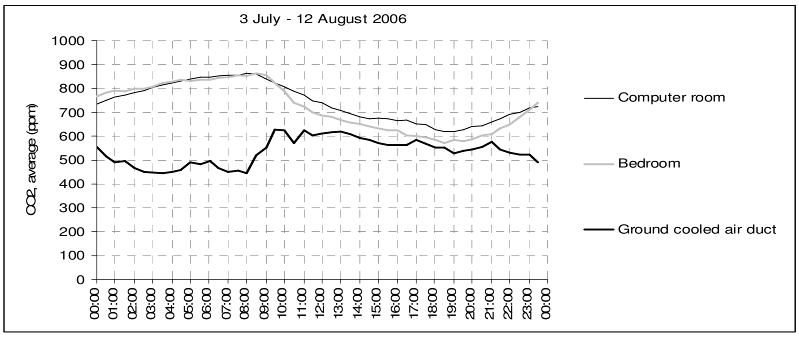


Fig.4 Average CO2 measurements (B – D) in CoolTek house before installation of fan

As expected, Figure 4 shows that the ground cooled air duct has the lowest CO_2 level, as it is connected directly to the outdoor air. The difference in CO_2 levels is particularly high at night, where indoor CO_2 levels are about twice that measure in the ground cooled air duct. In the day time, however, the difference in CO_2 levels is smaller between the three measuring points. Interestingly, the CO_2 level of the ground cooled air duct is seen to increase about 100 ppm from night time levels indicating that the air flow in the pipe has decreased or perhaps reversed during the day time. The CO_2 readings also show that the CoolTek house is adequately ventilated for occupation by two persons as the CO_2 levels stay below the recommended 1000 ppm.

4.3 Absolute humidity measurements

The outdoor absolute humidity levels are more or less constant at 22 g/m³ air, whereas the 24 hour air-conditioned indoor environment of the CoolTek house has a humidity level of about half of that, namely 11.8 g/m³ air. In Figure 5 below the average absolute humidity measurements are shown.

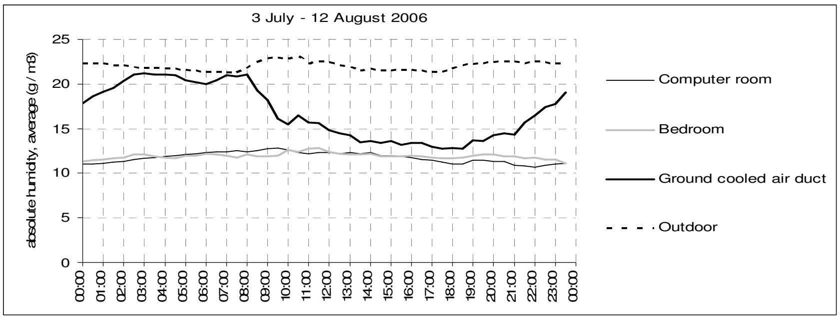


Fig.5 Average absolute humidity measurements (A – D) in CoolTek house

Figure 4 shows that the absolute humidity level measured in the ground cooled air duct nearly matches the outdoor level at night time and nearly matches the indoor level in the day time. This indicates that the origin of the air in the ground cooled air duct comes from outdoors in the night time and from indoors in the day time.

4.4 Sub-conclusions

The above measurements of temperature, humidity and CO_2 levels all point to the same conclusion, namely that air flows through the ground cooled air duct pipe and into the house during night time and out of the house during the night time. From a thermal buoyancy point of view this is understandable, because the 'thermal pull' delivered by the solar chimney simply is not strong enough to counteract the reverse buoyancy effect delivered by the air-conditioned and 'heavy' air (24°C) that drops out of the floor ventilation pipes and is being replaced by warm and 'light' outdoor air (30°C). Only at night when the temperature difference between indoor and outdoor air is 2°C or less does is the air-flow reverse and fresh air enters through the ground cooled air duct and into the house; see Figure 6.

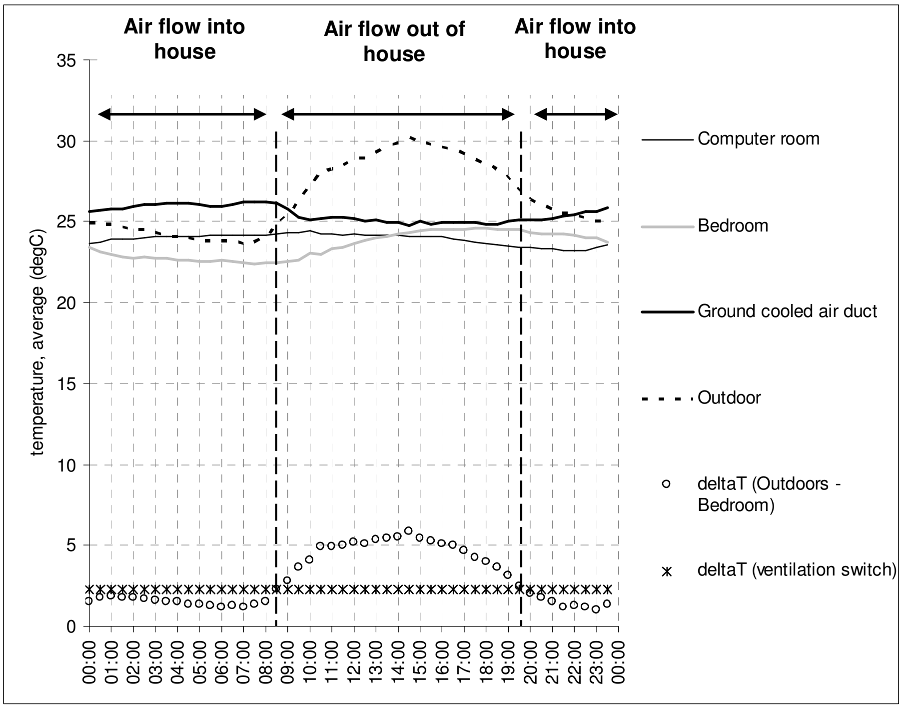


Fig.6 Switching air flow directions in ground cooled air ducts of CoolTek house

Figure 6 shows the switching of the air flow in the ground cooled air ducts at about 8:30 and about 19:30 o'clock. The reversal of flow is found to take place when the temperature difference between indoors (bedroom temperature) and outdoors equals 2°C. During the night (19:30 – 8:30) this temperature difference is less than 2°C and air flows from outdoors and into the house. During the day (8:30 – 19:30) the temperature difference is higher than 2°C and air flows from inside to outside. From an energy point of view the ground cooling system does not add to the energy efficiency of the house. On the contrary, when fresh air enters the house through the ground cooled ducts at night the air is 1-2°C warmer than if the air had come directly though the windows (Figure 6). In the day time, cool air-conditioned air drops through the ground cooled ducts and is replace by outdoor air that penetrates the building envelope – some of which might come from the warm solar chimney. A mechanical fan was mounted as a result of the above findings to assist the solar chimney in driving inlet air through the ground cooled ventilation ducts.

5. Results of mechanically ventilated ground cooled air ducts

A small 35 Watt fan was mounted in the opening between the living room and the solar chimney. This auxiliary fan would assist the solar chimney, so that fresh air could be pulled through the ground cooled ducts in the day time. At the time of writing this paper only a few measured data with the fan in operation were available, as the fan was initially installed without any controls. After continuous operation of the fan for less than three days the occupants switch it off. They found that the fan over-ventilated the indoor space and introduced too much moist outdoor air. Thus, only one full day of continuous fan operation measurements (4 June) has been recorded; see Figure 7 below.

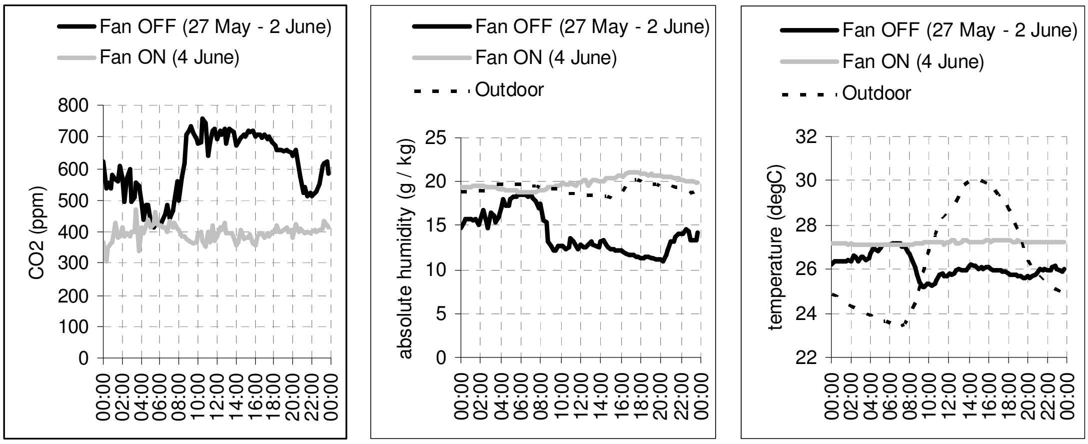
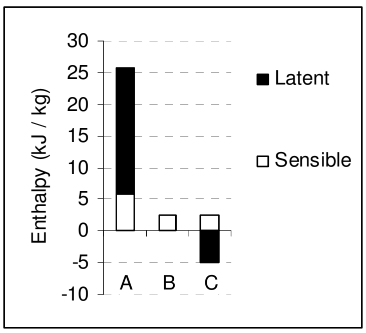


Fig.7 Temperature, humidity and CO_2 in the ground cooled air duct with and without fan operation

Figure 7 shows a clear change in measured ground cooled air values when the 35 Watt fan is switch on. The fan is strong enough to suck fresh air through the ground cooled duct at all times, which can be concluded from the low and constant CO_2 level of around 400 ppm. The temperature is also seen to be stable around 27.2°C, which shows that the ground cooled air duct effectively can cool (or heat) incoming outdoor air. The absolute humidity coming out of the ground cooled air duct is also stable across the day but seems to attain slightly higher values during the day time than outdoor measurements. This slight moisturisation, which causes an energy penalty to the air-con system, happens presumably because warm outdoor air absorbs vapour from the moist sub-soil concrete chambers. An air enthalpy calculation is undertaken for 14:30 hours (peak outdoor temperature) to analyse the energy performance of the ground cooled air duct system when the fan is operating; see Table 3 below.

Table 3. Schedule of measurements

	Temperature (°C)	Absolute humidity (g/kg)	Relative humidity (%)	Enthalpy (kJ/kg)
Outdoor	30.1	18.19	66.5	76.0
Indoor	24.3	10.3	53.6	50.3



Ground cooled air	27.3	18.3	79.2	73.5
Ground cooled air with moisture increase	27.3	20.3	87.9	78.6

A: (Outdoor air) - (Indoor air)

B: (Outdoor air) - (Ground cooled air)

C: (Outdoor air) - (Ground cooled air with moisture increase)

The enthalpy analysis in Table 3 shows that the enthalpy difference of outdoor and indoor air at 14:30 o'clock is 25.7 kJ/kg with the sensible and latent difference accounting for 22% and 78%, respectively. The ground cooling system can reduce the outdoor air enthalpy to 73.5 kJ/kg, or 9.8% of the cooling load. However, if the ground cooled air experiences slight moisturisation in the sub-soil chamber, then the outdoor air enthalpy is increased slightly to 78.6 kJ/kg, or adding a 9.8% to the cooling load. Please note that these enthalpy measurement findings need to be verified by additional measurements.

6. Discussion

Due to lack of measuring equipment the measurements were done over 2-week periods at each location. Subsequently, the average values for those periods were compared. Given the regularity of the Malaysian climate and the uniform usage of the CoolTek house the staggered 2-week measurements are comparable, though co-current measurements of course always are preferred. The most uncertain analysis is that during fan operation, as only one day of measurements were available. Moreover, contrary to the other analyses, no co-current outdoor measurements were taken. The humidification of intake air in the ground cooled duct is therefore rather uncertain.

The determining factors for the direction of air flow in the ground cooled duct system should be explored in more detail as factors of wind and outdoor air pressure presently have not been accounted for. The driving forces of the thermal buoyancy also needs further analysis, as there are four different players. Starting from the top there is the 'light' warm air in the solar chimney below which the 'heavy' 24°C air-conditioned air inside the house is to be found. And one step below is the slightly lighter 27°C air inside the ground ducts. Finally, the outside air (24 – 32°C) acts with different thermal force across the day.

7. Conclusion

The ground cooled air duct system of the CoolTek house in Melaka, Malaysia, was analysed using continuous datalogging of temperature, humidity and CO2 levels inside the house, outside the house and inside the ground cooled air ducts. Measurements were carried out during two modes of operation, namely when the house was passively ventilated by the solar chimney and when the house was actively ventilated by a small auxiliary fans mounted in the solar chimney.

When the CoolTek house only is ventilated by the solar chimney, the air flow in the ground cooled ducts was found to flow in opposite directions day and night. In the day time (8:30 – 19:30), outdoor air was not being cooled by the ground cooled duct, as air flowed from indoors to outdoors. Only at night did the flow reverse, when the outdoor temperature was less than 2°C warmer than the indoor temperature (24°C). At this time, however, it would mostly be cooler to get the fresh air directly through the window, as the ground cooled ducts heated the air 1-2°C before it entered the house.

When the CoolTek house is ventilated with an auxiliary fan in the solar chimney an air flow into the house through the ground cooled pipe can be ensured at all times. The ground cooled pipe was seen to deliver an almost constant air temperature of 27.2°C both day and night. In the afternoon when outdoor temperatures peak the ground cooling system was found decrease the sensible load amounting to 9.8% of the entire air-conditioning load. However, the measurements indicate that the ground cooling system adds moisture to the outdoor air, hence, resulting in a net 9.8% increase in the air-conditioning load.

Based on the above findings it is recommended to operate the exhaust fan when the outdoor temperature exceeds 28°C. The fan should not over-ventilate the indoor space and could be controlled by a CO_2 sensor set to 1000 ppm. Measures should also be taken such that the ground cooled air ducts do not add moisture to the incoming air, as this we result in a net penalty to the air-conditioning system. The reverse air flow through ground cooling duct could be stopped by a damper. Alternatively, the outdoor air intake of the ground cooling system could be placed higher than the ceiling of the CoolTek house to prevent cool air-conditioned air to 'drop' out of the air intake, which currently is 4.55 meter below the floor level.

It is generally concluded that the potential for ground cooled ventilation is relatively small in tropical Malaysia, because the bulk of the cooling load is latent. The peak sensible cooling load during the afternoon hours only made up 22% of net cooling load.