Coolhouse – Cooling Buildings in Southern Europe Using Innovative Ventilation Strategies

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Synopsis

The Coolhouse project is exploring the viability of alternatives to air-conditioning in southern European countries using innovative passive and low energy cooling and ventilating techniques, with an emphasis on ground cooling.

The project will demonstrate a variety of passive cooling techniques and the use of ground cooling systems for housing in Crete and Portugal, a nursing home in southern France and a community centre in Italy. The project partners include architects, energy designers, social housing providers and developers, the project will last 48 months.

One of the principle objectives is to determine the potential of passive and low energy control of internal temperatures with the aim of providing occupant comfort, while reducing energy consumption and CO_2 emissions. The Coolhouse partners aim to design ground cooling systems that are low energy, practical, low maintenance and easy to replicate at reasonable cost.

The paper will describe the design parameters that influence the efficiency and cooling capacity of the ground cooling system, and cleaning, maintenance and possible drawbacks will also be discussed. Each of the projects will be described, with an emphasis on the technical aspects of the project in Portugal as it is the most advanced.

1 Introduction

The energy used for air conditioning in domestic buildings in southern European countries has overtaken that of heating. If energy consumption can be reduced by passive or low energy control of internal temperatures, the release of millions of tons of carbon dioxide into the atmosphere would be reduced and the countries could go a long way to achieving their Kyoto commitments for the reduction of CO_2 emissions.

2 Introduction to the Coolhouse project

The Coolhouse project is a European Commission supported demonstration project in the ENERGIE Programme. The project aims to test the viability of alternatives to air conditioning using passive and low energy cooling and ventilating techniques in Mediterranean and coastal climates and to demonstrate that such strategies can be practical and provide comfortable internal conditions for the occupants. One objective of the Coolhouse project is to reduce the energy demand and the environmental impact of the developments. Another is to provide economic and environmental arguments to justify the cost (life cycle versus capital cost) of the systems and to design and construct ground cooling systems that are easy to replicate at reasonable cost.

Potential natural ventilation and cooling strategies[1] originally considered included wind catchers, wind towers, ground pipes, and rock stores. However, the concept of ground cooling systems is common to all four sites. The Coolhouse project involves the architectural integration of ground cooling systems into new housing developments in Crete and Portugal, a nursing home in southern France and a community centre in Italy.

The developers in each country are working in partnership with energy consultants to achieve the project aims. The Coolhouse partners come from southern France, Portugal, Italy, the UK and Greece. As well as our role providing concept and detailed design support for the design team in Portugal, ECD are also responsible for co-ordinating the project input of the eight European partners. Coolhouse started in January 2000 and the project will last about 4 years.

Currently, the design process is being undertaken, using computer modelling and simulation. The proposed designs will then be built with the aim of completing construction by 2003. After completion, system usage and the internal conditions will be monitored in the occupied buildings for one year.

3 Ground cooling

Ground cooling is one of the technologies likely to be used in all projects and has been given early consideration.

3.1 Introduction to ground cooling

The thermal properties of the ground, with the aid of earth-to-air heat exchangers, can be used for the indirect cooling of the indoor air of a building. The cooling effect is achieved by burying earth-to-air heat exchangers (ground pipes) horizontally at a designated depth, and circulating air through them with the assistance of fans. This technique, popularised in the 1970's and 1980's as an environmental alternative to conventional air-conditioning and further developed recently, is based on a similar concept applied by the Persians and Greeks in the pre-Christian era. Constructions from the 16th century using natural cavities ("covoli") have been unearthed in the hills of Vicenza, Italy[1]. To date, there are few resources and little practical information available on ground cooling systems and research conducted to improve design and efficiency has been limited. There are relatively few known functioning examples of ground cooling installations and little quantitative post-construction performance-related data. Monitoring the performance of the installations in four different countries in the Coolhouse project will be beneficial to ground cooling research.

3.2 The principles of ground cooling systems

The principle concept of a modern ground cooling system is the drawing of fresh ambient air, with the assistance of fans, through pipes buried under ground. In summer, the temperature of the ground is lower than the ambient air. As the air circulates through the ground pipes, it loses heat to the surrounding soil before being drawn into the building, cooling the indoor air.

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[1] Santamouris M. and Asimakopolous, D. (editors); p.367

The converse occurs in winter, with the air circulating through the ground pipes gaining heat from the soil, effectively pre-heating the ventilation air for the building. The ground cooling system can be either an open or closed-loop design. In an open-loop configuration, ambient air is drawn through the ground pipes, cooled by the surrounding soil, and dispatched to the interior spaces of the building, providing ventilation and cooling (See Fig. 1). In a closed-loop system the air inlet and outlet are located in the building and the building's air is recirculated through the ground pipe system. A closed-loop system is considered to be more efficient as it does not exchange air with the outside (See Fig. 2). Both ground cooling systems could be used for night cooling during the summer months.

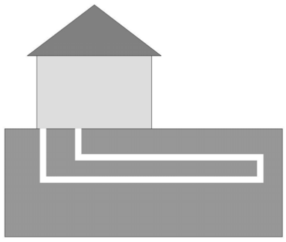

Fig. 1 Open-loop system **Fig. 2 Closed-loop system**

3.3 Design parameters

Several design parameters will influence the cooling capacity of the ground cooling system. The length and diameter of the pipes is critical, as they must be long enough to induce the required amount of cooling at the appropriate air change rate within the constraint of site area. The flow velocity, the flow volume, the variety of commercially available ground pipe products and cost should also be considered. The cooling effect produced (decrease in air temperature) depends on the inlet air temperature, the thermal diffusivity of the soil and its temperature at the depth of the ground pipes, the thermal conductivity of the pipes and the air velocity and pipe dimensions[2]. Santamouris et al. [3] maintain that, as a rule of thumb, the length of the ground pipes should be at least 10m and the air velocity through them should range between 4 and 8m/s. According to the U.S. Department of Energy[4], pipe diameters between 6 and 18 inches (15.2 and 45.7cm) appear to be most appropriate. According to Evans[5], the pipe diameter should be larger for open-loop systems to facilitate cleaning and maintenance and to prevent the growth of mould and bacteria. Where the site constraints allow, the pipes should be located under soil that is shaded for a significant part of the day, as the temperature of the soil varies significantly from sunny to shaded locations and this can affect ground pipe performance and the extent of the cooling effect. Santamouris et al.[6] believe that the optimum pipe depth should be between 1.5 and 3m. A minimum ground pipe depth of 2m would probably be sufficient. A ground pipe depth of greater then 3.5m is rarely justified as the cooling effect produced is not significantly greater and large depths can contribute to dangerous cave-ins during the excavation and installation process. A 2m separation between the pipes is recommended to reduce the possibility of thermal saturation and interference. Pipe bends should not be sharper than 90° due to the resultant air pressure

[2] Santamouris, M. and Asimakopolous, D. (Editors); p.367

[3] Santamouris M. and Asimakopolous, D. (editors); p. 389-390.

[4] Energy Efficiency and Renewable Energy Clearinghouse (EREC); p.1

[5] Evans, B.; p. 48

[6] Santamouris M. and Asimakopolous, D. (editors); p. 390

loss and to facilitate cleaning. The material of the ground cooling pipes must maintain a good balance of durability, ease of installation, cost, resistance to corrosion, ease of cleaning and low environmental impact. The ground pipes can be made of metal (e.g. aluminium), plastic (PVC or polypropylene) or concrete. However, the choice of material has little influence on thermal performance.[7] The thermal capacity of the surrounding soil type is important, as is the careful selection of backfill for the pipes to maximise their cooling capacity. The ground pipe system must have optimum thermal contact with the soil in order to produce the maximum cooling effect. Santamouris et al.[8] recommend that the pipes are surrounded by a 50mm layer of sand before being buried. Sand has relatively good thermal conductivity and provides a better insulative cover than raw earth, which would contain air pockets when backfilled. The air inlet should be constructed in an unobstructed area to maximise the positive wind pressure, reducing the need for fan power. This terminal should be located in a shaded area to prevent direct sun heating the inlet and thus, the incoming air. The type of inlet terminal is dependent on whether the prevailing wind direction is constant for the desired period of cooling and/or heating. The terminal could be fixed if the prevailing wind direction is constant, or omni-directional to account for the differences in wind direction. The average wind speed for the location should be determined during the design phase. To maximise the efficiency and operation of the ground cooling system an automatic control algorithm must be included. The algorithm should compare the inlet (ambient) and outlet (indoor) temperatures and be linked to fan regulation. Detailed calculations and the use of computer analysis and simulation tools are needed to optimise a ground cooling system.

3.4 Potential Problems

Appropriate precautions should be taken when undertaking excavation works and digging deep trenches in order to lay the ground pipes. Cave-ins are a potential hazard. Potential drawbacks could be possible health issues and the transfer of odours through the ground pipes. Ground cooling pipes are most suitable for hot, dry climates. In hot, humid climates the ground does not remain cool enough at a reasonable depth during summer. The relative humidity of the building location must also be taken into account, as there can be a risk of condensation if the soil (and therefore pipe wall) temperature is significantly lower than the ambient temperature, encouraging the growth of mould and odour-producing bacteria. According to Santamouris et al.[9] the accumulation of condensation in ground pipes is rare, but will affect the quality of the air drawn into the building, if it occurs. This problem can be countered by installing a well-designed drainage system and placing the appropriate type of filter at the air outlet. Drainage sumps could be provided at regular intervals or at the bends in the pipes and the pipe length designed to fall toward them. Access to the ground pipe system should be provided and cleaning and maintenance should be carried out regularly. A vacuum-type cleaner may be effective for pipe maintenance. The installation of a screen or mesh grill over the air inlet could be used to remove airborne grit at the air inlet, and would prevent the problems associated with the entry of insects or rodents into open-loop systems. However, these would have to be cleaned regularly and may cause a slight drop in incoming air pressure. The fan designated to assist the ground cooling system must be carefully chosen for efficiency and to avoid potential noise problems. Earth-to-air heat exchangers, in the form of ground cooling systems, are relatively simple systems, however, as their design and installation is still in the experimental stage, the system could potentially be very expensive

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[7] Energy Efficiency and Renewable Energy Clearinghouse (EREC); p.1

[8] Santamouris, M. and Asimakopolous, D. (Editors); p.390

[9] Santamouris, M. and Asimakopolous, D. (Editors); p.388

in terms of labour, excavation, cost of materials and equipment. These factors will all be investigated in the Coolhouse project.

4 The demonstration sites

The four sites currently included in the project are:-

4.1 Italy

Fig. 3
Vigevano, Italy

The ***Pietrasana neighbourhood, Vigevano, Italy,*** is an area of existing social housing undergoing refurbishment by ALER Pavia. The project consists of 220 dwellings located in 10 buildings. The central courtyard area is to be refurbished and a new community centre ("CircoLab") built. The community centre, part of the Coolhouse project, is a multi-purpose facility with corporate, conference, recreational, cultural and community functions. It is anticipated that one-third of the cooling will be derived from passive and low-energy means; an atrium and a ground cooling system. This system will improve thermal comfort, have a low impact on the environment and reduce maintenance costs. The remainder will come from radiant chilled ceilings and ground water cooling tubes. Softech Consultants have been using a spreadsheet developed in-house to analyse and simulate the thermal performance of the ground pipes in order to design and size the ground cooling system. The results of preliminary simulations are presented below in Table 1. The ground temperature at a depth of 4m has been calculated at 16.7°C when the ambient temperature in summer is 30°C. The ground cooling system design presented in Table 1 reduces the ambient temperature by 12.3°C to 17.7°C. This outlet temperature can be achieved by maintaining a constant air speed of 3.75m/s and an air flow of 0.47m^3 /s in the ground pipes. The ground pipe cooling system is 60m in length, while the pipes have a diameter of 400mm and are located at a depth of 4m below the ground surface. It is likely that a mechanical ventilation system will be installed for further cooling the ventilation air when necessary in the CircoLab, as the meeting facility can be occupied by up to 300 people. The relative air humidity in the Vigevano area is usually over 80% in summer. Due to the fact that humidity in the ground pipes may result in poor air quality, it has been decided to install a heat recovery unit (with separate inlet/outlet flows) to provide essential dehumidification. At this stage the ground pipe system will not form part of the heating strategy in winter. 6 glazed air solar collectors are to be integrated into the design of the CircoLab roof. It is estimated that the warm air from these solar collectors will pre-heat 1/3 of the fresh air needs of the building. The remaining 2/3 will be pre-heated by a heat recovery unit on the mechanical ventilation system. Designing the controls for this building, which will have a complex pattern of use and will include the operation of at least 3 different systems plus heat recovery, is going to be a challenge. The winner of the architectural competition to design the community centre has been chosen. The system design of the ground cooling pipes and other energy-efficient systems is currently being undertaken. Liaison has been made with the local authorities to obtain building permission. The tender is currently being prepared. The final design will be complete in late 2001 and construction should be complete by the end of 2002.

Selected Pipe Size		
Pipe diameter	0.40	m
Pipe length	60	m
Pipe depth	4	m
General assumptions		
Air density	1.14	Kg/m^3
Air specific heat	1010	J/Kg°C
Thermal contact resistance ground/pipe	0.01	m^2°C/W
Thermal exchange coefficient air/pipe	23	W/m^2°C
External conditions		
Ground temperature (at – 4 m)	16.7	°C
Inlet air temperature	30	°C
Air speed in the pipe	3.75	m/s
Air flow in the pipe	0.47	m^3/s
Air flow in the pipe	1696	m^3/h
EXPECTED RESULT		
Outlet air temperature	17.7	°C

Table 1 Simulation of the thermal performance of the ground pipe, Italy

4.2 Greece

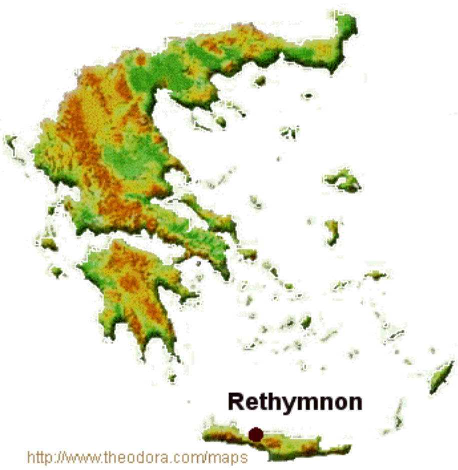

Fig. 4
Rethymnon, Crete, Greece

El Greco Ecological Development, Rethymnon, Crete, Greece is situated on the north coast of the island, close to Chania, on the shores of the freshwater Lake Kourna below Mount Trypali. 2% of the site will be occupied by buildings; consisting of 450 villas, 500 apartments, a 200-room hotel and conference centre, commercial space with sporting, cultural, leisure and tourist facilities. The community will have a population of around 2 200; including 350-400 tourists per day. Due to the climate, the majority of the total energy use consists of the cooling load. The use of passive cooling techniques will significantly reduce the cooling energy required by the residential buildings in summer. The passive and low energy cooling strategies such as, ground cooling, evaporative cooling, night time forced ventilation and the utilisation of high efficiency heat pumps for cooling, will lead to significant energy savings and a reduction in CO_2 emissions. There are 20 residences, of approximately 200m^2 floor area each, that form part of the Coolhouse project. The ground cooling system will be open-loop and will consist of three 350mm diameter pipes around 30m in length at a depth of 3m below the ground surface. Detailed design has not yet started.

4.3 France

Fig. 5
Fréjus, France

L'Aubier de Cybelle, Fréjus, France is an 80-bed nursing home to be built on a site a few kilometres from the "French Riviera" in Provence. The building consists of 3 floors on a south-facing site close to the city centre. Passive cooling strategies include the optimum use of insulation, overhangs, roller shutters, thermal mass, fixed and moveable shading devices, landscaping and vegetation. No compression cooling will be installed. An innovative, low energy cooling strategy, in the form of a fan-driven ground cooling system, is currently being designed. It has been decided that the ground cooling system will only be used during the day where the internal gains are highest. Therefore, the system has been restricted to the amenity wing and communal spaces of the building and fan-assisted night ventilation for the southern most bedroom wing is planned. The internal air distribution and controls are also being designed. Computer analysis and simulation tools such as "Costic" and "COMFIE" are being used to design and size the ground cooling system. The system will consist of 10-12 pipes (with a diameter of 150mm) at a depth of 2m below the ground surface. The pipe length will be determined by the availability of the commercially products on the market. Construction should start on site by late 2001 and will be complete within a year to 18 months.

4.4 Portugal

Fig. 6
Vila do Bispo, Portugal

Alma Verde Village and Spa, Vila do Bispo, Portugal is a development in the western Algarve region on Europe's Atlantic coast. The 36-hectare site is located on a hillside above the main coastal road, which runs from Faro through Lagos to Sagres. This new community will consist of 128 villas, 45 townhouses and 35 apartments, a spa, gymnasium, health centre, library, tennis courts, pools, alternative therapies, restaurants and bars. The climate is considered "Mediterranean" with an average temperature of 18^0C and approximately 3000 hours of sunshine per annum. However, the site is between 10 and 60m above sea level, affected by Atlantic winds all year round and has 500mm of rainfall annually. The design of the ground cooling system at Alma Verde is the most advanced of the 4 sites at present. A fan-driven ground cooling system will provide summer cooling (and possible night ventilation) for the villas; no air-conditioning will be installed. A 3^0C temperature difference is predicted to be achieved by the passive and low energy cooling techniques, resulting in improved comfort for the occupants and a reduction in the environmental impact of the development.

4.4.1. Alma Verde Ground Cooling modelling

Modelling description and procedure

A report on ground cooling modelling was prepared by ECD with the aim of sizing and optimising the design of the ground pipe system for summer cooling through simulation. The ground-cooling model was developed by University of Athens (CIENE) as part of the Summer 2.0 suite of passive cooling tools[10]. It is a simplified system design tool, based on an analytical solution of the conservation of heat energy equation for heat transfer from pipes in soils[11]. Model inputs include; weather (hourly average air temperature etc.), pipe properties (length, depth, air velocity etc.), soil properties (soil type, moisture content, thermal properties etc) and output calculation nodes (co-ordinate locations of the nodes for which output temperature data is required). The main limitations of the model appear to lie in the modelling of the ground temperature distribution and the assumption that the air speed in the pipes is constant over the whole period. The data from a METEONORM weather station for Faro was used. The modelling procedure consists of using the outlet temperatures predicted by the ground cooling tool (Summer 2.0) to model resulting building thermal performance in the TAS dynamic thermal simulation program.

System design considerations

An external temperature of 27°C is exceeded for just under 10% of the year. The mean exceedance temperature is 3°C (Max. = 10.5°C). Therefore, the goal of this system design is to reduce the external temperature by 3°C as this will maintain internal comfort for just over 96% of the year. A peak cooling load of 3kW was projected by TAS modelling of the whole house. Neglecting latent heat gains, an approximate flow rate of the order of 0.83 m^3s^{-1} would be required to balance the internal gains through a supply temperature 3°C lower than ambient or internal air. The resulting ventilation rate is of the order of $7h^{-1}$. This would require excessive pipe flow speeds for a single pipe. Therefore it is clear that multiple pipes are required. Rough calculations show that half of this could be supplied by three 160mm diameter pipes operating at a flow rate of $7ms^{-1}$ (Total flow rate = 0.41 $m3s^{-1}$). This is the maximum permissible within the given constraints. A reduction of 6°C would enable the peak cooling load to be met with less than $4h^{-1}$, which would enable the system to run at lower pipe speeds of 2.4 and 1.2 ms^{-1} for 110mm and 160mm diameter pipes respectively.

Soil type was analysed and found to be a composite of sand and white clay. No data on moisture content of the soil was available. This has a significant effect on soil thermal properties. Sand has a higher thermal conductivity but a lower specific heat capacity than clay. The exact type of bedding is not yet known. A model sensitivity analysis was performed for the range of possible values for this soil mix from data sources in literature (See Table below). The values are for a range of soil moisture content (0.3%-36%). The sensitivity refers to the percentage change in peak temperature predictions and peak energy absorption by the soil with respect to the soil values that are used for this study. Soil thermal conductivity clearly has the largest impact, with differences of up to 15% on peak temperature prediction and 70% on energy absorption across the range of possible values. Model sensitivities to incremental changes of 10% in soil properties were generally less than changes in pipe parameters.

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[10] Klitsikas, N., Geros, M., Santamouris, M., Dascalaki, E., Kontoyiannidis, S. and Argiriou A.

[11] Mihalakakou, G., Santamouris, M. and Asimakopoulos, D. p.301-305

Property	Range	Sensitivity
Type	Sand – Fine Clay	3% on T_{max} 14% on E_{max}
Thermal diffusivity (α)	0.139 – 1.26 x 10^{-6} m^2 s^{-1}	-1 – 0.3% T_{max} 4 -- -1.4% E_{max}
Thermal Conductivity (λ)	0.16 – 2.30 W m^{-1} K^{-1}	15 -- -4.9% T_{max} -67 -- 25% E_{max}
Specific Heat Capacity (c_p)	712 – 837 J kg^{-1} K^{-1}	0.3% T_{max} -1.4 -- 0% E_{max}
Density (ρ)	1200 – 5240 kg m^{-3}	No direct effect

Table 2 Soil properties.

The temperatures go through waves of hot periods with a slow cool-down. These cycles have a periodicity of about three weeks, after which night-time temperatures can go as low as 13°C. These cycles should ensure that the ground does not become fully thermally saturated in summer. However, solar radiation is high in summer, therefore the ground above the earth tube system needs to be shaded as much as possible.

Modelled scenarios

The base case is taken as a starting point for the optimisation process (See Table 3 below). The base air speed is selected in order to maintain an air change rate of $4h^{-1}$. The effect of varying depth, length and airflow rate is demonstrated.

Parameter	Modelled Base Case
No. of Pipes	3
No. of Nodes	10
Pipe Length	24.5m, 16m and 10m
Pipe Radius	0.080m
Pipe depth	2m
Air speed	7 ms^{-1}
Separation	2m
Pipe material	PVC
Pipe thickness	0.003m
Soil Type:	Sand
α	1.168x10^{-6} m^2 s^{-1}
λ	1.83 W m^{-1} K^{-1}
c_p	712 J kg^{-1} K^{-1}
ρ	2200 kg m^{-3}
Soil RH	40% default
Ground Temp.	Mean Ann. Surf. = 17°C
	Ampl. of Surf. Wave = 8.8°C

Table 3 Base case parameters.

The base case was run first for July, in which external air temperatures peaked at 37.5°C (See results in Table 4 below). Peak cooling delivered by the 10m, 16m and 24m pipes was 0.75, 1,09 and 1.51 kW respectively, giving a total peak cooling of 3.3kW, comfortably meeting the projected peak cooling demand. Mean delivered total cooling of this configuration was 0.23kW.

	Inlet Temperature (°C)		Outlet Temperature (°C)		Cooling Energy (W)	
	Mean	**Max**	**Mean**	**Max**	**Mean**	**Max**
Pipe 1 (L=25m)	24.0	37.5	22.1	29.1	330.1	1510.7
Pipe 2 (L=16m)	24.0	37.5	22.7	31.5	222.9	1086.3
Pipe 3 (L=10m)	24.0	37.5	23.2	33.3	142.5	746.8
Total 3 Pipes	24.0	37.5	22.7	31.3	695.5	3343.8

Table 4 Predicted outlet temperatures and cooling energy rates for the base case.

Variations

The predicted impacts of variations in pipe and soil parameters on the full 3-pipe arrangement of the base case, with resulting outlet temperatures and cooling energy, are summarised in Table 5 below.

Case name	Variation	Inlet Temp. (°C)		Outlet Temp. (°C)		Cooling Energy (W)	
		Mean	**Max**	**Mean**	**Max**	**Mean**	**Max**
Mod1	**Base**	24.0	37.5	22.7	31.3	696	3344
Mod-s	**Clay Soil**	24.0	37.5	23.2	32.9	405	2478
Mod-d0	**Depth=1.5m**	24.0	37.5	22.8	31.4	619	3293
Mod-d0	**Depth=2.5m**	24.0	37.5	22.5	31.1	771	3395
Mod-r2	**Radius=55mm**	24.0	37.5	21.9	28.5	523	2254
Mod-v2	**$V=2ms^{-1}$**	24.0	37.5	21.2	26.6	415	1629
Mod-v3	**$V=3ms^{-1}$**	24.0	37.5	21.7	28.1	510	2117
Mod-v4	**$V=4ms^{-1}$**	24.0	37.5	22.0	29.3	576	2512
Mod-v5	**$V=5ms^{-1}$**	24.0	37.5	22.3	30.1	626	2837
Mod-v6	**$V=6ms^{-1}$**	24.0	37.5	22.5	30.7	665	3099

Table 5 Comparison of model results.

The base case simulation clearly demonstrates the effect of **pipe length** on outlet temperatures and cooling. The 25m pipe delivers twice the mean and peak cooling of the 10m pipe and twice the mean and peak temperature reductions on inlet temperatures. Site constraints would make it difficult to increase the **number of pipes** on the base case. As cooling energies are additive, the impact of a reduction in pipe number can also be seen from the base case; if the 10m pipe were to be removed a 2.5kW peak cooling energy would produce peak outlet temperatures in the region of 31°C. Clay **soil type** was also tested. This gave a reduction of 26% in the peak cooling capacity of the base case (sand). Given that the soil type is a variable mix of sand and soil in the range of 8-64% soil, this could produce an error of up to 20% on the base case predictions. Increasing or decreasing the **pipe depth** by 0.5m produced a change of only ±2% in the peak cooling capacity. This does not justify additional excavation, but indicates that a depth of 1.5m may be acceptable. The 110mm **pipe diameter** option was also tested but at the same pipe velocities as the base case, hence a reduction in flow rate. This reduces the house air change rate to 1.8 h^{-1} from the base case of 3.8 h^{-1}. Consequently the peak cooling capacity is also reduced by one third. Increasing the pipe velocities further for this diameter is impractical. There is some scope for reducing **pipe velocities** (improving the thermal performance of the pipe) given that the 25m pipe delivers just under half of the total peak cooling, but at a temperature reduction of 8.4°C, rather than the 3°C anticipated in the sizing calculations. Reduction in pipe velocity was tested in the range 2-6ms^{-1}. Results show that a peak of 1.6kW of cooling can be supplied with pipe velocities of 2ms^{-1}. Peak outlet temperatures at this rate were predicted to be 26.6°C. However the dwelling air change rate will only be 1.1 h^{-1}. A more reasonable compromise in terms of energy efficiency is offered by velocities of 3-4ms^{-1}, which can deliver a peak cooling energy rate if 2.1-2.5kW. Dwelling air change rates of 1.6-2.2h^{-1} are provided at temperatures of 28-29°C, substantially lower than the peak external temperatures. The pipe wall temperature was extracted and compared with the dewpoint temperature for all variations. The greatest drops below dewpoint temperature were predicted for the pipe at depth 2.5m (T-Td=2.7°C) and for pipe velocity of 3ms^{-1} (T-Td=2.1°C). However this was for a very short period only and the magnitude of temperature drop does not pose a serious **risk of condensation** in the pipe.

Preliminary Design

The ground cooling system design below (Fig. 7 and 8.) is the outcome of performance analysis, system design, simulation and modelling, and discussions with engineers. The 200mm x 200mm air inlet is approximately 1.5m above the ground and is fixed due to the constant prevailing wind direction in summer. It is located on the shaded side of the building facing north-west so the air is not further heated on entry by direct sun falling on the inlet terminal. On entry, the air is directed downward to a single 11.6m long horizontal PVC ground pipe, which lies 1.3m away from the other pipes, due to site constraints. The air flows towards a node where the air volume is divided into three 23.5m long pipes at a depth of 1.5m below the ground surface. The 3 pipes have a diameter of 160mm, are located 2m apart and have a 1:80 fall towards the second node. Inside the house, an insulated plenum is located below the ground floor and is approximately 500mm deep. The plenum has been designed for the purpose of circulating and distributing the cooled air to the interior spaces of the villa. The external walls form the boundary of the plenum and it is divided into 2 spaces by the continuation of some of the internal walls below ground level. This is so that the air can be distributed to either the bedroom spaces or the living spaces, as they are used at different times, thus giving the occupants greater individual control over the two areas. From the second node the air, cooled from travelling through the buried earth tubes, is separated into two 250mm pipes and a separate fan for each pipe draws air into each of the two sections of the plenum. The cool air passes through the plenum, up through gaps between the wall and the floor slab and out of slots above the skirting in either the living spaces or the bedroom area. The air circulates through the interior spaces of the villa, cooling them and the stale air is exhausted through the open windows. The feasibility of implementing a night time ventilation strategy is currently being explored. In winter radiant hot water filled pipes in the skirting heat the interior spaces. The ground cooling system can be used to provide ventilation air when required in winter. As the ventilation air is drawn from the plenum into the living spaces it can be pre-heated by the radiant skirting system.

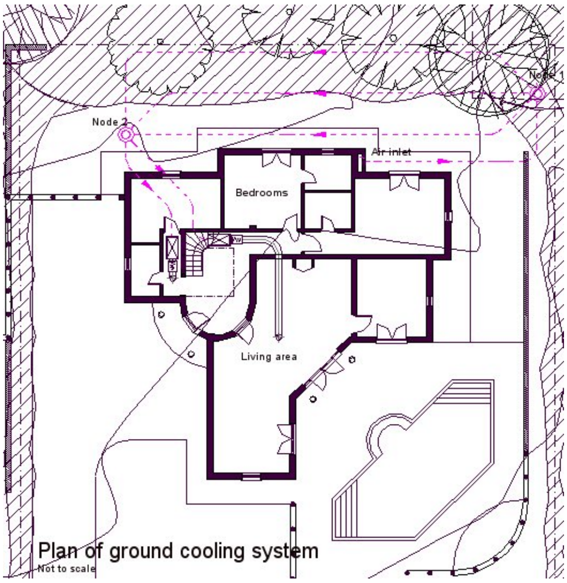

Fig. 7

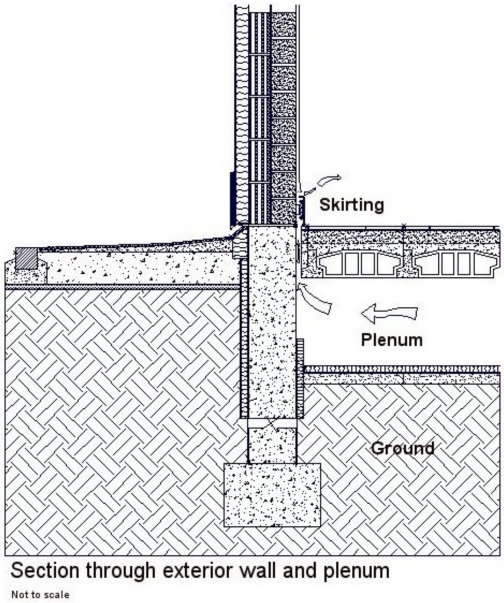

Fig. 8

The architectural design of the villas is complete, planning permission has been granted and the project is out to tender. Construction is expected to begin towards the end of 2001.

5 Preliminary conclusions

Ground cooling systems represent a hybrid combination of passive and active low-energy cooling techniques. The main principle of this system is that the ground, below a certain depth, maintains a constant temperature throughout the year; higher than the ambient temperature in winter and lower than the outside temperature in summer. There is a variety of ground cooling system types (such as direct thermal contact), but earth-to-air heat exchangers, in the form of buried ground pipes, has been explored in this paper. The ground cooling systems can be designed, sized and optimised through the use of calculations and computer analysis and simulations. Analysis of the Portuguese site has predicted outlet temperatures of 3-4°C below the ambient temperature. Particular attention should be paid to the avoidance of air quality problems and the design of simple and flexible operation controls.

References

- Energy Efficiency and Renewable Energy Clearinghouse (EREC); "*Earth Cooling Tubes*", U.S. Department of Energy, May 2001,
  Website: http://www.eren.doe.gov/consumerinfo/rebriefs/aa1.html
- Evans, B.; "*Ventilation Using Earth Tubes*", The Architect's Journal, 7th April, 1993.
- Klitsikas, N., Geros, M., Santamouris, M., Dascalaki, E., Kontoyiannidis, S. and Argiriou, A., SUMMER (Version 2.0) – A tool for passive cooling of buildings, EC DGXVII SAVE Programme, 2000.
- Mihalakakou, G., Santamouris, M. and Asimakopoulos, D.; *"Modelling the thermal performance of earth-air heat exchangers"*, Solar Energy, 1994, **53**(3): p.301-305
- Santamouris, M. and Asimakopolous, D. (Editors); "*Passive Cooling of Buildings*", James & James (Science Publishers) Ltd., 1996, London, pp.367 – 403