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USE OF BURIED PIPES FOR ENERGY CONSERVATION IN COOLING OF AGRICULTURAL GREENHOUSES

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Abstract—Earth-to-air heat exchangers can be used for energy conservation in cooling of agricultural greenhouses. A parametric analysis performed for a typical glass greenhouse illustrates the effect of pipe length, pipe diameter, and air velocity inside the pipes on the performance of the system. Measured data of indoor air temperature collected from a 1000 m^2 fiberglass covered greenhouse, equipped with four buried pipes, are compared with calculated data and are found to be in very good agreement.

1. INTRODUCTION

Agricultural greenhouses have been proven a viable solution to world-wide increased demand for expanding production, facilitating out of season cultivation, protecting crops from unfavourable outdoor conditions, and allowing the growth of certain varieties in areas where it was not possible before. Agricultural greenhouses in the European Community now exceed 60,000 ha, Von Zabeltitz (1988). In Greece they now exceed 3900 ha, Vasiliou (1992).

During summer and even clear days of winter, high solar radiation intensity increases the air temperature inside a greenhouse to excessively high levels. Temperatures exceeding 45°C are common in Greek greenhouses. Large temperature variations between day and night hours, and indoor temperature increases well above optimum levels during the day, can have a significant impact on the quality and quantity of the cultivation. To overcome this kind of problems, it is of primary importance to utilize low-cost, efficient and dependable alternative cooling technologies, like the use of natural or hybrid ventilation with roof or side openings, shading of cover material, improved efficiency cooling systems, like indirect or direct evaporative coolers, and better exploitation of alternative energy sources, which can provide optimum indoor conditions during summer.

The installation of a conventional cooling system is avoided in most applications, due to capital and operational cost increases. This is a particularly critical problem for small scale installations. Even for applications equipped with cooling systems, there is a great interest for energy conservation, which will make the operation of the systems more attractive and could benefit individual growers. On a larger scale, this could also benefit national economies, since according to Caouris *et al.* (1989), agricultural greenhouses consume for indoor thermal control (primary for heating and in some cases for cooling) approx. 1.5% of Europe's total energy budget.

The problem of high indoor temperatures can be solved with mechanical cooling systems, although this will increase the installation and operation cost of the greenhouse. Alternatively, passive solar agricultural greenhouses solely rely on natural ventilation and shading. Side or roof openings allow for air movement inside the greenhouse, which can be enhanced by using mechanical fans. This allows for better control of the air velocities and direction. During the summer, shading can contribute significantly to the reduction of indoor air temperatures. The external side of the greenhouse cover is simply painted with a white reflective coat, which is washed away by rain during fall. This way the transmissivity of the cover is significantly reduced during the summer, thus decreasing the amount of solar radiation that is trapped inside the greenhouse.

Alternatively, the greenhouse can be coupled with the ground which can be viewed as an easily accessible heat source or heat sink. Several greenhouse applications using the underground soil as a heat source, have demonstrated the success of such systems for reducing the heating requirements. In a similar manner, the same system can be used during the cooling periods,

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to transfer heat from inside the greenhouse to the lower temperature underground soil which acts as a heat sink. A simple drawing demonstrating the system and its operation, is shown in Fig. 1.

The European Commission is promoting the use of such systems through its research and development, and demonstration programmes. A typical passive solar agricultural greenhouse, designed, constructed and monitored in Greece (Santamouris *et al.*, 1994) within the frame of the Energy Demonstrations Programme of the European Commission, has provided valuable information on the success of similar systems. Some experimental results from this project are presented in Section 3.

2. GREENHOUSES WITH UNDERGROUND PIPES

Soil temperature remains much lower than summer ambient air temperatures, in depths only a few meters (around 1.5 m) from the ground surface. Using plastic or aluminum buried pipes, excess heat is transferred with the air from inside the greenhouse, through the underground pipes, and is dissipated to the lower temperature soil. Pipes usually run along the length of the greenhouse, with entrance and exit points of the circulating air at opposing sides.

During daytime, warm, humid air is drawn from the upper parts of the greenhouse and is driven through the underground pipes, which act as earth-to-air heat exchangers. The warm air gives up its heat content to the pipe, by condensation, and is then dissipated to the soil by conduction. The cooler air is then returned back inside the greenhouse.

The same system can also be used for periods when both cooling during the day and heating during the night, are desirable. In the heating mode, cold air from inside the greenhouse is circulated through the pipes which act now as earth-to-air heat exchangers. Heat is transferred from the soil to the air stream and then back to the greenhouse. The water condensed within the underground heat storage pipe is either drained away or evaporated by the forced air flow. The pipes are placed with a tilt of a few degrees, so that any condensation is drained away through a small opening at the end of the pipe. In any event though, from personal experience, we have never observed any significant condensation problems at various monitored greenhouse installations.

The control of indoor conditions depends on the type of the greenhouse. For simple passive greenhouses, natural ventilation through the cell's large openings provide sufficient air changes for maintaining acceptable indoor gas concentrations and depending on outdoor conditions, analogous temperature and humidity. More elaborate installations may use a micro-computer controller which implement the complex control strategies (Santamouris and Lefas, 1986), for example ventilation, watering, temperature or CO_2.

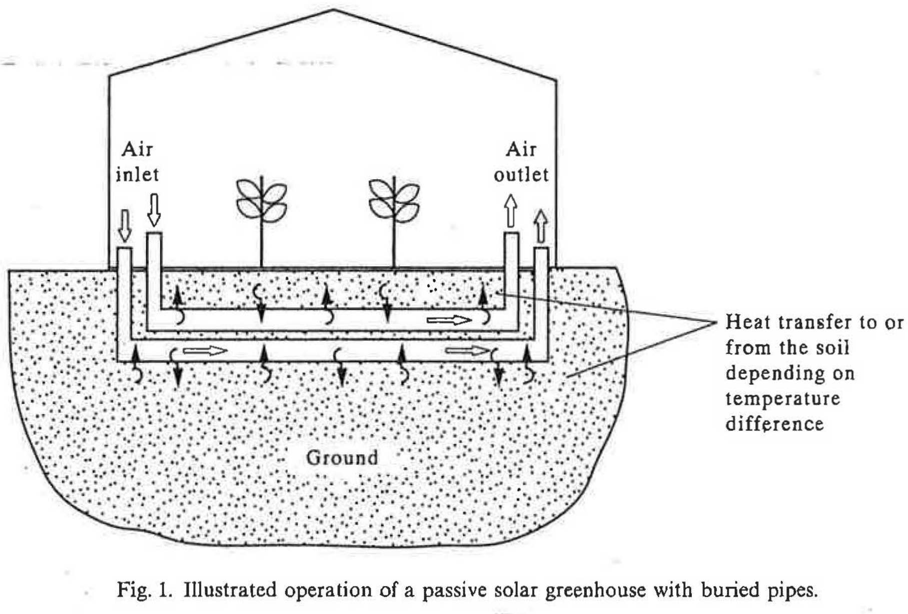


Fig. 1. Illustrated operation of a passive solar greenhouse with buried pipes.

2.1. Representative applications

A representative number of passive solar greenhouses using underground pipes for heating purposes which have been identified during a CEC Thermie Programme, Santamouris *et al.* (1991a), are summarized in Table 1. Since the same system can be used for cooling purposes, during the summer, it is of interest to review the technical characteristics of representative applications, along with any available information on their performance and economical aspects. Their potential effectiveness for cooling is evaluated in Section 3, along with a presentation of experimental results from a pilot application in a Greek greenhouse.

The underground pipes act as simple earth-to-air heat exchangers. They are buried at depths varying between 50 and 200 cm and a spacing between them of approx. 40 cm. The heat exchangers are constructed using plastic, aluminum or concrete pipes, having 10–20 cm dia. Plastic pipes, with a total length of 100 m, buried at a depth of 80 cm, have been used in a 3000 m^2 glass cover greenhouse (Jaffrin *et al.*, 1982). Two rows of plastic pipes are also used at a 1736 m^2 glass greenhouse (Kozai, 1985), buried at a depth of 50 and 90 cm, respectively. The diameter of the pipes is 10 cm, with a total length of 5872 m. Plastic pipes are also used at a 100 m^2 glass covered greenhouse (Bernier *et al.*, 1987). In total, 16 pipes are buried at a depth of 0.45 and 0.75 m. The length of each pipe is 12 m and its diameter is 10.2 cm. The air is supplied at a rate of 3240 m^3/h. The system satisfies 35% of the annual heating requirements of the greenhouse. A single row, of 4 cm dia. plastic pipes, buried at a depth of 40 cm have been used in an experimental greenhouse (Imamkulov, 1986). The air circulates at a rate of 21.6 m^3/h. A small experimental greenhouse (Yoshioka, 1989) has also been equipped with nine plastic pipes (114 cm dia., 7.8 m long), buried underground at a depth of 50 cm. The temperature of the air inside the greenhouse was maintained 4°C higher than the minimum ambient temperature. A similar system is also used at a 835 m^2 polyethylene covered greenhouse (Bascetincelik, 1987). The 10 cm dia. plastic pipes are buried at a depth of 0.5 m from the ground surface. The air flow rates are maintained with axial propeller fans at 10,000 m^3/h. An average interior air temperature of 5°C higher than the outside air temperature was maintained during January and February. The

Table 1. Passive solar greenhouses using buried pipes

Location	Surface (m^2)	Cover material	Cultivation	Storage medium	Installed	Results	Reference
Adana, TU	835	P.E.	—	Plastic (50 cm deep)	1984	5°C higher	Bascetincelik (1987)
Montreal, CA	100	Glass	Plants	Plastic (45 and 65 cm deep)	1986	35% cover	Bernier *et al.* (1987)
Catania, IT	200	P.E.	—	Concrete (40 cm deep)	1989	3–4°C higher	Bombelli (1989)
Avignon, FR	176	Polycarbon	Vegetables	Concrete (0.4 and 0.8 m deep)	1985	50% cover	Boulard *et al.* (1989)
Quebec, CA	72	Fibreglass	Plants	Plastic (30 and 60 cm deep)	1985	10°C higher	Coffin (1985)
Jange, FR	1470	—	—	Rough cast (45 cm deep)	1985	—	Herve (1990)
Bukhara, USSR	—	—	Plants	Plastic (40 cm deep)	1986	—	Imamkulov (1986)
Nice, FR	3000	Glass	Eggplant	Plastic (80 cm deep)	1979	—	Jaffrin *et al.* (1982)
Rome, IT	1000	Glass	—	Concrete	1985	—	Johnson (1990)
Iver, UK	1000	Glass	—	Concrete	1985	—	Johnson (1990)
Yokohama, J	1736	Glass	Tomatoes	Plastic (0.5 and 0.9 m deep)	1984	28% cover	Kozai (1985)
Athens, GR	150	P.E.	—	Aluminum (2 m deep)	1981	3°C higher	Mavrogiannopoulos and Kyritsis (1985)
Valencienne, FR	58	Double P.E.	Plants	Plastic (2 and 2.1 m deep)	1980	62% cover	Mihalakakou (1994)
Agrinio, GR	1000	Fibreglass	Roses	Plastic (1.5 m deep)	1986	48% cover	Santamouris and Lefas (1986)
Athens, GR	1000	Glass	Flowers	Plastic (1.5 m deep)	1988	30% cover	Santamouris and Lefas (1986)
Volos, GR	2500	Polycarbon	—	Plastic (1.2 and 1.8 m deep)	1991	—	Santamouris *et al.* (1991)
Kumano, J	46	Plastic	—	Plastic (50 cm deep)	1988	4°C higher	Vasiliou (1992)
Saintes, FR	297	P.E.	—	Plastic (1.2 m deep)	—	—	Yoshioka (1989)

operating ventilators caused a decrease of relative humidity inside the greenhouse to 65%.

Aluminum pipes, with a diameter of 20 cm and a length of 15 m each, are buried at a depth of 2 m, at a 150 m^2 polyethylene cover experimental greenhouse (Mavrogiannopoulos and Kyritsis, 1985). A 58 m^2 double polyethylene cover experimental greenhouse, described by Portales *et al.* (1982), uses two rows of plastic buried pipes, at a depth of 80 and 210 cm. In a similar application described by Boulard *et al.* (1989), a 176 m^2 polycarbonate cover experimental greenhouse, uses 19 plastic pipes buried into two rows at a depth of 40 and 80 cm, with a distance of 80 cm between them and an air flow rate of 7400 m^3/h. Concrete pipes, with a 15 cm pipe dia., 21 cm pipe length, buried at a depth of 40 cm, are used in a 200 m^2 polyethylene cover greenhouse, described by Bombelli (1989). The distribution of the air inside the greenhouse can be performed using a centrifuge fan that circulates the air through a perforated polyethylene duct. During the winter months, the night air inside a greenhouse equipped with underground pipes, can reach temperatures ranging between 3 and 5°C higher than a conventional greenhouse.

A 1470 m^2 market garden greenhouse is described in Herve (1990). The installation consists of an air suction system using centrifugal fans, downward air ducting, an underground rough cast pipe (at a 45 cm depth) and a return air distribution network. Control equipment, using hygrometric/thermometric instrumentation and suitably positioned sensors, ensure automatic regulation and operation. However, the depth of the underground storage pipe was found insufficient for the necessary transfer of heat to the soil. The payback period is estimated at 2.6–3.2 yr.

In some applications, the underground pipes are combined with a north storage wall, another commonly used passive heat storage system. Material with high heat storage capacity, like concrete blocks, poured concrete, or water barrels, are used to absorb the incident solar radiation. The absorbed energy increases the material temperature, which however remains smaller than the air temperature inside the greenhouse. During the night, the temperature of the wall is higher than the air temperature inside the greenhouse and heat is convected and radiated from the wall to the air. During the winter days, the excess heat from the greenhouse is transported through the buried pipes to the ground, as it was previously described. The presence of the wall also reduces the peak daytime temperature, during the summer. A portion of the available energy from the high solar gains during the day is absorbed and stored by the wall material, and is then progressively released to the indoor environment at a later time. As a result, it regulates the magnitude of indoor temperature swings, there is a time shift of the peak load, a reduction of the maximum load value and a time lag of the heat release from the material to the indoor air. The heat released during latter part of the day can then be removed from the interior by either natural ventilation, since the outdoor conditions are more favourable, or by using the underground pipes.

A 1000 m^2 fiberglass greenhouse in Agrinion, Santamouris *et al.* (1987), is equipped with a north storage concrete wall (30 cm thick cement blocks filled with concrete), externally insulated with a 5 cm polyurethane layer and internally painted black, and four plastic earth-to-air heat exchangers (22 cm in dia. and a length of 30 m each), buried at a depth of 1.5 m. Monitoring of the greenhouse for over a period of 2 yr has shown that the passive systems have supplied energy equal to 35% of the heating requirements of an identical conventional greenhouse. A similar 1000 m^2 glass greenhouse in Athens, Santamouris *et al.* (1987), combines a concrete north storage wall (30 cm wide concrete blocks) and four ground to air heat exchangers (25 cm in dia. and a length of 25 m each), buried at a depth of 1.5 m. A 2500 m^2 polycarbonate cover greenhouse, Santamouris (1991b), uses underground plastic pipes (25 cm in dia.), buried in two rows at a depth of 1.2 and 1.8 m, respectively. A small experimental greenhouse, Coffin (1985), is connected to the underground through 10 cm dia. air pipes, buried in two rows at a depth of 30 and 60 cm. The system maintained the interior air temperature at 10°C higher than the minimum outdoor air temperature. Overall, the combination of a north storage wall and a network of buried pipes can satisfy 30–55% of the annual heating needs of the greenhouse.

All the above applications have demonstrated the success of underground heat storage and retrieval in reducing the heating load of agricultural greenhouses. However, since the same system can also be utilized for cooling purposes it is essential to estimate its cooling potential. The following section presents the results from a detailed analysis for estimating the effectiveness and performance of a typical agricultural greenhouse equipped with underground pipes during the summer months.

3. COOLING PERFORMANCE OF UNDERGROUND PIPES

The analysis is performed for a 1000 m^2 glass covered greenhouse, located in Athens (37.5°N lat), which is connected to four plastic underground parallel pipes. The greenhouse air temperature was calculated using the transient system simulation program TRNSYS (1990), which processes the thermal behavior of the greenhouse equipped with a system containing multiple parallel buried pipes. A new, transient numerical model to handle the thermal performance of a single pipe as well as of a multiple parallel earth-to-air heat exchangers system has been presented in Mihalakakou *et al.* (1993a). The model takes into account the coupled simultaneous movement of heat and moisture in the soil under temperature gradient, as well as the vertical thermal stratification in the soil, which breaks down the axial symmetry of heat flow from the pipe. It includes a complete mathemati-

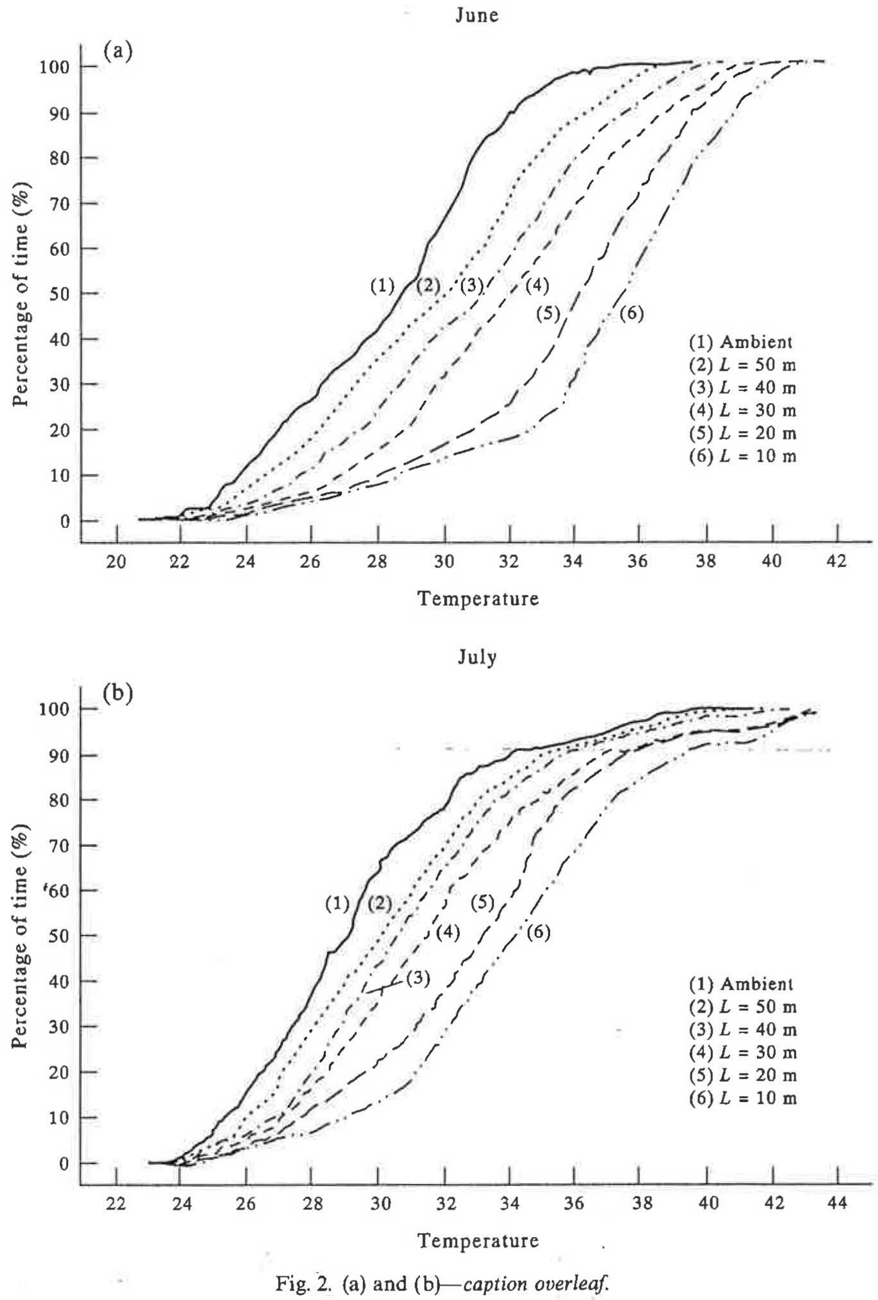
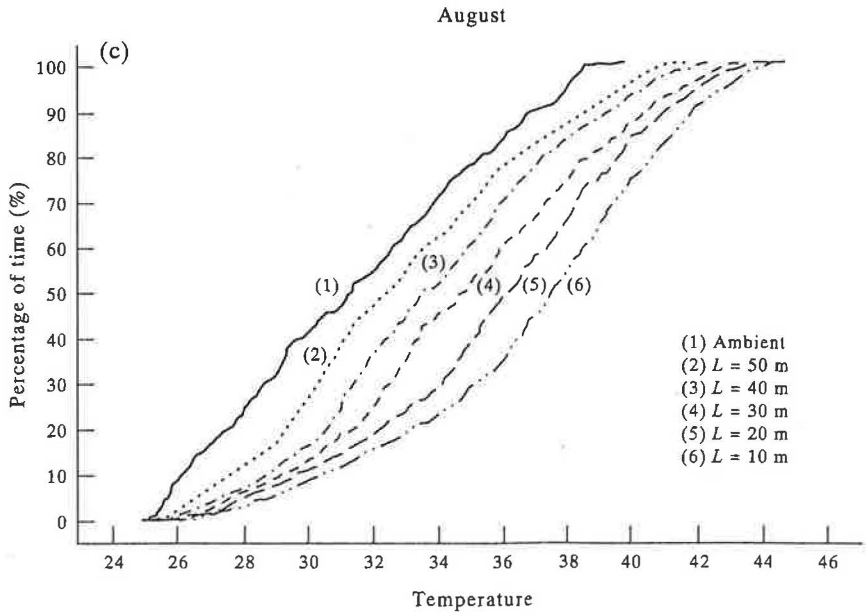


Fig. 2. (a) and (b)—*caption overleaf.*



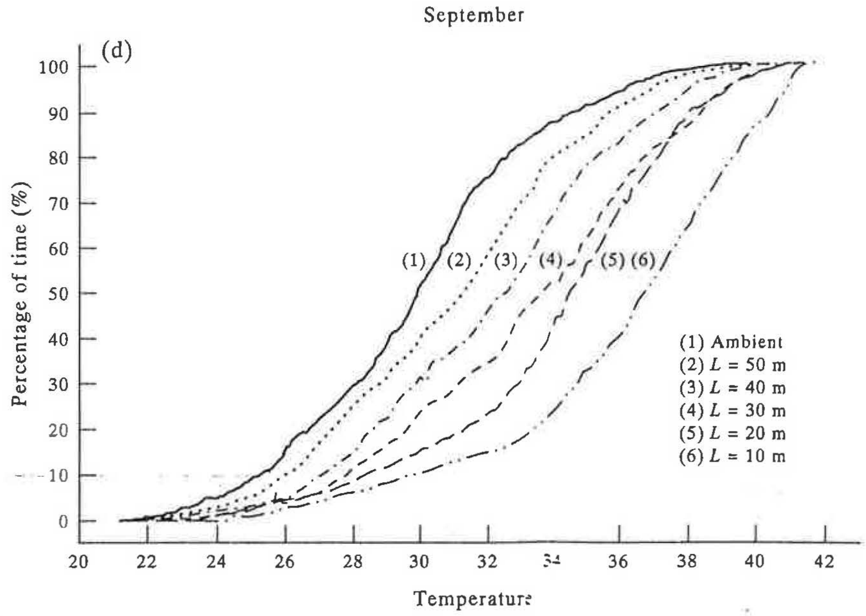


Fig. 2. Cumulative distribution of outdoor air temperature and greenhouse indoor air temperature for various pipe lengths, during the four summer months.

cal description of moisture migration through the soil under a thermal gradient from higher to lower temperature regions, while it simultaneously redistributes itself in reverse order due to the resulting moisture gradient. The natural thermal stratification is taken into account, with ground surface boundary conditions. The thermal model describing the performance of a single as well as of a system of multiple parallel earth-to-air heat exchangers, was entirely developed inside TRNSYS environment. The proposed model was validated against an extensive set of experimental data and it was found that it could accurately predict the temperature and the humidity of the circulating air, the distribution of the temperature and moisture into the soil, as well as the overall thermal performance of the buried pipes system (Mihalakakou *et al.*, 1993b). Moreover, a new numerical model, based on heat conduction equation into the soil and on superposition technique, was developed inside TRNSYS and presented in Mihalakakou *et al.* (1994), in order to calculate the heat loss from the greenhouse to the ground and therefore the ground temperature distribution below the greenhouse.

The performance of a given system is influenced by the size of greenhouse, the cover material, the type of cultivation (or the desired day and night temperature of the inside air), the location of the greenhouse (or the outdoor conditions) and the characteristics of the heat exchangers.

In this study, the parametric analysis on the performance of the system focuses on the earth-to-air heat exchangers, specifically the pipe length, pipe radius, air velocity and soil depth. The calculations are performed over a 9 yr period (1981–1990), for the summer months of June, July, August and September, using hourly ambient air and ground temperatures between 9 a.m. and 7 p.m. The data were provided by

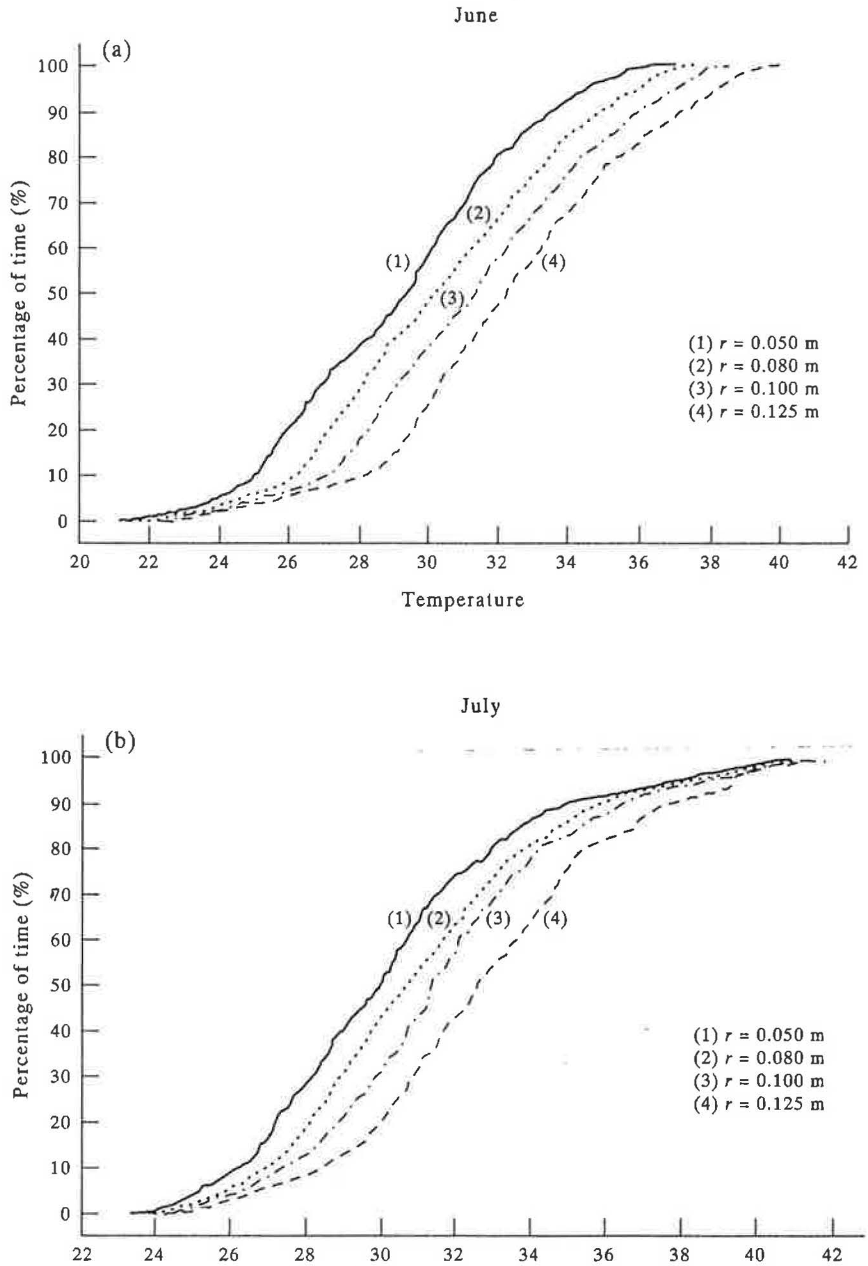


Fig. 3. (a) and (b)—*caption overleaf.*

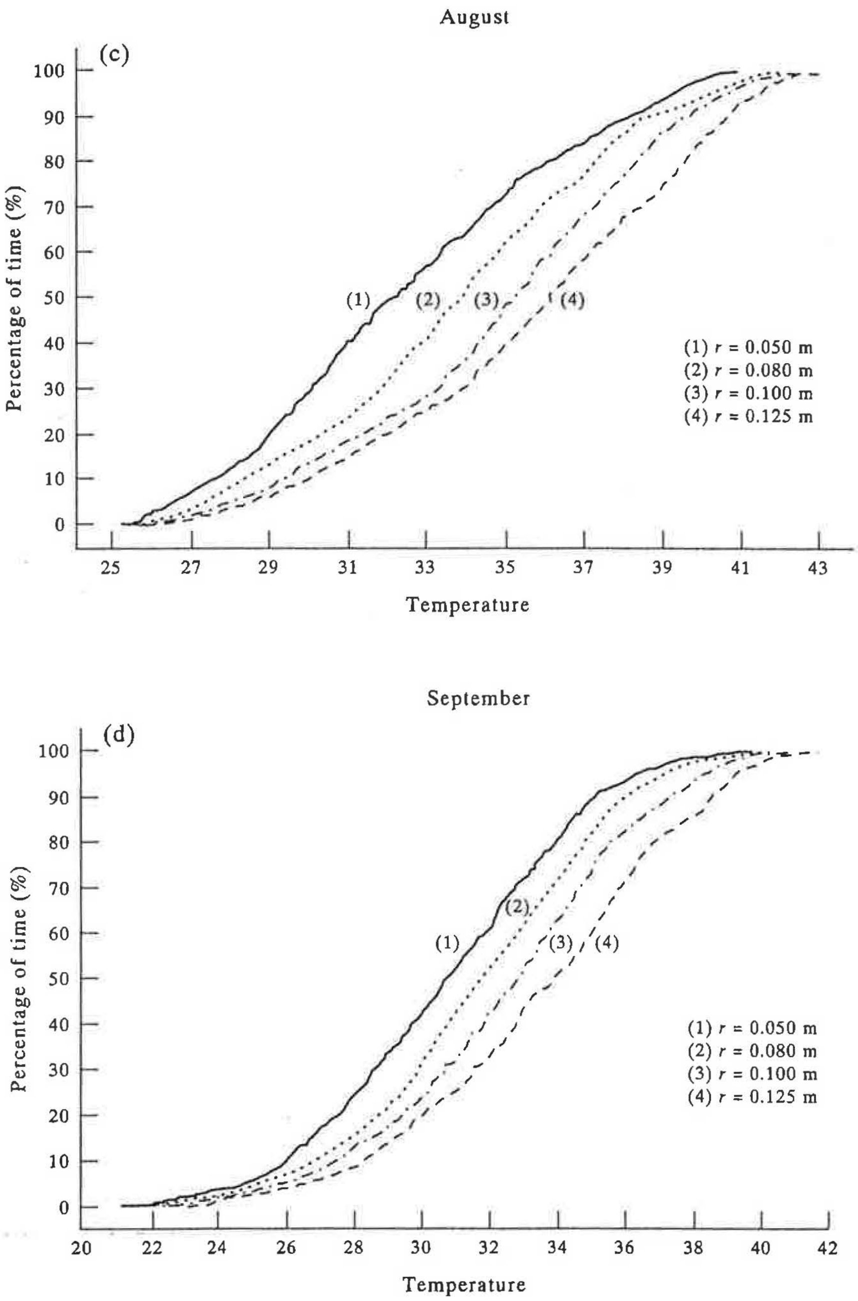


Fig. 3. Cumulative distribution of outdoor air temperature and greenhouse indoor air temperature for various pipe radius, during the four summer months.

the National Observatory of Athens (NOA). A fully equipped meteorological station measures among other climatic parameters, surface ground temperatures over bare and short grass covered soil, and ground temperatures at 0.3, 0.6, 0.9, and 1.2 m depths under short grass covered soil.

3.1. *Influence of pipe length*

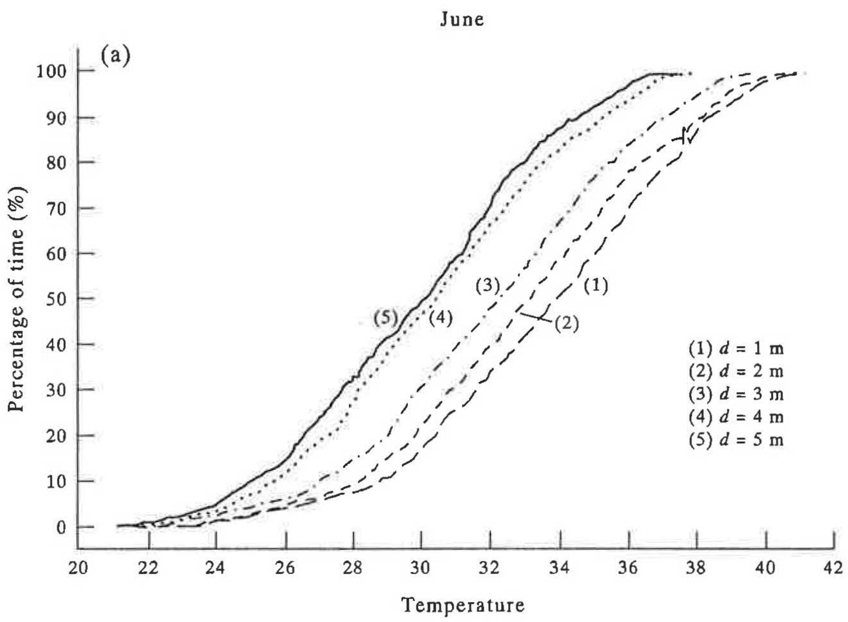
The calculations were performed for five different pipe lengths, namely 10, 20, 30, 40 and 50 m. The radius of the four pipes was fixed at 0.1 m, placed at a depth of 1.5 m with a 2 m spacing between each row of pipes, while the air velocity inside the pipes was fixed at 8 m/s.

The cumulative frequency distributions of the air temperature inside the greenhouse, for the five different pipe lengths and for the four summer months, respectively, are shown in Fig. 2. Accordingly, in the case of a 10 m pipe length, 95% of the time the greenhouse air temperature is lower than 40°C for June, 41.2°C for July, 42.3°C for August and 40.8°C for September. For the case of a 50 m pipe length, the corresponding results are 37.6°C for June, 39.1°C for July, 40.2°C for August and 38.3°C for September. The outdoor air temperature, also shown in Fig. 2, varies between 20.8 and 37.3°C in June, 23.1 and 39.9°C in July, 25.3 and 39.3°C in August, and 21.1 and 38.4°C in September.

Although the outdoor air temperature is higher during July and August, the greenhouse air temperature during August is consistently higher. This is mainly due to the time lag of the ground temperature, which delays the temperature variation at various depths below the ground surface, throughout the year.

3.2. Influence of pipe radius

The calculations were performed for four different pipe radii, namely 0.05, 0.08, 0.1 and 0.125 m. The length of the pipes was fixed at 30 m, placed at a depth of 1.5 m with a 2 m spacing between each row of pipes, while the air velocity inside the pipes was fixed at 8 m/s.



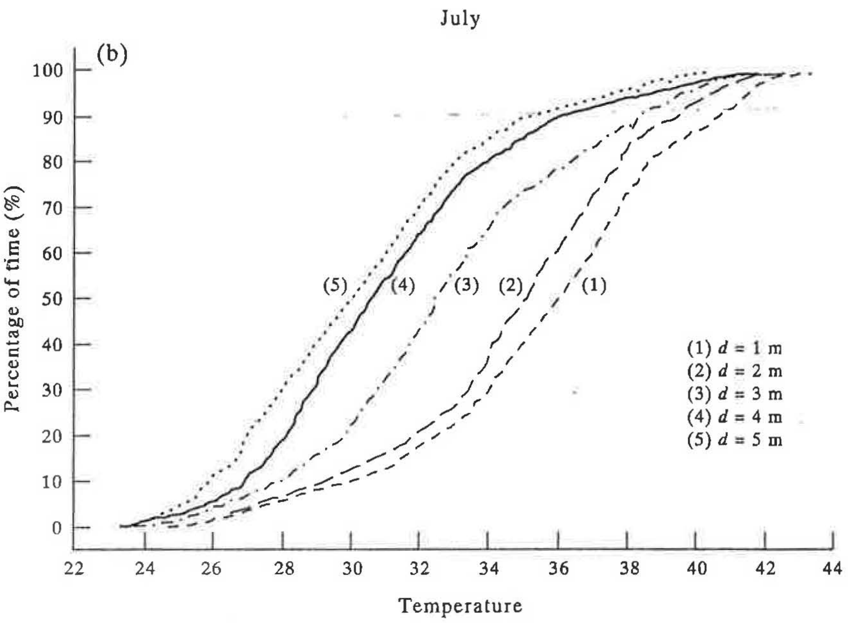


Fig. 4. (a) and (b)—*caption overleaf.*

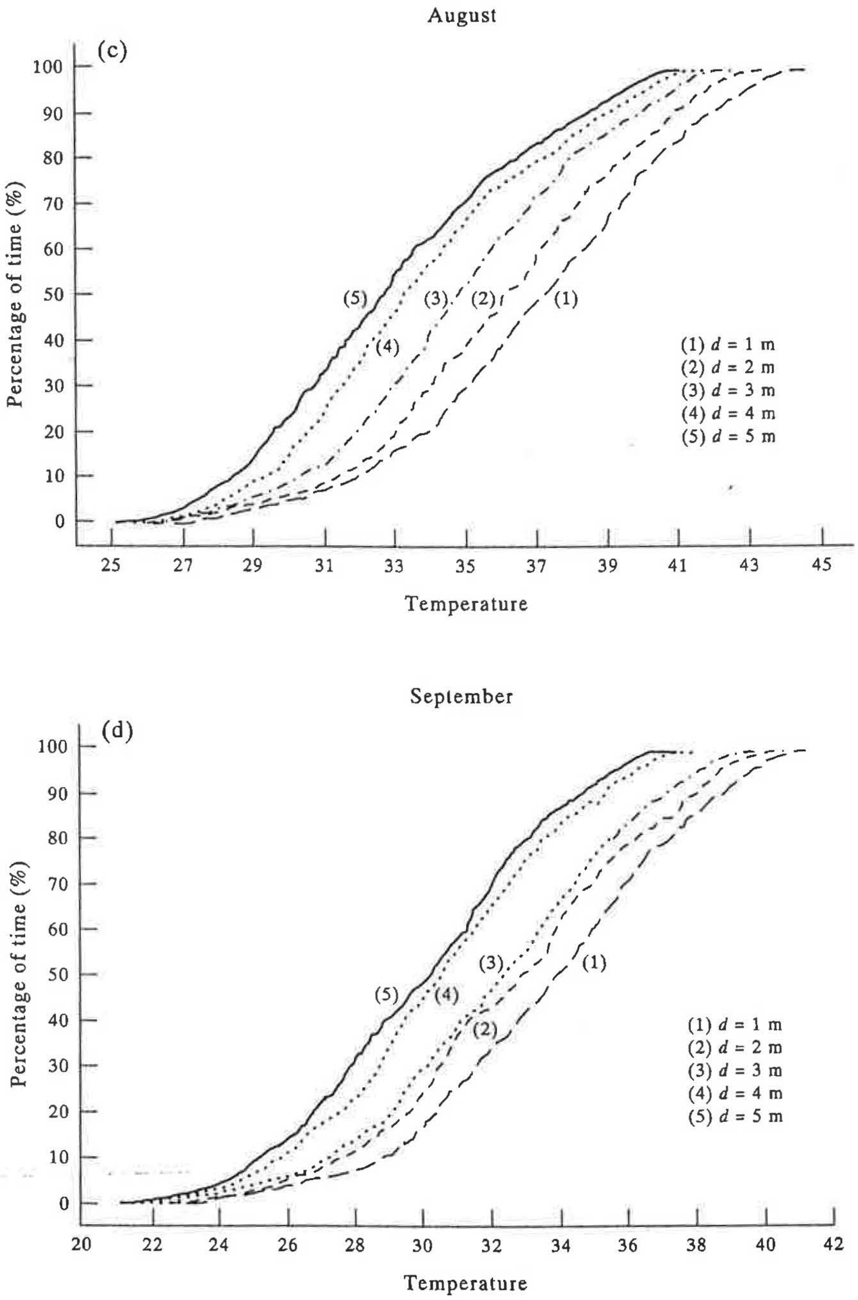


Fig. 4. Cumulative distribution of outdoor air temperature and greenhouse indoor air temperature for various depths, during the four summer months.

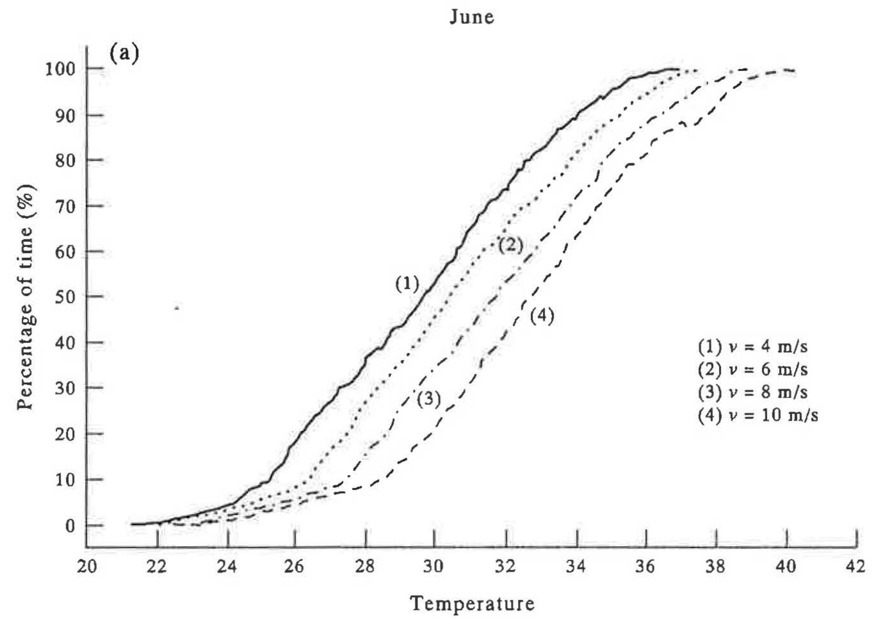
The cumulative frequency distributions of the air temperature inside the greenhouse, for the four different pipes and for each summer month, are shown in Fig. 3. For pipes with a radius of 0.05 m, the greenhouse air temperature varies between 21.1 and 36.9°C in June, 23.2 and 39.5°C in July, 25.5 and 40.6°C in August, and 21.6 and 38.3°C in September. For 0.1 m pipe radius, 95% of the time the greenhouse air temperature is lower than 37.9°C for June, 40.8°C for July, 41.7°C for August and 39.5°C for September.

An increase of the pipe radius results to higher indoor air temperatures. This is caused by an increase of the air temperature at the pipe's outlet, as a result of the lower convective heat transfer coefficient caused by the increase of the pipe radius.

3.3. Influence of depth

Soil temperature varies with depth. As a result, it is necessary to consider diurnal, seasonal and annual variations in the system design. Based on the available data from NOA, an accurate prediction model for the annual and daily variation of ground temperature at various depths has been developed by Mihalakakou *et al.* (1992). This model was used to predict the soil temperature at various depths, including 1, 2, 3, 4 and 5 m. The length of the pipes was fixed at 30 m with a pipe radius of 0.1 m, a 2 m spacing between each row of pipes, while the air velocity inside the pipes was fixed at 8 m/s.

The cooling capacity of soil increases with depth. The cumulative distributions of the greenhouse air temperature are shown in Fig. 4. Accordingly, for the case of a 1 m depth, 90% of the time the indoor air temperature was below 37°C in June, 40.2°C in July, 41.7°C in August and 38.3°C in September. For the case



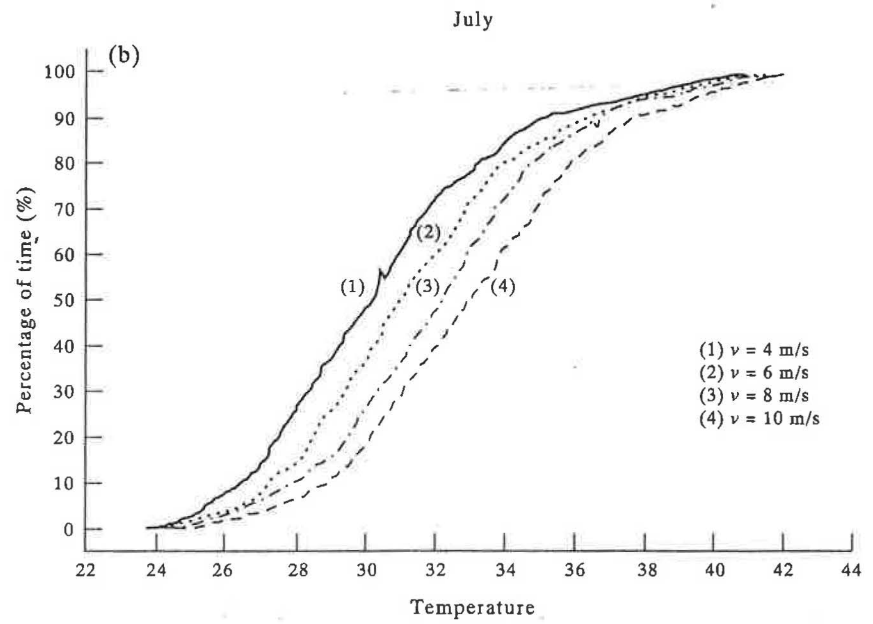
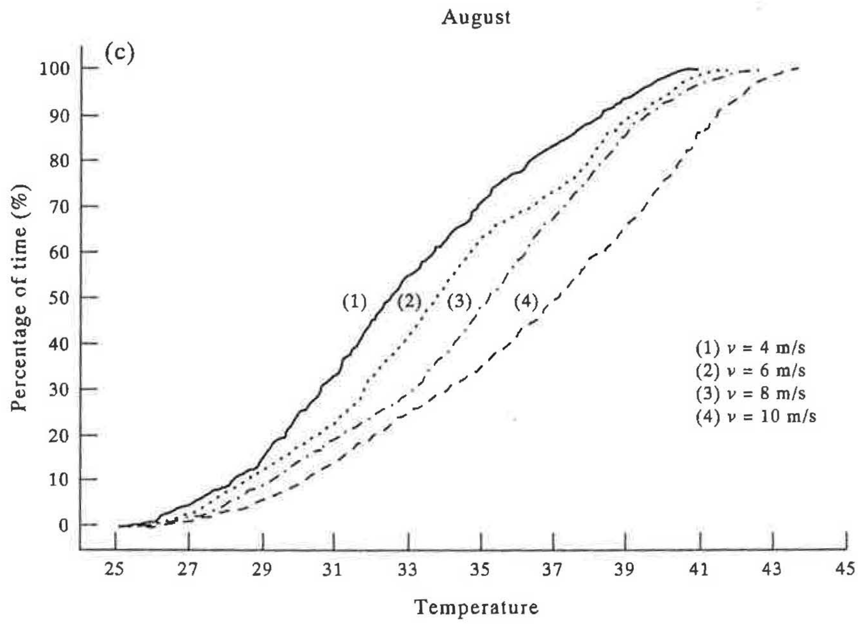


Fig. 5. (a) and (b)—*caption overleaf.*



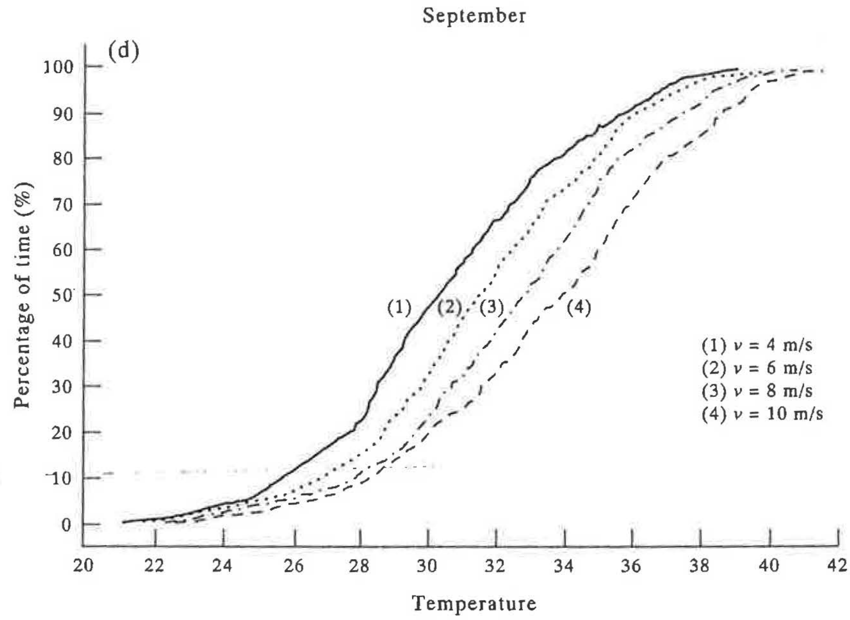


Fig. 5. Cumulative distribution of outdoor air temperature and greenhouse indoor air temperature for various air velocities, during the four summer months.

of a 3 m depth, the indoor air temperatures ranged between 22.2 and 38.3°C for June, 23.5 and 41°C for July, 25.2 and 41.8°C for August, and 23.1 and 38.5°C for September. Finally, for the 5 m depth, the maximum indoor air temperature was 36.9°C in June, 39.9°C in July, 40.3°C in August and 37.8°C in September.

3.4. *Influence of air velocity*

Simulations were performed for four different air velocities, namely 4, 6, 8 and 10 m/s. The length of the pipes was fixed at 30 m, with a pipe radius of 0.1 m, buried at a depth of 1.5 m and a 2 m spacing between each row of pipes.

The cumulative frequency distributions of the greenhouse indoor air temperature for the four different air velocities and for each summer month, are shown in Fig. 5. For the case of 4 m/s air velocity, the greenhouse air temperatures vary beween 21.1 and 36.4°C in June, 24.1 and 40.1°C in July, 25 and 40.5°C in August