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AN EXPERIMENTAL ANALYSIS OF A SOLAR ASSISTED ABSORPTION HEAT PUMP WITH EARTH SEASONAL STORAGE

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SUMMARY

A plant composed of an energy roof, a seasonal earth storage and an absorption heat pump has been experimented. The purpose was to study the behaviour of the various components and their interaction. The surveys were carried out over a two year period. The following operations were considered: the charging of the earth storage by the energy roof and the working of an absorption heat pump connected either to the energy roof or to the earth storage.

KEY WORDS Solar energy Heat pumps Energy storage Solar assisted heatpumps Earth storage Energy roof

INTRODUCTION

Ammonia-water absorption heat pumps want a cold source possibly higher than 5°C in order to achieve an acceptable Primary Energy Ratio (PER). In the absence of well or surface water solar assistance is welcome even for mild temperate climates. Heat pump solar assistance is affected by two main problems:

1. the cost of a sufficient collecting area; and
2. the poor summer utilization of the solar section.

As regards the first point, the absorption heat pump needs less collecting area than a compression one at the same PER and capacity (about half demand from the cold source), but the required temperature is higher.[1-5] The cost of the collecting area can be reduced by adopting an energy roof, that is a simple system which substitutes the traditional roof and collects useful heat at a low level by suitable channels under the tiles.

Regarding the second point, it is advisable to provide the plant with a seasonal storage so that useful solar heat can be collected all year round and can be supplemented during periods of poor or no insolation. Earth storage with vertical pipes is attractive to store energy, because the occupied surface area can be very limited, increasing eventually the depth of the pipes and therefore it is almost always disposable near a building in contrast to horizontal pipes systems.[6-14]

The aim of this experimental work, carried out at Musile di Piave near Venice, was to study the performance of an ammonia-water absorption heat pump in ambient heating coupled either to a vertical tube earth storage or to an energy roof. For a period heating was provided by an electric compression heat pump with the same cold sources. During summer the energy roof charges the storage. Thus, it is possible not only to survey the behaviour of the system, but also to sketch the performance of single components in different couplings.

SYSTEM DESCRIPTION

The absorption heat pump heats a two floor building obtained by widening a factory: it consists of 180 m^2 floor area, with heated volume of about 1080 m^3. The first floor is designated to office, the second one is to a home. The energy roof was installed on a shed oriented toward South 17° tilt; the roof is 25 m long, 4 m wide giving a total area of 100 m^2 (Figure 1).

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Figure 1. A photograph of the copper energy roof

The heating machinery is an absorption heat pump of water–water type with a nominal heating capacity of 25 kW. It supplies hot water to floor heating coils through a water storage (2 m^3) placed between the heat pump and demand so that transient operations are minimized. No auxiliary was provided since the heat pump capacity was well in excess of the requirements (the smallest commercially available size).

The earth storage is formed by 16 reinforced polyethylene vertical tubes set in a 4 × 4 array 9 m square (Figure 2). Each tube is composed by two concentric pipes. The tubes are 15 m long and parallel-connected in order to limit pressure drops. Circuit connections are represented in Figure 3. Two pairs of valves allow the four central tubes of the array to be isolated, so that charging or discharging may be actuated only in the centre. Working operations of the system are multiple, since the energy roof is connected both to the evaporator of the absorption heat pump and to the earth storage. Thus the evaporator may be supplemented either directly by the energy roof or by the earth storage. Moreover, when the heat pump is not working and the roof can collect useful energy, the energy roof can be connected to the earth storage in order to charge it: this is the normal summer operation.

Meteoattinometric data, temperatures at various points of the earth storage and thermal fluxes of the heat pump were measured and recorded.

ENERGY ROOF PERFORMANCES

The energy roof as a cold source

The energy roof is a ventilated one, i.e. a gap exists between tile and shed where natural air circulation is encouraged. The aim is to increase the heat exchange between air and roof: of course the disposition is unfavourable whenever the working temperature of the roof exceeds the outside air temperature. In Figure 4 the collected specific power (W m^{-2}) is expressed as a function of the difference between the outside air and the

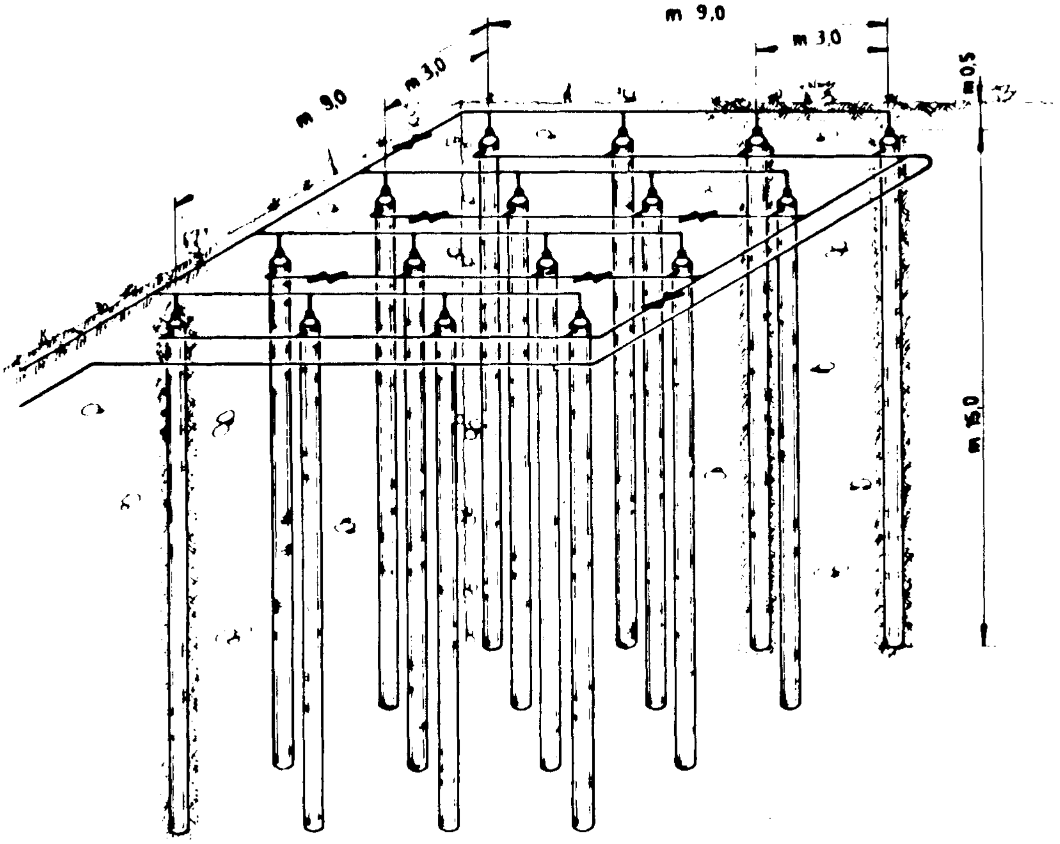

Figure 2. A schematic view of the earth storage

inlet temperatures. When solar radiation increases, it would increase also the useful collected power, but once the evaporator heat pump requirements satisfied, the energy roof working temperature increases instead, overcoming the outside temperature just when the insolation is higher, thus the conditions are more favourable. This explains the rather unexpected decreasing trend.

The collected specific power is represented in Figure 5 as a function of solar radiation intensity: as one can see, the increment is rather small. This was already explained by the higher working temperatures for stronger insolation. Higher temperatures were soon penalizing in the examined roof, conceived to encourage the heat exchange with the outside air, i.e. the losses in the circumstance. The losses are higher than can be suggested at first sight by the inlet fluid temperature. In fact, one must take into account the fin effect between the tile and the channel, which was studied by a thermographic analysis.

The energy roof was thermographically analysed through an AGA Thermovision 680 unit with the purpose of evaluating the thermal distribution between the tiles and the influence of the channels, clamped by two adjacent tiles. Above all the amount of temperature drops in the thermal pattern due to the channels was investigated.

The roof was studied at various heights. A first thermogram is given in Fig. 6, referring to the top of the roof: one can see the silhouette of the vent valve at the middle right of the photograph. The vertical lines at the top are not to be considered: they are disturbances due to the shed in the background. The horizontal lines at the middle are the return tubes. Beneath them are the tiles. One can easily recognize the rhombed shape, once

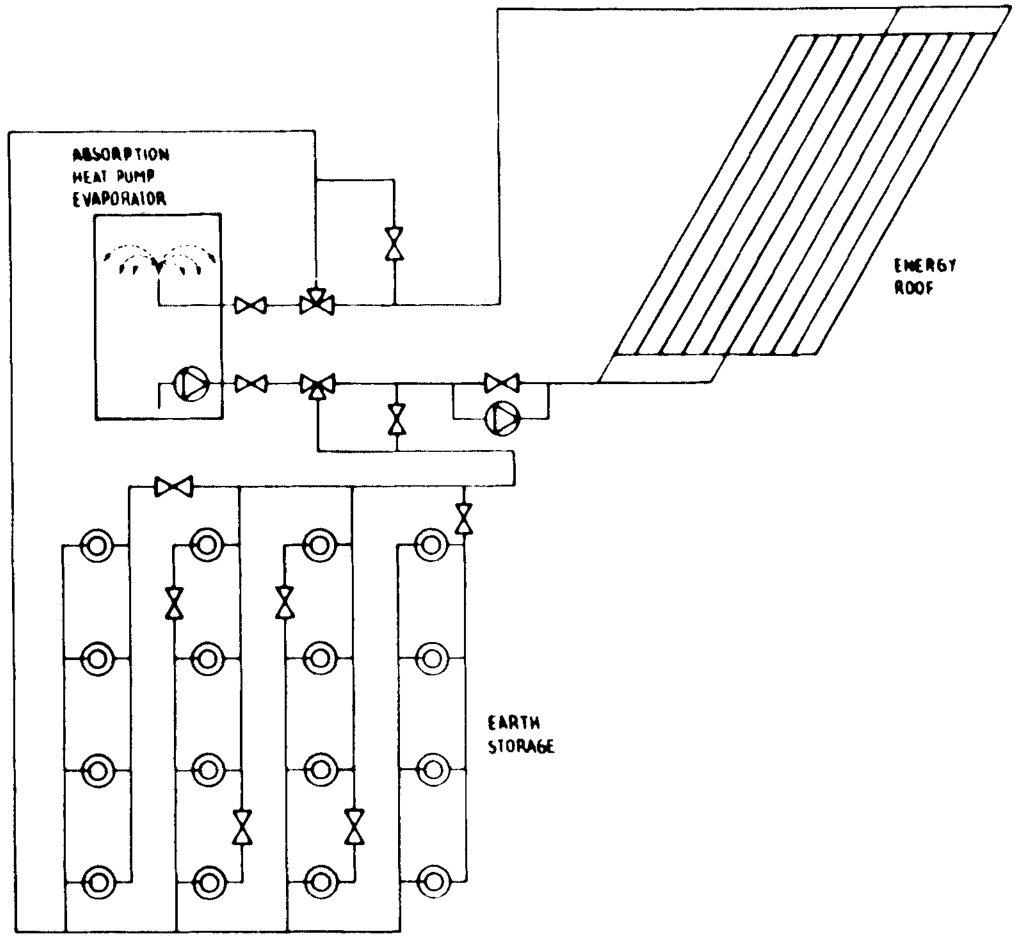

Figure 3. Block diagram of the system composed of absorption heat pump, energy roof and earth storage

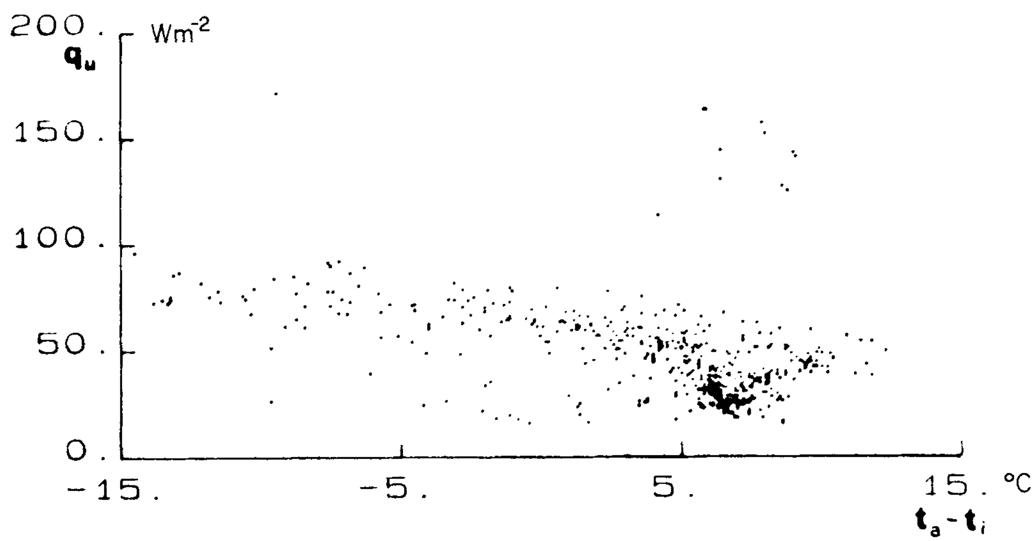

Figure 4. Specific collected power (W m^{-2}) as a function of the difference between outside air and inlet temperatures

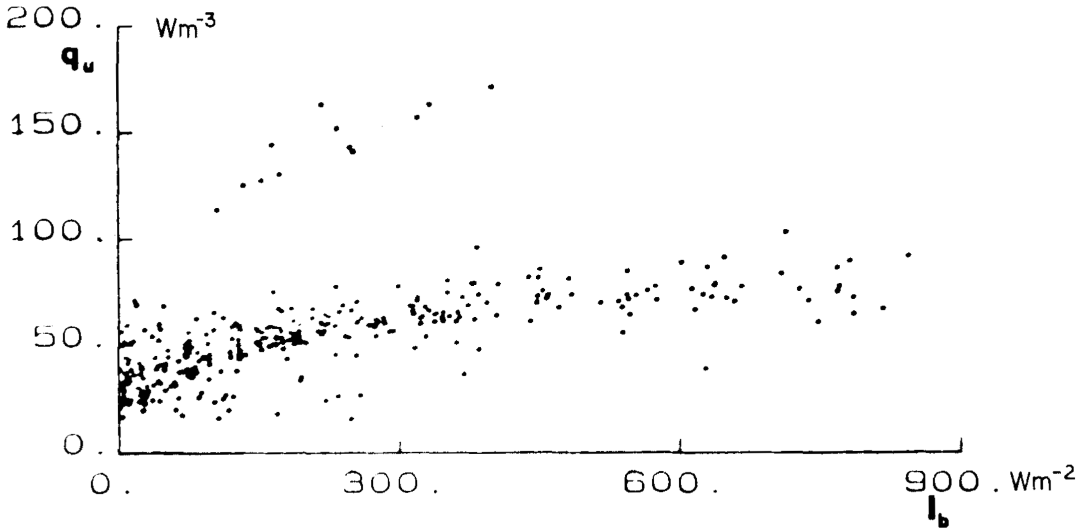

Figure 5. Specific collected power as a function of the insolation

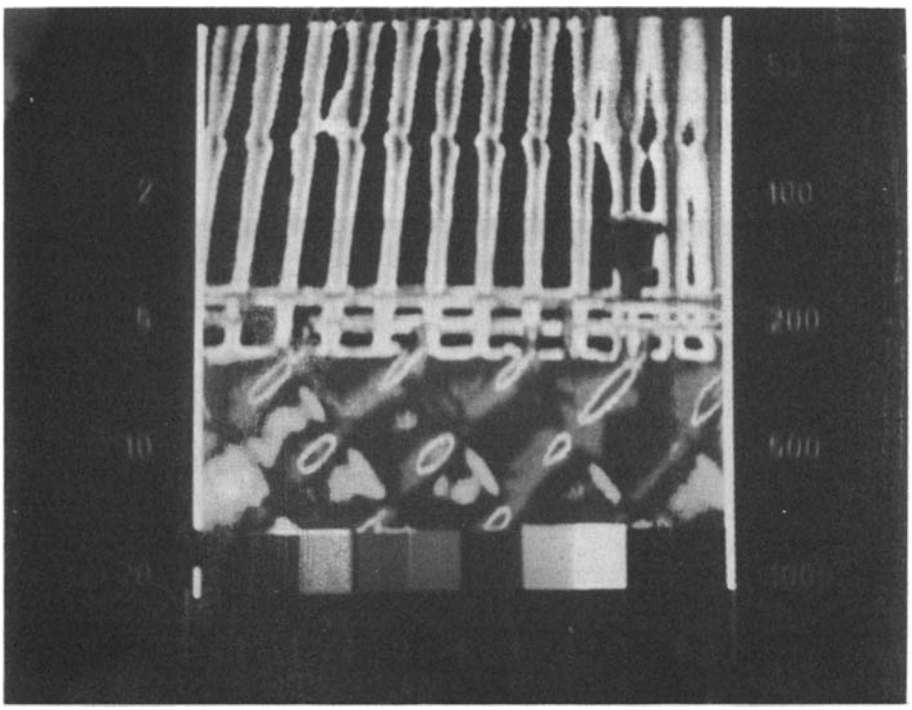

Figure 6. A thermogram of the top of the energy roof

realizing that the channels run diagonally from left to right (from the bottom to the top). The channels are revealed by colder spots that show a good contact between tile and channel. The contact is not always assured, so that some brighter zones can be distinguished where the temperature is 35–36°C against the 32°C of the darker spots. A coloured illustration would reveal that red prevails, particularly in the middle of the tile with 37–38°C. The highest value is reached in the brightest zone with more than 40°C.

In Figure 7 the study of the middle part of the roof follows. The tones are brighter: in fact, the boundary convective effects are not operating. The contact between tile and channel is not uniform throughout, particularly in the middle left of the thermogram. It is interesting to observe the diagonals from right to left (from the bottom to the top) as brighter oblong spots, i.e. at higher temperatures. This effect can be explained by the presence of hot stagnant air in the false channels which the tiles delimit in the diagonals from right to left. Similar surveys can be repeated in Figure 8, which represents a bottom zone of the energy roof. The three dark horizontal lines are the distributing tubes: the highest line is the distribution header from which two vertical smaller tubes leave. From them the cold diagonal begins, revealed again by grey oblong spots, whose temperature is between 32–36°C. In this thermogram the 'hot' diagonals are easily recognized. The three thermograms (Figures 6, 7, 8) refer to the same meteorological conditions: solar radiation intensity of about 700 $W m^{-2}$, wind velocity 3 ms^{-1}, outside air temperature 25°C.

The thermograms reveal that the thermal distribution in the energy roof is far from an ideal one with frequent non-uniformities and hot spots which are positive sources of losses. Therefore, the energy roof seems not very ideal for collecting high specific powers for which it is not able to efficiently exchange. However, its working appears satisfactory for the 100–200 Wm^{-2} heat collection required when coupled to a heat pump.

The energy roof during summer charging

During summer the energy roof has working features completely different than in winter operation; in fact, it charges the storage. Specific heat gains during the day as a function of the difference between ambient and inlet fluid temperatures are given in Figure 9. The dispersion of the results is very high. However, an increasing trend can be observed from the difference of zero and 10°C with the points contained in a 60 Wm^{-2} interval. The values near zero apart, most fall between 60 and 140 $W m^{-2}$. The temperature difference seldom exceeds 11°C. The strong dispersion means that the temperature difference is not the only explicating factor. Other

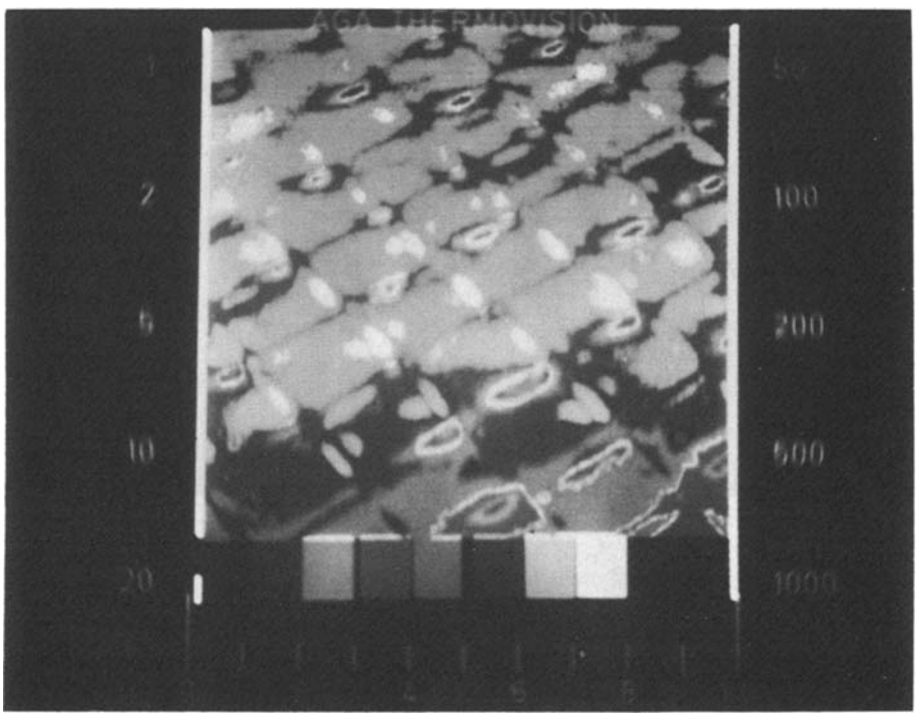

Figure 7. A thermogram of the middle of the energy roof

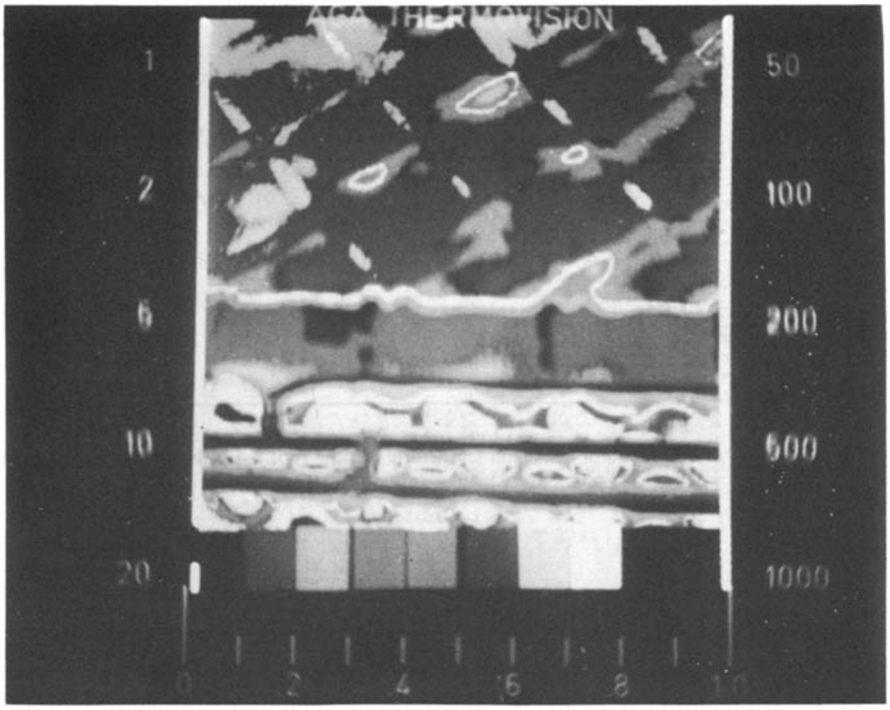

Figure 8. A thermogram of the bottom of the energy roof

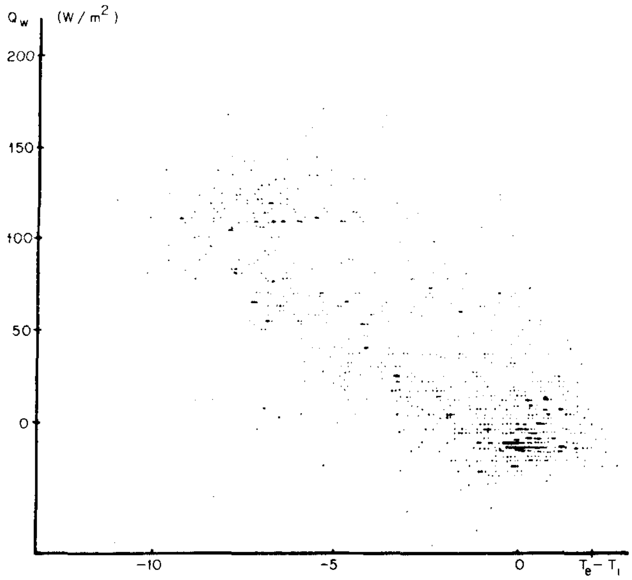

Figure 9. Specific heat gains during the day as a function of the difference between ambient and inlet fluid temperatures

fundamental ones are solar radiation intensity and working temperatures of the fluid.

Regarding inlet temperatures to the roof consider Figure 10 where the values of specific collected power are represented. Two kinds of symbols may be noted: asterisks between dawn and 14.00, points for the values after 14.00. It is interesting to recognize a typical lens shape with characteristically higher values of asterisks with

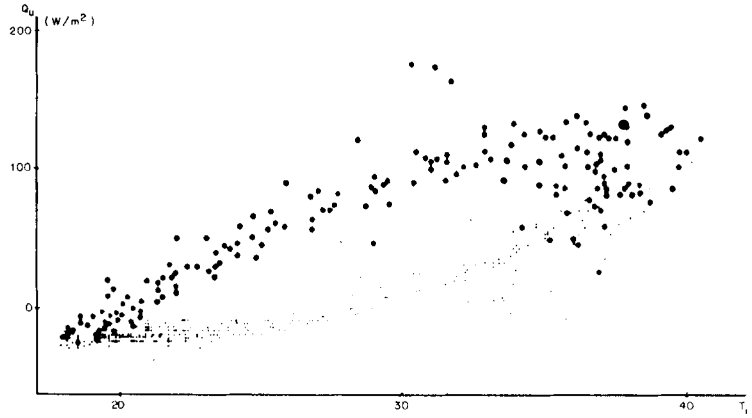

Figure 10. Specific collected power as a function of inlet fluid temperature to the roof: asterisks refer to the period between dawn and 14.00, points for the values after 14.00

respect to points. In other words: heat collection is more favourable in the morning than in the afternoon. This is partly due to the lower insolation levels (in the afternoon the ambient temperatures are higher).

Another factor is probably the condition of the ground heat exchange which is easier during the morning with colder layers near the tubes: these layers very near to the tube surface are warmed up in the first hours of collection so that they make it more difficult for heat exchange later. During the night the heat exchanges proceed in the layers and in the next morning favourable conditions appear once again. With regards to solar radiation consider Figure 11 where the specific power is given as a function of solar radiation intensity. The trend is of course an increasing one. However, the response is roughly linear until a solar radiation of 500 W m^{-2}, then the increase is declining. This can be explained by examining the hourly shape of the inlet temperature curve.

Further insight can be obtained by examining a full summer day. One example can be taken as given in Figure 12 where the hourly values of outlet temperature, together with solar radiation intensity, ambient temperature and wind velocity, is reported for a typical summer day (July 23rd, 1984) and in Figure 13 where inlet temperature, collected power and efficiency are also given. For a minimum value at the start the inlet temperature rapidly increases for higher solar intensities: apparently the ground is not able to accept all the thermal input available. In other words the increase in the collected energy means a higher input into the ground only in the first hours, then the ground becomes somewhat saturated and the fluid temperature must increase in order to keep, or slightly increase, the heat exchange. It is easily seen from Figures 12 and 13 that the exchanged power is not proportional to the temperature level of the fluid. At the same time when the fluid temperature increases, it prevents good solar collection because of the larger losses by radiation and convection. Further, one can also recognize that input into the ground is more difficult in the afternoon than in the morning. This is evidenced both from the asymmetrical shape of the useful power P_u contrasting with the symmetrical one of solar radiation and by Figure 14. Here the cumulative curve during the considered day of solar radiation and useful power are given. The useful power curve rises more quickly which signifies an increase in collection more rapid than for solar radiation: at noon half of the energy is already collected, but only 40 per cent of solar radiation has impinged on the roof.

EARTH STORAGE PERFORMANCES

The temperature distribution in the storage for a given depth was not uniform after the first summer charging, but in a similar manner as on the starting date: at 8 m depth tube 2 was at 12·6°C and tube 4 at 10·7°C on

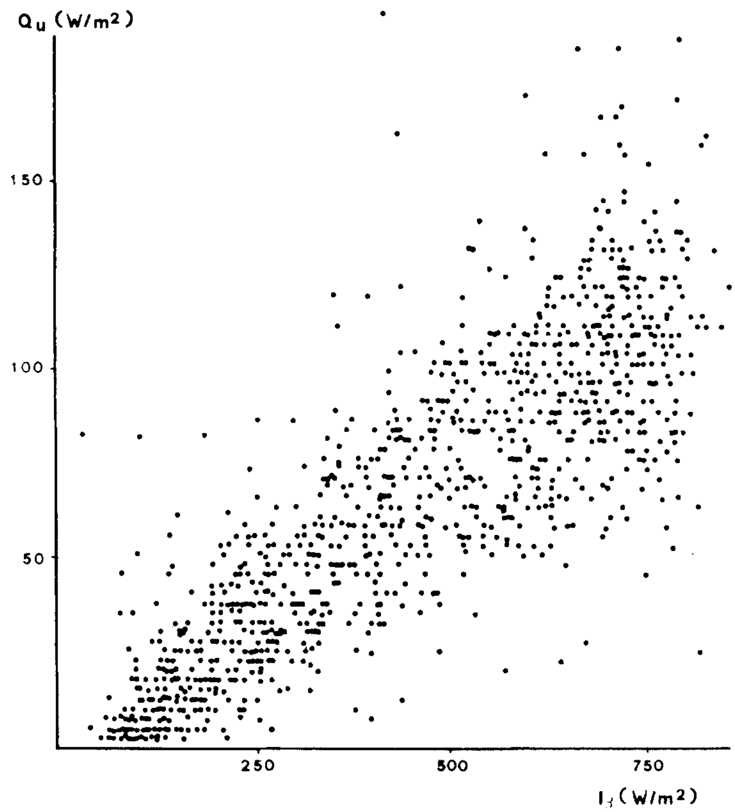

Figure 11. Specific collected power as a function of solar radiation intensity

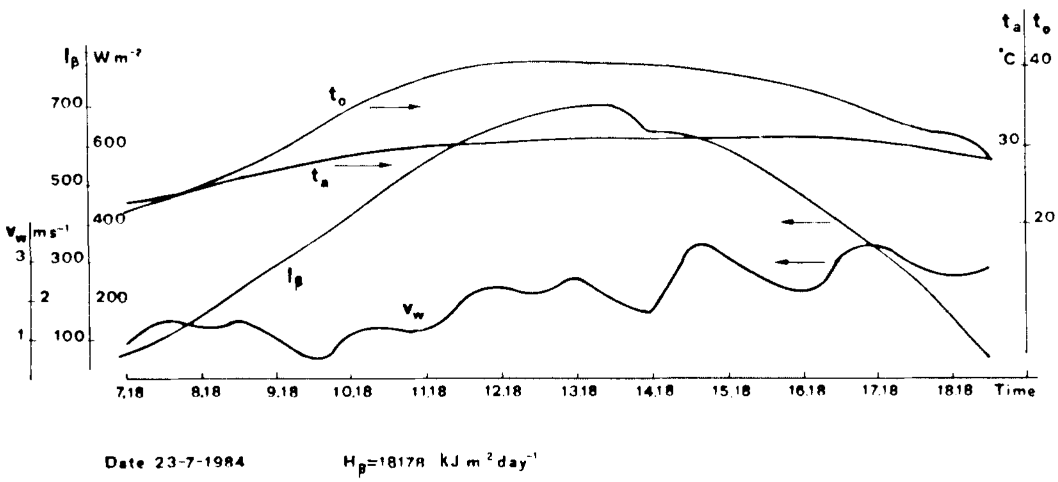

Figure 12. Outlet fluid temperature, ambient temperature, solar radiation intensity and wind velocity during a whole day (23 July)

starting day; at 15·2°C at 13·7°C at the end of charging; at 13·5°C and at 11·6°C on the new starting in 1984, i.e. the disuniformities in all the experiment were roughly maintained.

In the first winter the storage was not utilized. The starting thermal level was therefore higher than at the commencement. Not so much, however, due to the fact that the first summer charging lasted only two months.

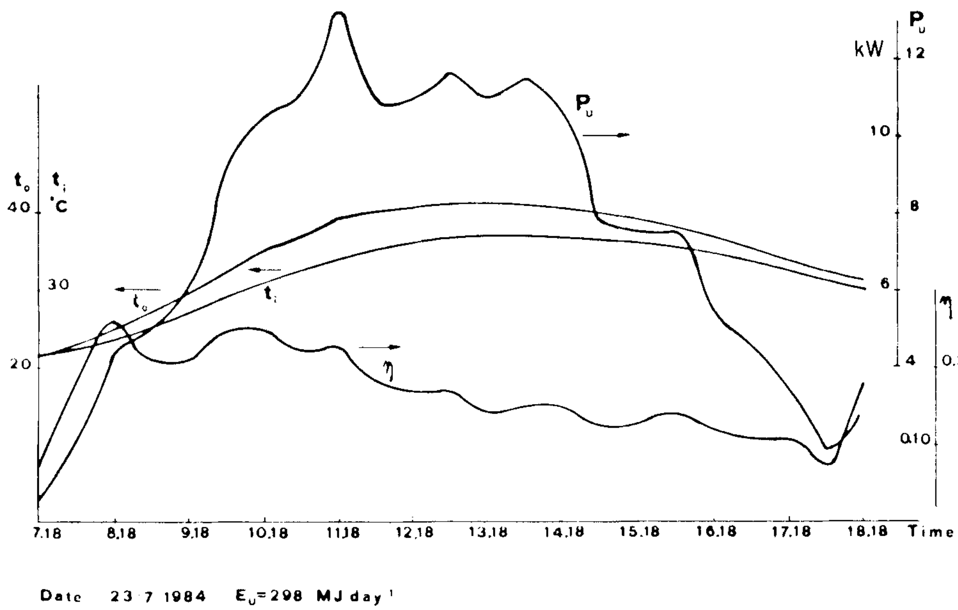

Figure 13. Inlet and outlet fluid temperature, collected power and efficiency during a whole day (23 July)

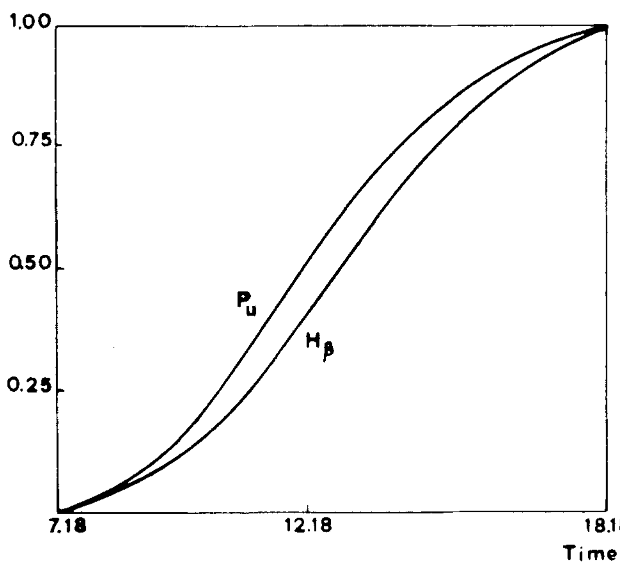

Figure 14. Cumulative curve during a day (23 July) of solar radiation and collected energy

During the winter some heat was dispersed: the lowering at 8 m depth was about 2°C (the new starting value was at 1°C higher than before), whereas at 15 m the lowering was only about 0·5°C with a new starting value ranging from 0·8 to 1·7°C higher than previously.

The heat exchange at ground level is usually given per linear meter of tube. Taking into account only the vertical tubes, it must be remembered that the total length is 16 × 15 = 240 m. The maximum recorded linear flux was 91 W m^{-1} with a temperature drop of 11·8°C between inlet and outlet of the ground. This referred to an instantaneous value (half-an-hour). The highest daily average value was at 44 W m^{-1} with a temperature drop of 5·8°C. It can be useful to represent the linear heat exchange as in Figure 15 as a function of inlet

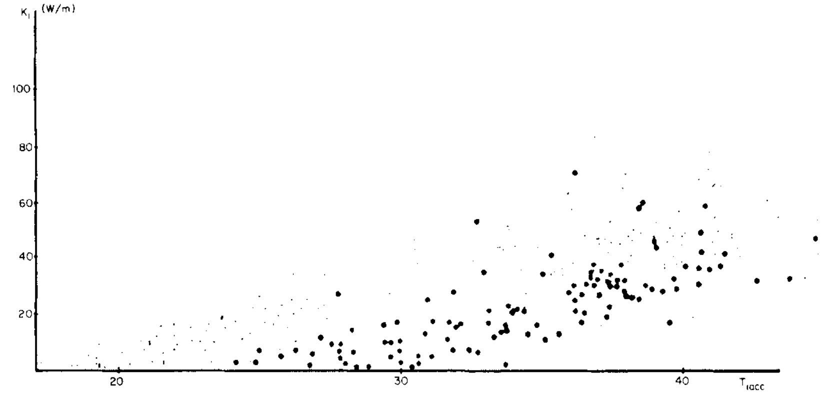

Figure 15. Linear heat exchange as a function of inlet fluid temperature (period 3–16 July). Asterisks are for the declining exchange in the afternoon, points for the increasing values in the first part of the day

temperature. The figure refers to the period 3–16 July 1984 and only to positive values. It was already cited that the most common trend of fluid temperature was an increasing one until a maximum, usually reached in the early afternoon, and then a decreasing for the daily hours left. The results in the increasing tail are represented by points, whereas the decreasing values by asterisks. One can easily recognize the very different behaviour of the ground in the two parts of the day. The difference is so strong that without subdivision of results, an effectively increasing trend could have been masked. One can recognize instead two separate increases. Moreover, in the declining part of the day the threshold of collection is placed at higher inlet values, confirming the hypothesis already mentioned of a progressive saturation of the layers of ground in the immediate nearness of the tube wall during the diurnal hours. The night can equilibrate again the various layers so that in the early morning the threshold can be as low as 20°C. It may be worth citing that linear power during occasional night losses was uniformly at 10 W m^{-1}.

In many considered figures a few results appear quite outside the usual range. This is due to the fact that the reported values are instantaneous ones, recorded at half-an-hour intervals, so that they are sometimes altered by inertia effects. Anyhow the results are below the ones reported usually by literature. One possible reason lies in the relatively strong temperatures which are often higher than 40–50°C. This temperature may cause the eventual evaporation of the water film at the surface of the tube and the migration of vapour from the nearness of the tube leaving empty and poor conductive spaces.

HEAT PUMP PERFORMANCES

Absorption heat pump performances can be described by COP and capacity distribution of experimental values as a function of inlet evaporator temperature (Figures 16 and 17). The COP refers to a thermal input, i.e. it does not account for the burner efficiency. The values are spread between 1·2 and 1·8, i.e. the PER can be evaluated between 1·0 and 1·5. In the average the COP is at 1·4 with a PER of 1·2, slightly below the only value claimed by the builder, which is 1·3. Liquid Petroleum Gas (LPG) was utilized instead of natural gas; the nozzles were properly changed. A much lower capacity was obtained of 14–18 kW instead of the claimed 25 kW nominal capacity.

A known and appreciated feature of the absorption heat pump is the small variation of capacity with cold source temperature variation. Our experiment confirmed this feature: capacity varied only from 13 to 18 kW with a cold source variation from 0 to 20°C, i.e. only about a 25 per cent reduction in capacity. A compression heat pump would be expected to yield more than a 40 per cent variation in the same range. Another known characteristic of an absorption heat pump is a similar modest variation in COP. Experiments did not fully

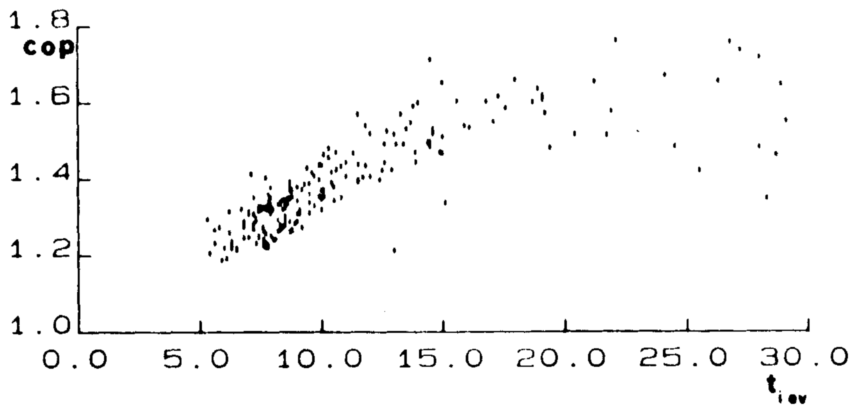

Figure 16. COP as a function of evaporator inlet temperature (°C); hot return at 36–39°C with a useful outlet at about 42–46°C

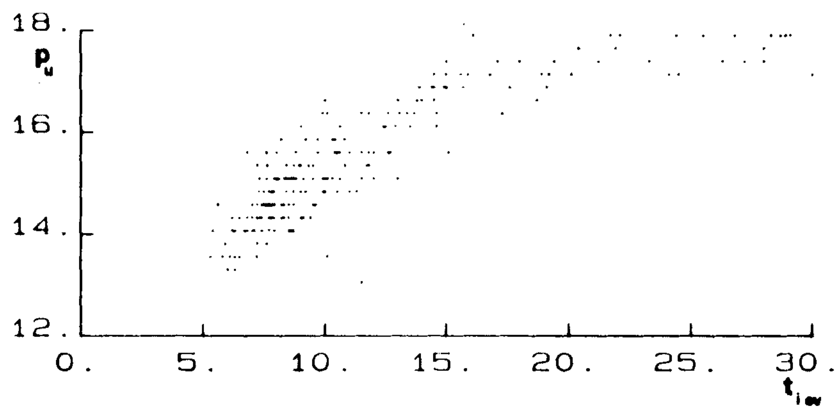

Figure 17. Heating capacity (kW) as a function of evaporator inlet temperature (°C); hot return at 36–39°C with a useful outlet at about 42–46°C

confirm this: a variation from 1·8–1·2 is a strong one since the COP cannot go below a unit value. However, a great number of values were located in the range 1·2–1·5 (expected PER 1·0–1·3), which is a more restricted field.

Different evaluations of PER were obtained utilizing the useful energy value of the heat pump measured through a heat meter and the LPG consumption taken from weighing the gas bottles. Results for some periods are reported in Table I. One can observe that the average PER is 1·25 in the surveyed period. An average 0·85 efficiency of the burner was observed.

During the second winter the absorption heat pump was driven by natural gas as the factory Metalux was connected to natural gas distribution. It was difficult to match the machine to the different conditions, since it was not sufficient just to change the nozzles, but also a different disc had to be placed at the chimney inlet. The machine was operated mainly connected to the earth storage at a feeding temperature always in the range of 8–11°C. The experiments could start only after 7 March. The machine continued working for two months with favourable outside conditions; therefore, the capacity had to be controlled even reaching 40–50 on/off during one day. This can partly justify the results that remained unsatisfactory.

Conditions of near-steady operations were chosen by the data logger recordings in order to eliminate most of the transient effects. As a whole near-steady observations arrived at 718 values. The values obtained, using the ground storage as the cold source, are given in Figure 18 for the COP and in Figure 19 for the heating

Table I. Useful thermal energy, Q_u (kWh), thermal COP, gas consumption, LPG (kg), Primary Energy Ratio (PER), during specified periods (time/date)

Time/date	Hours	Q_u (kWh)	COP	COP (with pump)	(kg) LPG	PER	PER (with pump ×3)
16.40–30/4 to 10.37–1/5	18	285	1·45	1·41	16·3	1·25	1·17
10·37–1/5 to 17·42–1/5	7	119	1·63	1·58	6·0	1·42	1·32
18·07–1/5 to 11·37–2/5	17·5	259	1·40	1·36	15·6	1·19	1·11
11·37–2/5 to 18·07–2/5	6·5	100	1·48	1·44	5·7	1·26	1·17
Whole period	49	763	1·46	1·42	43·6	1.25	1.17

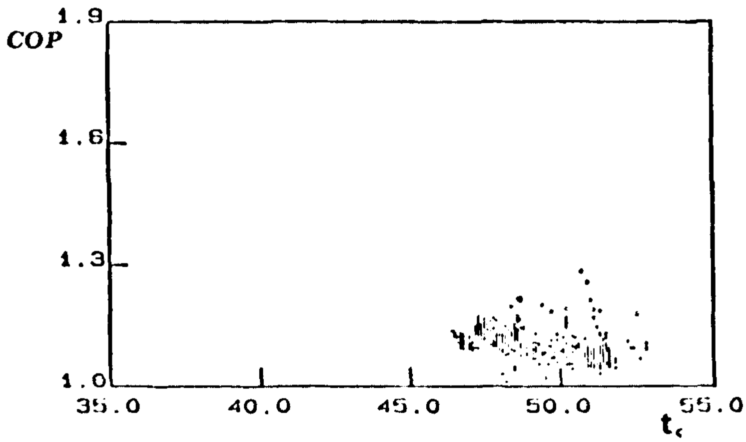

Figure 18. COP as a function of the outlet temperature of absorber/condenser; inlet temperature to the evaporator 8–11°C: ground source

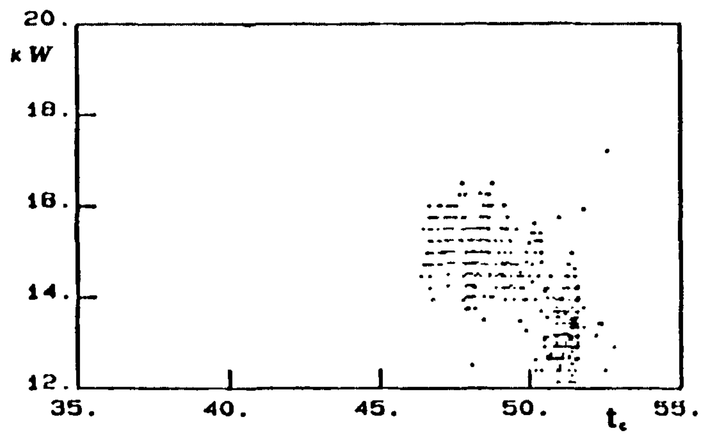

Figure 19. Heating capacity as a function of the outlet temperature of absorber/condenser; inlet temperature to the evaporator 8–11°C: ground source

capacity. The evaporator inlet temperature is in the range 8–11°C. The useful temperatures were between 46 and 54°C. In this operational field the COP was between 1·1 and 1·2, whereas the heating capacity had an average value of only 15 kW.

In Figures 20 and 21 are given the values referring to the earth source and the ones of the roof source in the range 8–11°C. The latter ones have, however, a useful temperature level between 36 and 46°C. This level very much affects the absorption heat pump performances. The trend of COP as a function of the outlet temperature of the absorber/condenser is represented in Figure 20, whereas the heating capacity is given in Figure 21.

In order to reach a good level of PER near the performance claimed by the builder a maximum level of about 40°C at the absorber/condenser cannot be overcome. This must be coupled with a temperature at the evaporator at about 10–15°C. These results are somewhat deceiving; it is mandatory that a strong effort to improve the commercially available absorption heat pumps is made in order to make these machines suitable for effective energy savings.

CONCLUSIONS AND FURTHER DEVELOPMENT

Absorption heat pump

A commercially available absorption heat pump was extensively tested. Information on these small size machines is not available either in literature or from the manufacturers. They limit to claim a PER of 1·3.

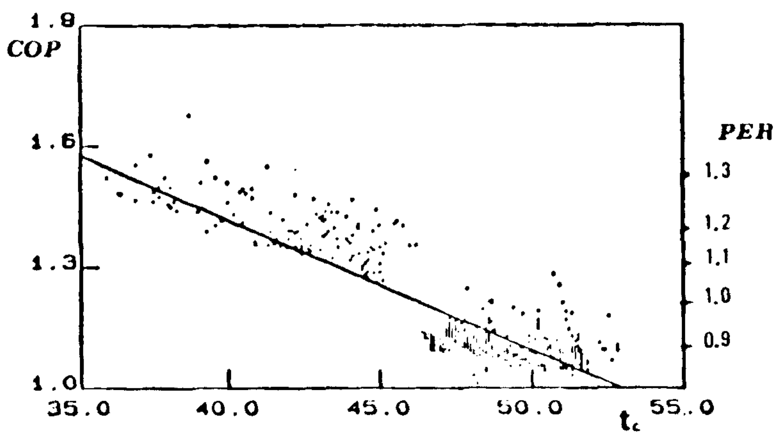

Figure 20. COP as a function of the outlet temperature of absorber/condenser; inlet temperature to the evaporator 8–11°C: total values and interpolation curve

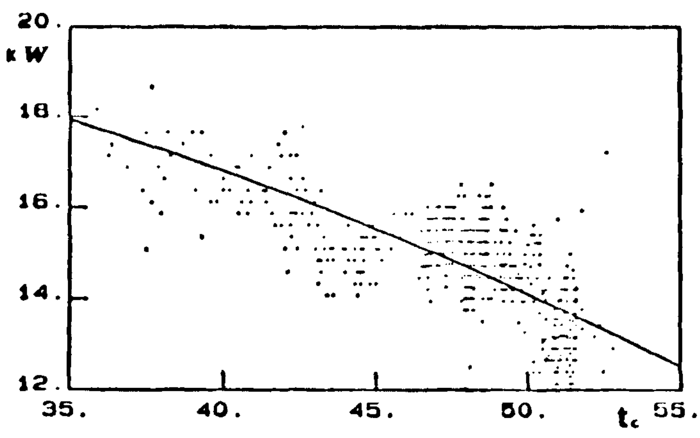

Figure 21. Heating capacity as a function of the outlet temperature of absorber/condenser; inlet temperature to the evaporator 8–11°C: total values and interpolation curve

The experimental results have been disappointing: the considered machine does not reach the claimed COP; moreover, it demonstrated much more noisily than expected.

Performance curves show that it is not advisable to operate at temperatures higher than 45°C, if a PER of about 1·2–1·3 is wanted. The cold source must be possibly higher than 10–15°C. The range is surely not exciting!

Of course the absorption heat pump can work, even at higher levels, with a lower temperature cold source, but performances are worse than with a good gas boiler.

Therefore great improvements are needed to be made to absorption heat pumps before they might be considered as an attractive energy saving alternative. Probably there is room for improvement in the actual single-stage device: however, it will be better to devote a special effort to multi-stage systems.

The energy roof

The experimented energy roof worked very well as a cold source for heat pumps. Particularly if connected to a compression machine, it could give up to 150 Wm^{-2} of low level energy.

The behaviour was different at higher levels. In effect, at increasing temperatures, the roof revealed a modest attitude to exchange heat. Thermographic analysis pointed out high temperature differences between channels and tiles and therefore losses were important on both faces of the roof. Of course if the energy roof could operate at higher temperatures (say more than 30–40°C), it would be advisable to consider an unventilated roof possibly with selective surface.

The ground storage

Vertical tube ground storage is surely an attractive system both for the small interested area and the cost. The employed reinforced polyethylene with special soldering demonstrated to be very reliable and durable. No leaks appeared in the storage subsystem in these two years.

The insertion of the tubes was simple enough and probably not greatly expensive when realized as routine.

The heat exchange in the ground was instead quite unsatisfactory, particularly in the phase of charging when the exchange was no longer proportional to the increasing inlet temperature. A decreasing exchange attitude was even observed during the day. The main reason for this behaviour is probably the poor contact between tube and earth. This contact could be improved by proper utilization of materials such as bentonite around the tubes. It was not possible to control cost and advantages of this technique. As regards heat conservation in the ground, with the experimented size and at the reached temperature levels, temperatures maintained slowly decreased during the whole winter. The discharging was satisfactory enough with available temperatures as high as 8–10°C. Due to the low demand of the absorption heat pump, this level did not change in the heating season.

Energy roof and heat pump

In the Italian climate the energy roof demonstrated a good cold source for heat pumping. No problems will be encountered with compression heat pumps: in fact, this heat pump can operate for the wide range of disposable energy levels that the roof can supply. Difficulties can be found with the actual absorption heat pumps which cannot already operate for an inlet temperature at the evaporator of 5°C. In fact the connection to an earth storage was suggested for this kind of device.

An interesting development would be the direct operation of the energy roof as an evaporator of a compression heat pump, operating as a condenser in summer. This development is very promising and should be studied experimentally.

6.5 *Earth storage and energy roof*

The energy roof experienced difficulties in charging the earth storage: this can be attributed mainly to the poor attitude to the heat exchange between tubes and earth. Once this question is solved the coupling is very suitable and allows utilization of an energy roof all summer long with possible connections to heat pumps with high requirements for the cold source.

The earth storage might be used as a cold storage and the energy roof as a dispersing system during winter. This possibility should satisfy most of the summer cooling demand according to developed simulations. It is a possibility to be studied further.

6.6 *Earth storage and heat pump*

The earth storage is able to supply heat at almost 10°C to heat pumps. The demand was low, therefore it cannot be said how long this operation is possible. However, it seems that at these levels of extraction the ground temperature is not greatly affected. With an appropriate size of the earth storage it seems possible a natural recovery of the ground even in vertical tube disposition, provided the nature of the ground is similar to the studied one (saturated sand prevailing and frequent rain). In this hypothesis (to be controlled) the earth storage may require no periodic recharge.

6.7 *The system as a whole*

The system as a whole has, of course, the sum of the defects encountered at the various points with an additional one of higher cost. If the components are improved as previously pointed out the whole system can be very attractive because it allows for a high level cold source. Of course, the heat pump must take full profit of this high level; therefore, it must be a high performance one (say a two-stage absorption heat pump). Only then will this complex system, developed to study different possibilities, find an economical justification.

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