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Solar Heating and Air Conditioning

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Solar heating and air conditioning

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Application of air conditioning is widespread in the United States; any new system for heating buildings must be at least compatible with it to be commercially viable. A wide variety of options exists to provide air conditioning along with solar heating for buildings. The effectiveness and efficiency of coupling these air conditioning options with solar heating depends strongly on which solar heating system is being contemplated. This paper discusses the relative merits and the state of development of several solar boosted heat pump systems with regard to their ability to provide air conditioning using conventional vapour compression refrigeration cycles. A brief description is given of the status of solar fired air conditioning. Clues to an approach to cool storage in solar air conditioning systems are given by an assessment of cool storage for reducing peak electrical loads from conventional air conditioning equipment. A system using hydrated salts in a rolling cylinder thermal energy storage device for compact and effective cool storage is described. References are given to provide the interested reader with more detailed information.

Solar heating and air conditioning

The U.S. air conditioning industry in 1977 had annual sales of more than \$3000 M; central air conditioning was included in 53 % of all new residential construction in 1977. The industry sold, in the domestic market, 2.6×10^6 unitary central air conditioners and heat pumps, and an additional 2.8×10^6 room air conditioning units.

These figures illustrate the importance of air conditioning to the U.S. market. Any innovative heating technology, including solar heating, must be at least compatible with air conditioning, if it is to achieve wide application. It is, for example, this combined need for air conditioning with heating, even in climates where winter temperatures reach -30 °C, which has caused heat pumps to be installed in 19 % of all new houses in the U.S. in 1977, creating a market of 498000 units.

There is a multifaceted relation between solar heating and air conditioning systems which can have important consequences on the efficiency, cost, reliability, and development cost of solar heating systems intended for broad application in the U.S. market. Air conditioning using the Sun as an energy source can be accomplished by solar fired absorption refrigeration systems, solar fired mechanical engines developing the shaft horsepower needed to drive vapour compression cycles, or solar heated chemical heat pumps. These latter use new chemical cycles bearing some relation to conventional absorption cycles, but are quite different in their operating advantages and disadvantages. Air conditioning can also be provided in conjunction with solar heating systems by conventional commercial equipment using electrically driven vapour compression cycles as air conditioners, or as heat pumps. This diversity of possible air conditioning equipment might be coupled to a variety of solar heating systems including simple collector, storage unit, and heat exchanger units and solar boosted heat pumps. Some combinations are compatible and work effectively together, while others will work only poorly at best, or in some cases not at all.

We shall discuss this relation in terms of

(i) solar assisted heat pumps, and the interaction of several configurations with air conditioning;

(ii) solar fired refrigeration cycles;

(iii) The impact on air conditioning energy requirements and peak electrical load of cool storage, a study that gives some clues on how to look at the optimization of cool storage for use with solar air conditioning;

(iv) a latent heat cool storage system using the rolling cylinder device and hydrated salts.

In the following discussion we are not concerned primarily with economic calculations or cost optimization of solar air conditioning systems. It is generally true that the most economic method of air conditioning a solar heated house is to use conventional electrically driven vapour compression air conditioners or heat pumps. Solar fired air conditioning is not today economically advantageous. A number of research programs are under way with the goal to reduce the cost and performance of such equipment.

Solar assisted heat pumps

For these economic reasons, and because electrically driven vapour compression equipment is available today while much of the solar fired cooling technology is still in the development stage, we will focus first on the impact of alternative solar heating systems on the applicability and efficiency of vapour compression air conditioning.

Heat pumps complement solar collectors and heat storage in solar boosted heat pump systems in several ways:

(i) heat pumps are more efficient and can provide more heat for a given heat pump size if their evaporators can operate from a warm source; thermal energy storage, heated by solar collectors, can provide that warming;

(ii) solar collectors operate more efficiently if they collect heat at lower temperatures; if the collected heat can be stored at lower temperature because it is used to warm the evaporator of a heat pump, the collector is more efficient, and therefore less collector area is needed to collect a required amount of heat;

(iii) heat pumps are the most efficient way to use electricity for back-up heat for a solar heating system, even if there is no direct thermal connection of the heat pump with the solar collector and storage system;

(iv) heat pumps can allow sensible heat storage units (water, rock beds) to operate over wide temperature ranges because stored heat down to 5 °C can be used in conjunction with heat pumps to heat a building.

The relationship between heat pumps and solar heating systems has been described elsewhere in more detail (Comly *et al.* 1975; Comly & Jaster 1978).

Several solar boosted heat pump systems will be described to illustrate their relation with air conditioning: simple parallel system; series system; three coil system; and cascade system.

Simple parallel system

Equipment is available today on the commercial market to build the parallel solar boosted heat pump system shown in figure 1. On the left is shown a simple solar heating system. The collector heats water when sunlight is available; hot water is stored in a tank; when the thermostat calls for heat, water from the tank is circulated through a water-to-air heat exchanger to heat the building air. If the tank temperature is too low (below 40 °C) when the house calls for heat, a controller shifts to an air-to-air heat pump which heats the house in the conventional way.

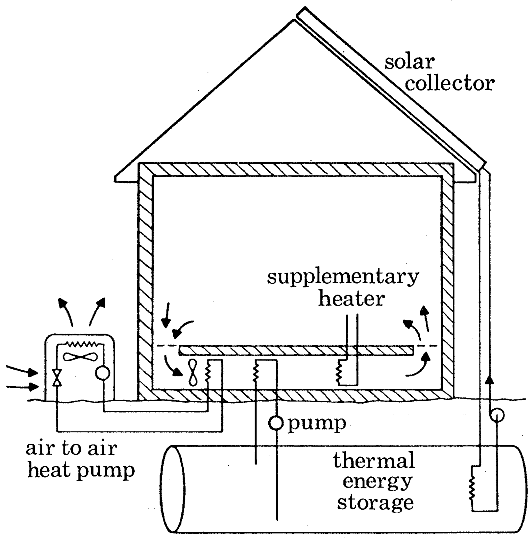

FIGURE 1. Parallel solar boosted heat pump system.

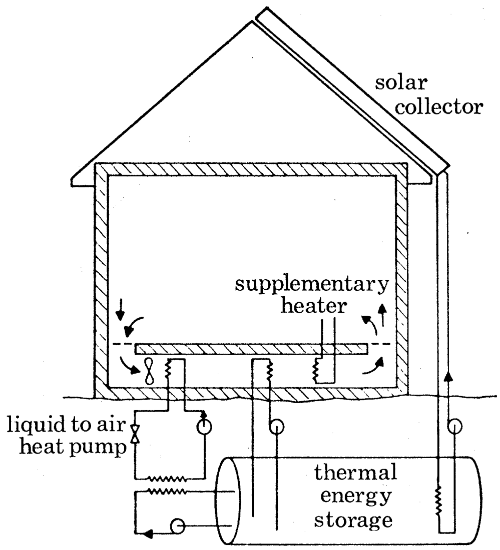

FIGURE 2. Series solar boosted heat pump system.

This system can provide air conditioning using the normal function of a reversible heat pump. The equipment is already available on the commercial market and no development is required. The air conditioning efficiency is the same as for a central air conditioning unit.

Series system

Figure 2 shows a series solar boosted heat pump system with the following: solar collector heating water; hot water stored in tank; tank providing heat directly to the house if the tank temperature is above 40 °C; heat pump drawing heat from the tank when the temperature of the tank is between 40 and 5 °C. This system has the advantages that the tank can be operated at lower temperatures when required, which allows the collector to operate with high efficiency, and allows the tank heat storage capacity to be increased by the amount of sensible heat stored between 5 and 40 °C. The disadvantage of the system is that when the tank temperature finally drops to 5 °C, the heat pump cannot be used further without danger of freeze-up in the water tank.

The system shown will not provide air conditioning because there is no way to exhaust the waste heat to outside air. It would be possible to provide air conditioning if there were another heat exchanger loop between the storage tank and outside air; this would add the cost of the heat exchanger and its associated circulating pump. A development effort is required on the heat pump in this system because residential heat pumps are not currently designed to operate efficiently with evaporator temperatures over 20 °C, and this one would have to operate up to 40 °C.

Three-coil system

This system, illustrated in figure 3, combines the advantages of the parallel and series systems, and overcomes their disadvantages. The solar collector, heat storage, and building heat exchanger all continue to work as a simple solar system as long as the tank temperature

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remains above 40 °C. At temperatures below that, the heat pump system is called upon by a microprocessor controller, and a decision is made as to whether it is better to draw the heat pump's heat from the tank, or from the outside air, The control strategy options are numerous for this system; it can be operated to optimize savings of electricity, or to reduce peak loads. It would be the most efficient of all the systems described here.

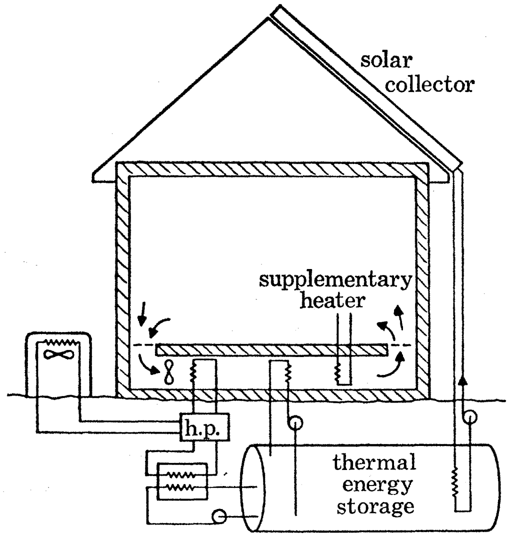

FIGURE 3. Three-coil solar boosted heat pump system.

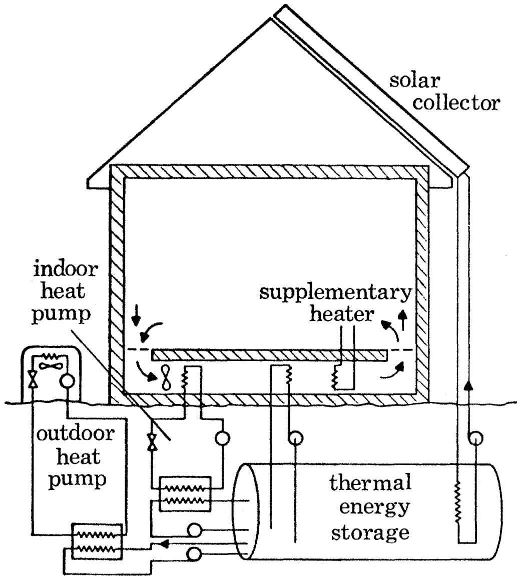

FIGURE 4. Cascade solar boosted heat pump system.

It has the disadvantage that the required heat pump is complex, and will be costly to manufacture; considerable development work will be required to assure that the unit can be operated in all sequences of all its modes with full reliability. With this system, air conditioning is accomplished by operating the unit as a simple air-to-air heat pump in the cooling mode, using only the outside heat exchanger as a condenser. The system is not capable of using the storage tank to reduce air conditioning peak loads in the summer because the heat pump cannot be used to cool the tank to the outside air.

Cascade system

As figure 4 shows, the cascade system allows complete access to the storage tank in both the heating and air conditioning mode. Two heat pumps are used, one between the outside air and the tank, and the other between the tank and the house. The inside heat pump allows the system to operate in the series heat pump mode, providing heat to the house when the tank temperature drops below 40 °C. When supplemental heat is required, the outside heat pump charges the tank with heat removed from the outside air. In air conditioning, the inside heat pump cools the house on demand, depositing the heat in storage; the outside heat pump then removes heat from the tank to outside air during off-peak periods.

Both of the heat pumps used in the cascade system require some development effort. The outside heat pump must be optimized for operation between outside air temperatures and the cool water temperatures of the storage tank. The inside heat pump is the same as the series unit described above, except that it must include the ability to air condition as well as heating.

Required development effort would probably be less than for a three-coil unit. This system is probably the most expensive of those described here, because of the cost of heat pump equipment.

When operating with the outside heat pump as a supplementary heat source it will be less efficient than the three-coil or parallel systems because the heat must go through a second heat pump in heating the house. On the other hand, it is the most flexible system, allowing full heating and air conditioning, and the use of the storage tank to store heat for off-peak use (solar, or electrical utility) during the heating season, and to reduce air conditioning peak loads during the cooling season.

Solar assisted heat pump summary

In the competition for commercial viability all solar heating systems must compete for some version of life-cycle economic advantage with alternative non-solar heating systems. In going to solar heating an economic balance is made between the high first cost of solar heating or cooling equipment and the cost savings realized by reduced use of fuel or electricity. One way to compare such systems is to determine the cost of electricity at which non-solar and solar heating systems have the same overall life-cycle cost. A rough comparison of this break-even cost of electricity shows that many of these systems will only be more cost-effective than the conventional air-to-air heat pump available in the U.S. today when electricity costs become greater than 10–12¢/kWh. The current national average cost of residential electricity is about 4¢/kWh, with a range up to about 10¢/kWh in some major urban utility systems. With the new tax credits allowed by the U.S. Government the break-even cost, for the parallel system for example, becomes 6¢/kWh.

Solar fired air conditioning

Solar fired air conditioning, using the heat from the Sun to drive any of several possible types of refrigeration cycle, is still primarily a research subject. Those technologies that have proved to be feasible technically in commercial packages (absorption cycles), are still too costly to compete with electrically driven air conditioners. Other technologies with interesting or promising features are still in the early stages of development to assure that their size, reliability, operating characteristics, and cost will allow them to compete. Examples of these are heat engines (e.g. Rankine expanders coupled to more or less conventional compressors) and chemical heat pumps. A brief review of these technologies is given in Gordian Associates (1978).

Absorption cycle air conditioners

Absorption cycle air conditioners are well enough understood, and are based on sufficient commercial experience to allow us to identify their main problems and limitations: complexity of plumbing compared to simpler rankine heat engine machines; generally lower coefficient of performance than the promise for rankine driven machines; material compatibility problems (toxicity for ammonia–water systems, and crystallization if temperature excursions occur for water–lithium bromide systems); greatly reduced cooling capacity when source temperatures drop much below 95 °C. Development continues on absorption cycles but, to date, available units are very large and costly for solar applications.

Chemical heat pumps

Chemical heat pumps operate with cycles that have some similarity to absorption systems. However, these chemical cycles use the latent heat of absorption or of chemical reactions as the primary heating mechanism, whereas absorption units use the latent heat of condensation and evaporation of refrigerant driven by absorption, e.g. of ammonia in water, or water in a concentrated lithium bromide solution. An example of a chemical heat pump is the absorption of water vapour into concentrated sulphuric acid. Chemical heat pump technology is currently reported in the proceedings of several meetings convened by the U.S. Department of Energy (1977*a*, 1978*a*, *b*) for its R. & D. contractors.

Heat engine air conditioners

Heat engines driving vapour compressors currently appear to represent the most promising technology for high efficiency solar fired air conditioning. They promise high efficiency or c.o.p. (cooling effect divided by thermal input). Systems using solar fired Rankine engines typically have performance figures in the range:

(i) c.o.p. = 0.4–0.7 depending on condensing temperature;

(ii) thermal source temperature (collector temperature) = 120 °C;

(iii) air flow requirements = approximately 56 m^2 min^{-1} t^{-1} cooling capacity, about twice the requirement for a conventional heat pump;

The principal problems still to be solved for Rankine engine air conditioners, beyond making them cost competitive, are:

(i) speed control to allow operation of the compressor in its optimum speed range; unfortunately, simple speed controls based on throttling of the working fluid in the Rankine engine loop reduce efficiency;

(ii) matching between torque requirements of the compressor which are maximum when evaporator (indoor) temperature is highest, and torque availability of Rankine engine which is minimum when condenser (outdoor) temperature is highest.

These requirements create a confined operating range for a Rankine engine system which is demanding on both the heat (or cool) storage system, and on the complexity and adaptability of the controller for the system.

Solar heat-fired air conditioning is reviewed in two U.S. Department of Energy Conference Proceedings (1977*b*, 1978*c*).

Cool storage

Thermal energy storage is an essential part of any solar heating and cooling system for buildings. It may be used to reduce peak electrical loads on utilities, or to make heating and cooling available during times when the Sun does not shine.

When considering air conditioning alone, thermal energy storage can be used on either the hot or the cool side of the system. For example, in the case of heat driven air conditioning, heat from the collectors may be stored for use to drive the air conditioning when it is needed. Alternatively, the air conditioner may be used whenever there is enough sunshine to drive it to cool a storage unit, and the cooling power stored thereby can be used to cool building air when it is needed. The balance between these two systems is complex and depends on the heating and cooling systems used. We will concentrate on cool storage in this paper.

To illustrate the considerations involved in cool storage, two projects will be summarized: an assessment of the application of sensible or latent heat storage to reduce the peak load on electric utilities from conventional air conditioning, a study that gives some clues about how to consider

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cool storage in solar driven air conditioning systems; and the promise for cool storage capability of the rolling cylinder thermal energy storage system.

Cool storage assessment

A brief study was made to explore methods to assess the relative merits of sensible and latent heat storage to reduce electrical loads from air conditioning during peak times for utilities. No solar energy source was considered. Estimates were made of the potential for such peak reduction and the concomitant use of overall energy to drive the air conditioning system (General Electric 1977). The study compared a conventional central air conditioner in a 140 m^2 house in Washington, D.C., against four combinations of sensible or latent heat, coupled with one heat pump between storage and outdoor air, or two heat pumps with the second unit operating between storage and the building, e.g. the cascade system described earlier in this paper. Most important among several conclusions from this study are that:

(i) the best system uses one heat pump between outdoors and storage, the latent heat storage device, and a heat exchange loop between storage and the building;

(ii) the latent heat storage device should have a freezing temperature between 7 and 13 °C, and a temperature drop of no more than 6 °C between freezing temperature and heat transfer medium;

(iii) a latent heat device using a material storage volume of approximately one cubic metre could reduce peak electrical load by 80 % during peak hours, with an increase of no more than 10 % in electrical energy use over the conventional air conditioner;

(iv) the same effect would require about ten times the volume of sensible heat storage medium (water).

Similar analysis could be applied to cool storage for a selected solar cooling system, to determine optimum storage requirements.

Rolling cylinder thermal storage for cool storage

The rolling cylinder device has shown considerable promise to solve long-standing problems in the use of incongruently melting hydrated salts for thermal energy storage, of which Glauber's salt ($Na_2SO_4 \cdot 10H_2O$) is the best known (Herrick & Golibersuch 1977; Thornton 1978). This device is a cylinder with horizontal axis, rotating slowly (approximately 3 rev/min) about the axis, and filled with a mixture of saturated water solution, anhydrous salt, and hydrated salt when it is partially 'charged' (melted). Considerable success has been found with Glauber's salt (melting point 32.3 °C) in the following; rapid nucleation with little supercooling; excellent heat transfer during the whole range of stored energy; and excellent mixing yielding cycling of over 200 freeze–melt cycles with no degradation or decrease in heat storage capacity.

The cool storage assessment study described above showed that for air conditioning applications, cool storage materials will be most useful if they freeze in the range 7–13 °C. Recent work has identified a material that has the promise of operating well in a rolling cylinder with a melting temperature of 11.1 °C. The material is made up of the following constituents (percentages by mass): 32.6 % Na_2SO_4; 13.6 % NaCl; 12.3 % NH_4Cl; 41.5 % H_2O; and additives 0.4 % sodium dichromate (corrosion control) and 0.7 % bentonite clay (anti-caking agent). This material has operated in a 5 l laboratory rolling cylinder for 150 freeze–melt cycles with excellent qualitative characteristics. This work is reported in more detail in Herrick & Zarnoch (1978).

Conclusion

A wide variety of options exists to provide air conditioning along with solar heating of buildings. The efficacy of coupling these options with a solar heating system depends strongly on which solar heating system is to be used, and whether one is considering systems that can be built reliably today, or that promise optimum performance in the future following extensive development efforts. This paper has discussed the relative merits of several solar boosted heat pump heating systems with regard to their ability to provide air conditioning. Some general comments have been made about the status of solar fired air conditioning equipment, and references are given to guide the interested reader to further information. Ways to look at cool storage from a systems point of view are described briefly with references to more detailed descriptions. Finally, a system of materials and a storage device, the rolling cylinder, are described, which seem to meet the rather narrow criteria for an optimum cool storage material for air conditioning peak load reduction.

These many options will ultimately require selectivity concerning pursuit of their development; however, it would be unwise to eliminate options at this point for reasons of seeming excessive expense or of detailed engineering problems such as minor material incompatibility. For solar heating to work in the U.S. market it must be compatible with air conditioning; for the best energy savings to be made, it is imperative in the long run to be able to use the energy from solar collectors already in place for solar heating, to drive air conditioning equipment in place of manufactured forms of energy.

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