SOLAR ENERGY IN GREENHOUSE ENVIRONMENTAL CONTROL

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Introduction

Before any serious discussion of solar energy for greenhouse environmental control it is important to keep firmly in mind the objective of greenhouses. Commercial greenhouses are used for intensive cultivation of high value plant products. Greenhouse facilities require far greater capital investment than equivalent areas of field production and generally greater inputs of labor and materials. Therefore it is essential that reliable productivity levels of high value crops be maintained to cover operating costs and amortize investments. High value crops must be of high quality and will almost always represent crops that cannot be grown well in unprotected cultivation in the same season.

In addition to commercial production, greenhouses are also used for research purposes, for retail display of products to be sold, for botanical gardens, and some other specialized purposes. In all cases environmental control is important but the specific objectives may be somewhat different than for commercial production of food and ornamental products. However, it remains fundamental that the utility of the greenhouse represent very high value, in the case of a research facility the knowledge gained must be valuable to justify the capital and operating costs. In commercial production and research facilities it is essential that the environmental control be precise with regard to not exceeding upper and lower set points on the environmental parameters being controlled. As control systems only satisfy the requirements at the location of the sensor it is very important that the system being controlled, i.e., using a heating system or a cooling system, perform in such a way that the conditions are uniform throughout the useful area of the greenhouse. If we are providing cooling that satisfies a thermostat in the middle of the greenhouse but the conditions are much to cool near the inlet of the cooling system and much to hot at the exhaust the total system is not performing adequately. System design must provide for spatial uniformity of conditions and unfortunately many operating designs fail to meet this requirement.

Energy Conservation Principles

Over the years there have been a number of research and demonstration projects on the application of "alternative" energy sources to greenhouse environmental control. Many of these were related to the use of solar energy or the recovery of reject heat from industrial processes and almost all have been directed at heating greenhouses in northern and temperate latitudes. In some of the solar projects there was a significant component of effort on energy conservation and the phrase "insulate then insolate" was popular with many solar energy research people. In the case of

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some solar projects and most reject heat recovery projects there was little to no attention paid to energy conservation. Indeed, in some recovery projects in which the thermal energy recovered is justification for preferential pricing of the co-generated electricity, the objective was to maximize the amount of thermal energy consumed in the greenhouse.

In the research programs on alternative energy for greenhouses conducted at Rutgers University, the concept of looking first to energy conservation and then to the integration of energy conservation and the alternative energy source has been an important aspect of all projects. The economic value of energy conservation is most obvious to many people when thinking of greenhouse heating as it is possible to easily relate investment in insulation, which reduces fuel requirement thereby amortizing the investment. There is another, intrinsic value to energy conservation which is related to the value of the final product as determined by the quality of the greenhouse environment. As noted above, the greenhouse manager will have an easier task in providing uniform, high quality products if the greenhouse environment is controlled uniformly throughout the growing area. It has been learned that keeping the environment constant across the growing area can be done better when energy conservation measures are employed that result in reducing the magnitude of the energy flow in the system.

Importance of Environmental Uniformity

The relationship between rate of energy movement and environmental uniformity is determined by the temperature gradient required to move energy. In the case of heating for a small greenhouse, energy is being lost through the roof, sidewalls and end walls and infiltration which is usually most pronounced along the walls. If the energy source is a hot air blower, the hot air must be circulated throughout the greenhouse and it is very normal to find temperatures are coldest near the walls as heat is flowing out the walls as well as up through the roof in the area near the walls. Near the center of the house the major heat loss is only straight up. If the heat is supplied uniformly throughout the house by means of circulating hot water through pipes and/or a floor or bench heating system, temperatures will be more uniform than will be the case with a hot air blower, but it is still common to find more heat loss and colder temperatures near the wall. Adding insulation by double-glazing and adding energy conserving thermal blankets reduces the energy flow requirement and therefore the differences in temperature required to drive the energy to and through the roof and walls, resulting in more uniform internal temperature distributions.

Similarly with cooling, the energy gradient required to remove heat is proportional to the amount of excess heat that has to be removed. However, the areas of the greenhouse through which energy that has to be removed is flowing in have a different relationship to the cropping area than is the case for heating. The solar energy flowing in through the roof is in some respects analogous to the problem of heat flowing out through the roof on a cold night, but the incoming solar energy is more dependant on roof design shape than is outgoing heat. Heat gain through the walls is also somewhat different as the east wall is more important in the morning, the west wall in the afternoon and the south wall during the middle of the day, particularly at more northern latitudes in the winter.

Natural ventilation systems are very common in many greenhouses and can be effective when well designed and when the amount of energy to be removed by ventilation is relatively modest. In small greenhouses, natural ventilation is often accomplished with a combination of sidewall and ridge vents in rigidly glazed structures and sidewall only vents are most common in Quonset shaped plastic film glazed structures. The uniformity of temperature and cooling achieved depend on the amount of solar radiation coming in, the temperature difference between inside and outside and the wind conditions, (speed and direction). In conditions of low wind speed it is only the temperature difference between inside and outside that provides ventilation so there must be a significant thermal gradient within the greenhouse. In multi-span gutter-connected structures natural ventilation is more difficult to achieve. In wide structures with many spans any sidewall inlets will have little benefit for interior spans and it is the ridge vents that provide most ventilation. Ridge vents are common on rigid glazed structures and in recent years some plastic film houses have been designed to have opening ridge vents.

Historically, plastic film structures, especially multi-span units, have been fan ventilated. The principles and design for fan ventilation systems are straightforward and well understood. As ventilation air is drawn in on one end of the greenhouse and exhausted at the opposite end there is a temperature gradient from inlet to outlet. This gradient is proportional to the rate of incoming solar radiation and the distance between inlet and outlet and inversely proportional to the rate of air movement per unit area. It is essential to evenly distribute the incoming air along the inlet side of the greenhouse but placement of the outlet is much less critical to internal temperature uniformity. Exhaust fans are far more common than pressurized systems. The issue of internal temperature uniformity is the same with wet pad evaporative cooling as for non-cooled inlet air. The evaporative pad lowers the temperature at the inlet but the increase across the span of the greenhouse is the same as it would be without the evaporative cooling.

The temperature gradient across the greenhouse for any given airflow can be reduced by reducing the amount of solar energy that has to be removed by shading the greenhouse. Thus shading a greenhouse results both in reducing the amount of energy that has to be removed and an improvement in the uniformity of temperature spatially within the greenhouse. In both heating and cooling the conservation concept, properly applied, can reduce system cost and operating cost, and can improve uniformity of conditions. In the case of cooling, uniformity can also be improved somewhat by bringing in ventilation air through a duct, such as a perforated plastic tube, and distributing it down the length of the greenhouse. This is most effective when there is only a modest amount of excess heat to be removed at a relatively low ventilation rate. Under very hot conditions the amount of airflow required is so great that it is not practical to install ducts of sufficient size. With evaporative cooling, uniformity can be improved by placing evaporative units, such as high-pressure fog nozzles, throughout the growing area.

Greenhouse Solar Energy Research Program in the USA in 1970's

In response to the "energy crisis" in the 1970's there arose a significant interest in solar energy as an alternative to fossil fuel energy. One expression of this interest was the development of a number of research projects and some commercial demonstration activity. With regard to environmental control in greenhouses, there were two programs involving the research group at Rutgers University. One was a USDA sponsored research project on solar energy for heating greenhouses and greenhouse-residence combinations. The second was a follow on DOE sponsored commercial demonstration of solar heating in commercial greenhouses. There were more than a dozen university based research programs and five commercial demonstration projects. Rutgers University was the only institution involved in both programs.

Under the research program a number of solar collector types were tried and a variety of energy storage methods investigated. Also, several projects looked into energy conservation measures to reduce the needed solar energy stored for heating. Systems investigated included air and water heating collectors and solar collectors integral with the greenhouse as well as external. While water was the most common storage medium, rock storage and packaged eutectic salt mixtures for air systems were also investigated as well as deep soil storage and concentrated salt solar ponds. While many interesting and potentially useful things were learned in this program, only a few of the concepts that were developed have been widely adopted by the greenhouse industry. Several of these were fundamental components of the commercial demonstration project conducted by Rutgers University at a private commercial greenhouse facility, Kube-Pak Corporation, Allentown, NJ.

With the solar system developed at Rutgers University, key aspects included a substantial energy reduction, use of the greenhouse floor for storing and delivering thermal energy, and low-cost plastic film solar collectors. The project was installed in a 0.54-hectare block of greenhouse in a much larger range. There were 10 gutter connected bays glazed with double layer polyethylene, an inherently energy efficient house. A house of this size has a small nominal wall surface area relative to floor and roof. Double layer polyethylene has about 2/3 the heat loss of single glass. Thus the heat requirement can be only about 1/2 that required for single span single glazed free standing houses of equivalent area. For further energy conservation, movable curtain insulation systems were developed that reduced the heat requirement to about 1/2 what was required without the curtain system.

For energy storage a flooded floor storage/heat exchanger was developed. An impervious plastic film liner similar to a swimming pool liner is lain down and filled with about 23 cm of nominal 2 cm diameter gravel having almost 50% void space, which can be filled with water. This gravel layer is capped with 10 cm of porous concrete made with cement and 1 cm diameter gravel but no sand. The resulting surface is hard, but spilled irrigation water drains into the water storage without leaving puddles on the surface. The water in the floor is pumped through external solar collectors during the day and heated to 25 to 35°C, which is warm enough to provide most of the heat required in the greenhouse. As the greenhouse is well-insulated and very energy efficient, and as the floor area is so large, the amount of heat required can be provided from the floor at a very modest temperature. Note that in smaller greenhouses without curtain insulation systems much greater heat delivery rates would be needed and the storage would have to be both larger and held at a higher temperature to be effective. This is important to the solar collector design as collection efficiency drops off quickly with increased operating temperature, particularly for the type of low-cost collector unit developed at Rutgers University.

This large commercial demonstration project turned out to be very important with regard to furthering the commercial acceptance of two important concepts. First was the idea of using floor heating with warm rather than hot water distribution systems. The solar floor, commonly called a wet or flooded floor, had the advantage of a large thermal storage mass coupled with a steady delivery of heat but at a modest level. In well-insulated and efficient greenhouses the floor heating idea can be utilized for almost all of the greenhouse heating requirement. As the temperature difference required between the stored heat and the greenhouse air is not great, there is little danger of greenhouse overheating even when the floor heating system is unregulated.

It has been learned through observation of the solar system first and later confirmed in a number of research programs that there is a substantial physiological advantage in having the thermal environment of the root zone controlled independently of the air temperature. In many cases the increased productivity or value of the crop was far more important to the overall economics of the operation than the energy savings achieved. While there have been some important fortuitous synergisms, it is important that attempts to conserve energy maintain or enhance the ability to produce quality. Many alternative floor and bench heating systems have been developed to take advantage of this concept. Such systems designed at Rutgers University can utilize fossil fuel energy or reject industrial energy as well as solar derived heat. Many hectares of floor-heated greenhouses have been built around the world, mostly in Northern and temperate climates.

"Solar Cooling" Attempts

Several of the projects conducted under the solar energy research program discussed above had significant cooling objectives even though the major thrust of the program was for heating. One project involved circulating air drawn from deep coalmines through greenhouses to condition the air for both heating and cooling. Another option investigated used rock bed systems to store heat from air heating solar collectors for night use in cold weather and circulated night air through the rock bed to cool it for greenhouse daytime cooling in hot weather. One difficulty with this approach is that the energy that must be removed on a hot day is an order of magnitude greater than what must be provided on a cold night in latitudes from the temperate zone south.

A very interesting concept developed in France involves circulating fluid with heat absorbing dye between the layers of a greenhouse roof glazed with a double layer rigid plastic panel. The idea is that non photosynthetically active radiation will be absorbed in the liquid thereby reducing the daytime cooling requirement and the energy collected can be stored for use at night. A very simplistic approach to this idea was tried at Rutgers University several years earlier in which plain water was sprayed in the space between the two layers of a double polyethylene glazed house. The water actually intercepted about 15% of the incoming energy but the idea was never fully exploited. Another idea involves circulating the greenhouse air through a network of pipes buried in the soil, either an external deep soil storage or a shallow storage under the greenhouse. This later idea has been studied fairly extensively in Japan and we understand it has found significant commercial application there.

Another concept previously investigated is a solar chimney to provide the motive force for ventilating a greenhouse. This entails building a solar air heater as a chimney with a black side and transparent sides toward the sun. As solar energy heats the chimney the hot air rises drawing cooler air into and through the greenhouse inlets and up the chimney. The volume of air that can be moved in this way has been small relative to what is needed in a large commercial greenhouse.

Another system utilizing a rock bed storage with air handling that provides some daytime cooling and night heating has been developed specifically for the production of foliage plants in warm climates. As foliage plants require a lot of shade it is possible to add a plastic ceiling and about 50% dark shade above that in the attic of a greenhouse. Fans circulate the heated air through the rock bed and the attic in the day and the rock bed and the greenhouse at night. The shade gives the major cooling benefit, but this level of shade is excessive for most greenhouse crops.

Greenhouse Cooling Options

The first step in greenhouse cooling is almost always ventilation, which brings in fresh CO_2 and removes moisture as well as heat. A general rule of thumb is that from 1/2 to 2/3 of the energy removed from the greenhouse is in the form of latent heat in the water transpired by the crop in a fully cropped greenhouse. This is true for natural ventilation as well as forced ventilation systems. One method of reducing the required airflow is to shade the greenhouse reducing the incoming solar radiation. External shade in the form of sprayed on white material such as whitewash has been extensively used on glass greenhouses and to some extent on plastic film. Another common shade is a woven dark plastic netting which comes in various shade densities and can be draped over the outside of the glazing or suspended on a secondary frame. Such shading systems are effective in reducing peak cooling requirements and reducing plant stress. A shortcoming is that the percentage of shade is constant and therefore in low light periods the plants are receiving less solar radiation than is optimum for growth.

An alternative is a movable shade system where the shade material is drawn closed when shading is required and removed during low light periods. It is very interesting to note that the development of movable curtain materials for peak daytime shading was substantially advanced by the concern for energy conservation during night heating. In research at Rutgers University on solar heating of greenhouses, the movable curtains, sometimes called thermal screens, were quickly found by the growers to be useful as shading systems during the day as well. It was not long before recommendations for heat saving curtain systems specified the curtain material be selected with the optimum percentage of shade for daytime use and accept the nighttime heat savings obtained, even if the material did not have the optimum heat retention characteristics. After a long evolution, commercial greenhouses now generally employ a material with alternating strips of clear and aluminized material with the percentage of aluminized material adjusted to provide the desired daytime shading.

Movable internal curtain systems developed for energy conservation have been widely utilized up to the present and it has been observed that aluminized materials are better than dark opaque materials for the shade component. Heat and light reflected back out of the greenhouse does not have to be removed by the ventilation system, but any heat absorbed by the curtain or greenhouse structure still needs to be exhausted. By mounting a movable curtain material external to the greenhouse all energy absorbed by the curtain is excluded from the greenhouse cooling load. External systems are now being installed commercially and are becoming increasingly popular. There has been significant development in improving the curtain materials and supporting structures to withstand the elements of the weather. It is likely the use of such systems will be increasing in warmer climates.

New Ideas for Solar Cooling in Hot Climates

In the early 1970's an energy saving greenhouse was designed at Rutgers University for use in the tropics. This was a double layer film greenhouse design with multiple spans but with a sloping roof on one side and a vertical roof wall on the other, which was filled with inflatable plastic tubes rather than fixed glazing. A slot around the base of the greenhouse was also closed off by inflating a plastic tube. By deflating the plastic tubes by simply shutting off the small fan inflating them, an open, sawtooth roof greenhouse was achieved. It was found that inside temperatures could be kept within 3°C of outside ambient with this design. It was intended for application where some electric power was available for low wattage inflation blowers, but not enough to power a fan ventilation systems. It has been noted that in remote locations low wattage inflation blowers can be operated with a photovoltaic system with battery storage.

Several ideas have been tried at Rutgers University for improving the uniformity of conditions within the greenhouse using evaporative cooling. In one project a cloth material for night insulation was adapted for daytime shading and a greenhouse misting system installed above the curtain. When evaporative cooling was required the mist nozzles were used to wet the curtain, which was the ceiling over the crop. Such a system does provide excellent spatial uniformity and has the added advantage that the water quality requirement for misters is not as stringent as for fog nozzles. Another system tried was mounting high-pressure fog nozzles on a moving boom, which travels back and forth over a span in the greenhouse. This system also provides good spatial uniformity and results in a need for less nozzles than if a distributed fixed nozzle array is used. In any high-pressure fog system, water filtration and quality is important with regard to the effectiveness of the system and the life of the nozzles.

In a collaborative project with Taiwan, a hot and humid climate, different combinations of natural ventilation, shading, forced ventilation, and evaporative cooling were investigated. The most effective system is forced convection with shading and evaporative cooling. Under natural ventilation alone, temperatures up to 7°C above outside ambient and very non-uniform within the greenhouse were obtained. With fans but without shading and evaporative cooling, internal greenhouse temperatures are up to 4°C above outside, and with evaporative cooling through wet pads at the inlet, temperatures from 3 to 6°C cooler than outside are attainable.

A number of greenhouses have been designed for plant quarantine stations in India. These are for a temperate zone, a hot humid zone, and a hot dry zone. In the hot zones the biological containment requirements of the client dictate mechanical refrigeration be used for cooling without significant ventilation. The size of refrigeration unit and the electrical load resulting from this are very substantial. Also, the author fears the effect on the plants of the rapid circulation of dry, refrigerated air under intense solar radiation may be a problem. It may turn out that this approach is not feasible. With regard to this discussion, it is noted that some research workers have advocated using solar energy to either generate electricity, to operate mechanical air conditioning, or to operate absorption type chillers to air condition greenhouses. It seems highly unlikely that this approach will be technically or economically practical.

Another approach to solar energy utilization for greenhouse cooling that should be evaluated is the use of photovoltaic cells for powering fans and/or evaporative or fog cooling pumps. The current status of photovoltaic generated electricity is that in most cases the costs are high and the systems are therefore only competitive in remote locations where any other alternative is also costly. It should be noted that there has been and it is expected there will continue to be, a relative decline in the cost of photovoltaic panels. It is therefore reasonable to look for applications for photovoltaic generated electricity where the load is closely matched to the available solar energy. If there are applications where the match is direct, it may be possible to eliminate the cost of battery storage systems and some of the more expensive control components.

Several years ago, Rutgers University conducted studies on the use of photovoltaics to power onion driers in Panama. In this application the panels provided electricity to power a small DC fan blowing air through a bed of onions being cured. The air was drawn through a plenum behind the photovoltaic cells and was heated by some of the energy absorbed by the panel. As it is necessary to circulate some air through the onions continuously this application also required a battery storage unit and sizing for 24 hour operation of the fan.

For greenhouse cooling it is important to note that the total energy entering the greenhouse is directly proportional to the solar intensity outside and that only a small percentage is extracted by photosynthesis. Therefore, most of the incoming energy must leave the greenhouse by conduction through the structure and by ventilation. As there is no significant conductive loss in hot weather there is a one to one match between the volume of air that must be circulated in order to maintain a constant temperature difference across the greenhouse and the incoming solar radiation. This important fact leads directly to the hypothesis that it should be possible to design a solar powered fan system where airflow would match requirements without any battery storage or sophisticated controls.

The power output of photovoltaic panels is essentially directly proportional to the intensity of incoming radiation on the panel surface. The voltage current relationship of this power does depend on the number of panels hooked in series, which determines open circuit voltage and the impedance of the attached load, as well as the panel area. The current drawn by a DC motor depends on the applied voltage, the type of winding of the motor, and the torque/speed characteristics of the load. The torque/speed characteristics of a fan depend upon the volume of air being moved by the fan and the pressure rise across the fan as well as the detailed design of the fan blades. It should therefore be possible to match a fan to a motor to a photovoltaic array such that as solar intensity increases the power and speed of the motor will match the fan characteristic to produce a proportional increase in air volume.

This concept needs to be demonstrated on a practical scale, and once this has been done optimizing the design of a greenhouse cooling system for any hot climate can be completed. It is expected that important elements of such a system will include a movable shade system to reduce peak cooling requirements which will also reduce the installed motor power and photovoltaic array area required. Evaporative cooling will be important in meeting the environmental requirements of some crops in some areas but it is important to recognize that evaporative cooling systems are very dependant upon acceptable water quality. Fog systems are most demanding in this regard, misting systems can be significantly affected in their performance by water quality, especially if mist settles on plant foliage. Evaporative pad systems can be designed to operate effectively as long a there is adequate water quantity to provide sufficient excess circulation of water to avoid build up of salt concentrations. It has been demonstrated that seawater can be used in greenhouse applications. It is absolutely essential to design evaporative cooling systems for the quality of water available. As the salts concentration of the cooling water increases, the recirculation rate of the water must be reduced and more excess water provided. For very saline cooling water no recirculation should be allowed and the evaporating water should make only one pass across the evaporative pads. The details of the pad design are also very important, particularly when water quality is poor.

Greenhouses have long been important in the production of very high value plant materials in northern and to some extent temperate climates. In recent years the importance of controlled environment agriculture has been on the increase throughout the world and significantly in warmer climates. There has been some increasing research activity on improving climate control regarding cooling, but greenhouse engineers still have vastly more experience in providing heat when it is too cold than coolness when it is too hot. Nevertheless, progress is being made and interestingly enough some of the progress, such as movable shading systems, has come as a direct result of trying to improve the efficiency and effectiveness of heating systems. The future of controlled environment agriculture is bright in all areas of the world. The ability to produce high value high quality plant material opens up many significant economic opportunities. Also, in controlled environment agriculture there is a potential, which is just beginning to be realized, to improve production with a substantial reduction of negative environmental side effects such as pollution by pesticides and nutrients and more efficient use of high quality irrigation water where this resource is scarce. With such a bright future it is incumbent upon researchers to continue to extend our understanding of the components of the integrated system so that we can give the greenhouse manager more versatile and effective management tools.