Phase Change Materials for Solar Heating of Greenhouses

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INTRODUCTION

Greenhouse heating frequently represents an important cost in nursery operations. Many greenhouses currently in use are of a European design and do not perform well under Australian conditions, particularly in terms of their energy requirements and ventilation performance Currently, methods of extracting and storing heat generated in the greenhouse itself, for later use for greenhouse heating, are being investigated. This is the basis of solar greenhouse technology

Recent research has led to the development of accurate methods of determining the rate of heat accumulation in greenhouses exposed to solar radiation (Garzoli, 1984). Air inside the greenhouse is heated by convective transfer from the floor, plants and other surfaces that absorb solar radiation. In conventional greenhouses, excess heat generated during the day is vented to waste; that is, once the greenhouse air is heated to above its required setpoint temperature, ventilators are opened to exhaust hot air and replace this with cooler outside air. In solar greenhouses, on the other hand, the hot air exhausted from the greenhouse is passed through a thermal storage medium where heat is transferred from the air to the thermal store, the cool air being returned to the greenhouse, forming a closed cycle In some cases a solar air heater is also incorporated into the system to augment the amount of heat delivered to the thermal store and to provide the air at a higher temperature, thus improving the rate of heat transfer between the air stream and the thermal store.

THERMAL STORAGE SYSTEMS

To date the energy storage systems for such solar greenhouses have consisted of pebbles or crushed rock. Such materials have the advantages of chemical inertness, reasonable heat capacity, high surface area to volume ratio that results in high rates of heat transfer at all air speeds, ready availability and generally low cost (depending on the transport cost). However there are a number of disadvantages that have proved to be a serious deterrent to the large-scale adoption of solar greenhouse technology. Recent research on phase change materials (PCM) (Brandstetter and Kneff, 1987) at the Australian National University has demonstrated their suitability for thermal energy storage systems for greenhouses. PCM offers considerable advantage over crushed rock, particularly its greatly reduced storage volume requirement.

PCM PROPERTIES AND ENCAPSULATION CRITERIA

The reason for the greatly reduced size requirements for PCM compared with crushed rock is its superior thermal capacity: it has a specific heat of 2 kJ/kg°C compared with 0.88 kJ/kg°C for basalt rock, but of far greater significance is its heat of fusion, which is about 190 kJ/kg for $CaCl_2 \cdot 6H_2O$ (calcium chloride hexahychate), with a phase change temperature of about 29.5°C. If the PCM is modified to provide phase change temperatures down to about 23°C, the heat of fusion is somewhat lower. The desirability of PCMs with a range of phase change temperatures from about 23°C to 29°C may be indicated as follows:

1) Suppose that the greenhouse operates without a separate solar air heater, i.e. sufficient heat is generated in the greenhouse alone to supply the nighttime requirement. In order to melt the PCM it would be necessary for the maximum greenhouse air temperature, at the top of the greenhouse, to be about 4 or 5°C higher than the phase change temperature. For example, a greenhouse operating at a daytime setpoint temperature of 26°C at plant level would be expected to deliver air at about 29°C at the ridge. *Thus the melting temperature of the PCM would need* to be about 24°C.

2) For a greenhouse with a solar air heater, it could be expected that air would be delivered to the thermal store at a temperature well in excess of 30°C. Thus it would be possible to use 29 5°C PCM, thereby taking advantage of the highest possible heat of fusion However, the air emerging from the thermal store would normally be too hot to return to the greenhouse. The preferred method of dealing with this situation is to use modules of PCM with different melt temperatures so that the air would cool on passing from the module with the highest melt temperature to that with the lowest, thereby emerging from the thermal store at a temperature suitable for return to the greenhouse.

3) When the direction of air flow is reversed for greenhouse heating at night the air is in contact with the hottest PCM module last, i.e. immediately prior to its re-emergence into the greenhouse, thereby maximising the efficiency of the greenhouse heating process and minimising the fan power requirement.

DESIGN OF PCM MODULES

In designing a PCM encapsulation system, the important considerations are:

1) Adequate energy storage capacity of the PCM.
2) Direction of the air flow relative to the PCM modules.
3) Sufficient surface area of the PCM modules to effect the necessary heat transfer between the air stream and the PCM.
4) Proper configuration and arrangement of the PCM modules so that resistance to air flow (and therefore fan power requirements) is minimised.

The design of the PCM encapsulation system takes account of a number of factors, including cost (of both the encapsulation material itself and the manufacturing process), chemical inertness, water vapour impenetrability, correct heat transfer characteristics, adequate strength, rigidity and robustness, and portability. The size and capacity of the system depends on the amount of energy that is required for greenhouse heating, the contribution from the greenhouse and solar air heater (if used), and the cost and availability of supplementary heat energy (i.e. gas, oil and electricity)

In the absence of solar radiation, the heating requirements of a greenhouse Q (in watts) is given by

$$Q = U'A_c(T_{ai} - T_{ao})$$

where U' is the heat loss coefficient, A_c is the cover area of the greenhouse, and T_{ai} and T_{ao} are the inside and outside temperatures respectively. The value of U' is generally taken as 9 for single glass or polyethylene, and 6 for double-skin houses.

These values can be reduced by about 35% if a good quality thermal screen is used. The rate at which heat can be removed from a greenhouse during the day, E (also in watts) is given by

$$E = \frac{A_{gi}[1 - (F_1 + F_2)]G_o\tau\alpha}{1 - (1 - \alpha)\rho_d} -- (U'A_c(T_{ai} - T_{ao})$$

where A_{gi} is the floor area of the greenhouse; F_1 and $_2$ are factors that take account of absorbed radiation that is used in photosynthesis and stored in the floor, respectively; G_o is the solar radiation intensity on a horizontal surface; τ is the average transmittance of the greenhouse to solar radiation; α is the average absorptance of the internal surfaces to solar radiation; and ρ_d is the reflectance of the cover to diffuse radiation that has already been reflected from inside the greenhouse. The value of τ is normally assured to be 0.7 for a single-skin greenhouse and 0.6 for a double-skin greenhouse; the value of α is normally taken as 0.84; and ρ_d is 0.16 for a single-skin greenhouse and 0.25 for a double-skin greenhouse. From this analysis it is possible to calculate the collection efficiency of such a solar greenhouse, i.e., the amount of useful energy that can be extracted as a percentage of the incoming solar energy. Table 1 shows calculated collector efficiencies for a range of conditions likely to be encountered in parts of Australia.

Table 1. Calculated greenhouse collector efficiencies

Ambient air temperature (°C)	Solar radiation (W/m²)	Greenhouse collector efficiency (%) Greenhouse temperature 22°C Single glazing	22°C Double glazing	27°C Single glazing	27°C Double glazing
0	100	0	0	0	0
	250	0	1.6	0	0
	300	0	9.3	0	3.9
5	250	0	14.6	0	4.9
	300	0	20.2	0	12.0
	450	0	29.4	0	23.9
10	300	0	25.3	0	18.0
	450	4.9	32.8	0	27.9
	600	17.4	36.5	1.8	32.9
15	450	24.6	37.9	4.9	31.8
	600	32.2	40.3	17.4	35.8
	750	36.7	41.8	24.9	38.2

Where the calculated collector efficiency is zero, the rate of heat lost from the greenhouse is greater than the heat gained by the absorption of solar radiation The greenhouse is then not able to maintain the set point daytime temperature and no excess energy is available.

Mathematical expressions that describe the absorption of solar radiation in greenhouses are similar to those used for flat plate solar collectors. The amount of useful absorbed energy in a greenhouse is lower, however because.

1) The solar transmittance of the cover is lower.
2) The solar absorptance of the interior of a greenhouse (plants, floor and structure) is lower than that of a matt black or selective surface.
3) A significant proportion of the absorbed radiation is used directly by plants in photosynthesis or stored in the floor.
4) A greenhouse cannot be tilted to maximize the interception of beam radiation. Similarly, rates of heat loss are greater in greenhouses because the cover area is large compared with the floor area and because some ventilation loss is inevitable. Further differences in performance occur in a greenhouse because extraction of heat is possible only under conditions that satisfy the requirements of plants and because transpiration of the foliage results in increases in both latent and sensible heat. Although greenhouses have relatively low collection efficiencies and can deliver useful heat over a more restricted range of climatic conditions, they nevertheless have the capacity to generate significant amounts of heat because of their large areas.

Once the amount of energy to be stored has been ascertained, the quantity of PCM required can be calculated from its known energy storage capacity. The next aspect to be addressed is the design of the PCM storage system in modular form. The requirements of strength, rigidity, robustness and water vapour impenetrability are met by using high density polyethylene with a wall thickness of at least 2 mm. Tubular channels through the module allow for the passage of air and provide the surface area for the transfer of heat between the air stream and the PCM module.

Most processes that involve heat transfer between an air stream and a heat-absorbing surface require that either (a) the rate of heat transfer is maximized or (b) that a certain temperature is to be achieved at the end of the heat transfer process In each case, the criteria are satisfied by choosing a particular air flow rate In solar greenhouses, on the other hand, this is not the case. The air speed may be just above zero, for example, on a sunny morning when the greenhouse has just reached its daytime setpoint temperature and a very small amount of excess energy is available for storage On the other hand, air speed may be that corresponding to full fan speed in the early afternoon when solar radiation intensity is at its maximum and the rate of heat loss from the greenhouse is at its minimum because of the relatively high outside temperature Any air speed in between these two limits is also possible, in all cases depending on the required conditions in the greenhouse and the outside climate. PCM modules must therefore be designed to perform adequately under all conditions For a given air flow rate, maximum heat transfer occurs with long flow paths and small diameter air channels. Such conditions also result in a high fan power requirement. PCM modular design requires that these competing requirements should be adequately addressed. Provided that the air flow is always turbulent, the following relationship between the Nusselt (*Nu*), Reynolds (*Re*) and Prandtl (*Pr*) numbers has been shown to apply.

$$Nu = 0.023\,Re^{0.8}Pr^{0.4}$$

Considering each of these numbers in turn for this application.

(1) Nusselt number, $Nu = \frac{hD_e}{k_a}$ where h is the heat transfer coefficient; D_e is the equivalent diameter of each air flow channel = 4 × cross sectional area of channel/perimeter of channel; and k_a is the thermal conductivity of air.

(2) Reynolds Number, $Re = \frac{vpD_e}{\mu}$ where v is the velocity of the air; p is the density of air, and is the viscosity of air.

(3) Prandtl Number, $Pr = \frac{\mu C_p}{k_a}$ where C_p is the specific heat of air.

Thus, from the known properties of air, its velocity and the dimensions of the module the heat transfer coefficient h can be calculated and thence the rate of heat transfer. The accuracy of this relationship was verified in a series of wind tunnel experiments at the ANU (Dymond, 1990) Computer simulation of performance over a wide range of conditions suggests that optimum performance is achieved with air flow channels of about 20 mm diameter and an air mass flow rate per unit area of about 5 kgs per sec per m^2. Modules can be stacked end-to-end, side-by-side, or one on top of the other to give best performance in a given situation.

CONCLUSIONS

Significant energy savings are possible when excess energy generated in the greenhouse is stored for later use in greenhouse heating. PCM encapsulation systems in modular form represent a convenient and efficient form of thermal storage.

LITERATURE CITED

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