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Evaluation of an Energy Storage Module as the Primary Heat Source for Greenhouse Production of Bedding Plants

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Summary. A phase change material (PCM) energy storage unit operating in a greenhouse from 29 Oct. through 21 Dec. 1992 cooled it on the average 1.7°C in the day and warmed it 2.2°C at night due to both sensible and latent heat absorbed, released, and circulated. *Tagetes patula* 'Mighty Marietta' and 'Early Queen Sophia' marigolds and *Viola × Wittrockiana* 'Yellow Blotch' and 'Blue Blotch' pansies were grown in a PCM and a control (no PCM) greenhouse. Temperatures went below 0°C 10 days in the control greenhouse and 4 days in the PCM greenhouse. The lowest temperature of -7.8°C killed the marigolds in the control greenhouse. Neither marigolds nor pansies were killed in the PCM greenhouse, which attained a low temperature of -3.3°C. On 4 Dec., plants were destructively harvested. Morphologically the marigolds were taller, and had more leaf area and dry matter when grown in the PCM greenhouse as compared to the control, but pansies were taller, and had more leaf area and dry matter when grown in the control greenhouse, as compared to the PCM greenhouse.

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Heating and cooling greenhouses is usually accomplished by heat from fossil fuels and cooling using exhaust fans. Other heating and cooling techniques are the use of rock storage (Willits and Peet, 1987) or a phase change material (PCM) energy storage device. PCMs have been reported to absorb solar heat in the daytime hours and release the heat energy during cool nighttime hours (Ting et al., 1990). The purposes of this study were: a) to evaluate the effectiveness of a redesigned PCM system to improve its performance to heat and cool a greenhouse, and b) to compare growth and development of marigold and pansy in a greenhouse with a PCM system vs. an unheated unvented greenhouse.

A PCM energy storage unit constructed by the Westech Co. (New Brunswick, N.J.) was installed in a 8.5 × 14.6-m plastic greenhouse in East Brunswick, N.J., and evaluated from 29 Oct. through 21 Dec. 1992 as a source of daytime cooling and nighttime heating for the production of bedding plants. A second plastic greenhouse of the same size adjacent to the PCM greenhouse was used as the control. Both greenhouses were covered by air-inflated double polyethylene (colorless 6-mil Nutrigro by Visqueen plastic). Neither greenhouse received supplemental heat or venting during the entire study, and the only difference between them was that one had the PCM unit in operation. The phase change material was Glauber's salt ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$), sodium carbonate decahydrate ($\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$)—nucleating and stabilizing agents. The mixture had a design phase change temperature of 16°C to enable the PCM to collect and store solar energy during daytime hours and to release this heat energy to the greenhouse during nighttime hours. Previous studies (Giacomelli et al., 1990; Wu, 1991) have evaluated plant growth in PCM-heated and -cooled greenhouses. The performance of this unit was evaluated for its effect on greenhouse temperature and its capability in storing and releasing thermal energy. The PCM unit contained 660 kg of phase change material packaged in 44 tube-sheets in a design similar to the unit described by Ting et al. (1990). A 250-W fan (Dayton Venture) ($0.25 \text{ kWh} \cdot \text{h}^{-1}$) was installed and operated continuously to provide an airflow of $1.274 \text{ m}^3 \cdot \text{s}^{-1}$ through the

unit. The operation of the fan motor increased air temperature in the PCM greenhouse by $\approx 0.2^{\circ}\text{C}$. Air served as the energy-carrying medium both during the charging process and the discharging process. When the temperature difference between the air at the inlet and outlet of the unit was positive, the PCM was being charged, and vice versa. A clear plastic tube was installed at roof level in the greenhouse to improve heated air movement into the PCM unit.

Air temperatures outside and inside the greenhouses were recorded electronically using shielded copper-constantan thermocouples attached to a datalogger (Campbell 21X) and shielded temperature sensors of a greenhouse environmental control system (Q-COM, Gem II). Photosynthetically active radiation (PAR) was measured by a LI-COR 100 with LI-190SB quantum sensors at plant canopy level and was also transmitted to the Q-COM Gem II system. A pyranometer sensitive to 300–1100 nm measured solar radiation in the PCM greenhouse. The concentration of CO_2 measured by the Q-COM system never went below 350 ppm. Carbon dioxide was not a factor in the unvented greenhouses because of very small plant populations in large greenhouses and air leakage from door openings and other loose plastic seals on the greenhouses.

The bedding plants grown in the two greenhouses were marigold cultivars Mighty Marietta and Early Queen Sophia and pansy cultivars Yellow Blotch and Blue Blotch. These cultivars were selected because it was determined from previous studies (Merritt, unpublished data) that they will survive at temperatures below 0°C .

Sufficient seeds of each cultivar were germinated to permit a crop population large enough to select four visually similar matched crops of five plants each (one plant per pot). Two replicate crops of each cultivar were placed pot to pot in the same locations in each of the two greenhouses and surrounded by one border row of pots to minimize edge effects. Marigolds were seeded 15 Oct., germinated in 3 days, and, on 29 Oct., were transplanted into 4-inch (10.2-cm) square pots and placed into treatment. Pansies were seeded 25 Aug., germinated 2 Sept., transplanted into 4-inch pots 16 Sept., and grown in a cool greenhouse until 29 Oct.,

when they were matched and placed into treatment. Marigolds were small seedlings with a height of 3 cm, four true leaves, and a leaf area of 2 cm^2 . Pansies were large, well-established plants; 5 cm in height with 100 to 140 cm^2 of leaf area, seven to 15 main leaves, four and five lateral branches, no flowers, but 80% had visible flower buds. A LI-COR 3100 was used to measure leaf area. Growth data were analyzed by an analysis of variance.

The greenhouse light and temperature environment. As shown in Table 1, light quantity was slightly lower in the PCM greenhouse due to shading by overhead heat-trapping plastic tubes. Temperatures in the PCM greenhouse were on the average 2.2°C warmer at night and 1.7°C cooler in the day due to both sensible and latent heat absorbed, released, and circulated by the PCM system.

A comparison of temperatures measured within the PCM and control greenhouses plus solar radiation avail-

able to the greenhouses over a 2-week period are described in Fig. 1. The measurement of total solar radiation was taken within the PCM greenhouse at a location $\approx 30\text{ cm}$ underneath the roof. When it was cloudy in the daytime, the PCM greenhouse temperature was higher than that in the control greenhouse. The reason was that the solar gain in both houses was low during cloudy days and, instead of removing energy from the PCM greenhouse, the PCM unit tended to release energy into the greenhouse (Fig. 1, 10–12 Dec.). The temperature difference between the two greenhouses is plotted against time along with the outside ambient temperature profile in Fig. 2. When the solid line is on the positive side, the PCM greenhouse is warmer than the control greenhouse, and vice versa. The ambient temperature curve provides a view of the ambient thermal environment surrounding the two test greenhouses. Under the conditions tested, the PCM unit dis-

Table 1. Mean daily light and temperature values in an unheated unvented greenhouse (control) and one heated and cooled by a phase change material (PCM) energy storage unit but unvented for the period 29 Oct.–21 Dec. 1992.

Greenhouse	Integrated PAR ($\text{mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)	Temperatures ($^{\circ}\text{C}$)						
		Min	Max	Mean	24-h distribution in four temperature ranges (h)			
					<8.3	8.3–17.8	17.8–29.4	>29.4
PCM	8.3	4.4	29.4	12.8	8.8	10	3.5	1.7
Control	8.8	2.2	31.1	11.1	10.6	8.6	3	1.8

Fig. 1. Temperatures and solar radiation in an unheated unvented greenhouse (control) or one heated and cooled by a phase change material (PCM) energy storage unit, but unvented for the period 6 to 19 Dec. 1992.

Fig. 2. Ambient temperatures and temperature differences between an unheated unvented greenhouse (control) and one heated and cooled by a phase change material (PCM) energy storage unit, but unvented for the period 6 to 18 Dec. 1992.

played a greater capability in heating than cooling the greenhouse. This could be due to several reasons, such as the ambient climatic pattern or the energy input by the fan (6 kWh/day). Over the 336-h study period (Fig. 2), there were 13.5 h when the PCM greenhouse temperature went below freezing, compared to 43.8 h for the control greenhouse.

The diurnal variation of temperature in the PCM greenhouse indicates a rise in the air temperature during the

charging process and a drop during the discharging process (Fig. 3). When the PCM material undergoes the phase change process, a rising or dropping trend will be interrupted by a "horizontal" segment. No horizontal line is shown during the period tested (Fig. 3). However, the curve showing the temperature change of the air when passing through the PCM unit reconfirms a temperature change in the PCM. Furthermore, it also allows for the calculation of energy transfer rate be-

Fig. 3. PCM temperature and temperature difference between inlet air and outlet air of PCM unit over a 96-h period.

tween the air and the PCM.

The transfer rate of thermal energy between the circulating air and the PCM is plotted in Fig. 4. The curve indicates that cumulative energy is the time integral of the energy transfer rate. The energy transfer rate is influenced by many factors, including air-flow rate, method of PCM packaging, physical/chemical state of the PCM, and temperature difference between air and PCM. As shown in Fig. 4, the PCM unit was found to be capable of storing up to 47 MJ of energy (or $71.31 \text{ kJ} \cdot \text{kg}^{-1}$ of PCM), mainly in the form of sensible heat.

In a previous study (Ting et al., 1990), a similar PCM thermal storage unit was tested through complete charging-discharging cycles. That unit displayed distinct latent heat-storing and -releasing processes. This study was designed to investigate the effects of PCM energy storage unit on the greenhouse environment by side-by-side comparison of two greenhouses: one with and one without a PCM unit. The PCM unit used in this study often did not display the desirable phase change characteristics because of the high 16°C phase change temperature of the mixture (Fig. 3).

Periods below freezing and plant response. Temperatures in the control greenhouse went as low as -3.3°C during the period 29 Oct.–4 Dec. On 9 Nov., it was below 0°C for 5 h. The marigolds wilted, but recovered fully with no plant loss. The PCM greenhouse temperature did not go below 0°C on 9 Nov. On both 15 and 16 Nov., the same low temperatures occurred in the control greenhouse as on 9 Nov., but no plant wilting or damage was noted on any plants. Again, no temperatures below 0°C occurred in the PCM greenhouse. Plants were harvested destructively on 4 Dec. to complete the morphological phase of the study, but we continued operating the greenhouses until 21 Dec. to evaluate more fully the PCM unit and left the border row plants of marigold and pansy in the greenhouses. On 7, 8, 9, 10, 15, 19, and 21 Dec., temperatures in the control greenhouse went down to -1.1 , -3.3 , -7.8 , -5.6 , -3.3 , -1.1 , and -5.6°C , respectively. There were about four times more hours of freezing temperatures in the control greenhouse than in the PCM greenhouse. The -7.8°C temperature killed the marigolds, but not the pansies.

Fig. 4. Energy transfer and cumulative energy of PCM over a 96-h period (07:00:00, 6 Dec 1992).

Fig. 4. Energy transfer and cumulative energy of PCM over a 96-h period.

Morphological responses

Marigold (Table 2). Marigolds were taller and had more leaf area and dry weight when grown in the PCM greenhouse. This was probably due to the PCM greenhouse being warmer than the control greenhouse. Another possibility is that the lower night temperatures and below freezing on 4, 15, and 16 Nov. in the control greenhouse affected plant growth adversely, even though no visible plant injury was noted (e.g., chlorosis or necrosis).

Pansy (Table 3). Growth responses of pansy to the greenhouse environment were the reverse of the marigold response in that plants grown in the colder control greenhouse were significantly taller, heavier, and had more leaf area than those grown in the PCM greenhouse. The increased growth response of pansy to lower temperatures may be the result of lower maintenance respiration costs in the colder greenhouse.

Table 2. Morphological response of two marigold cultivars to two greenhouse environments: a) an unheated unvented greenhouse (control), or b) one heated and cooled by a phase change material (PCM) energy storage unit, but unvented for the period 29 Oct to 4 Dec 1992. Data expressed are means of plants destructively harvested 4 Dec. 1992.

Cultivar	Plants (no.)	Greenhouse	Ht (cm)	Main	Lateral	Flowers (no.)	Bud (no.)	Leaf area (cm ²)		Total top dry matter (mg)
				leaves (no.)	shoots (no.)			Main	Total	
Mighty Marietta	10	PCM	10.4	6	5	0	1.2	49	101	450
										*
	10	Control	9.5	6	5	0	1	45	84	410
Early Queen Sophia	10	PCM	8.6	8	4	0	0.1	74	89	400
	10	Control	8.4	8	5	0	0.3	74	86	400
Mighty Marietta	20	---	9.9	6	5	0	1.1	47	92	430
				****			****			
Early Queen Sophia	20	---	8.5	8	5	0	0.2	74	88	400
Both cultivars	20	PCM	9.5	7	5	0	0.7	61	95	425
				****						*
Both cultivars	20	Control	8.9	7	5	0	0.7	60	85	405

*, **, ***, **** Significant difference at the 5%, 1%, 0.1%, or 0.01% levels, respectively, as determined by an analysis of variance F-test.

Table 3. Morphological response of two pansy cultivars to two greenhouse environments: a) an unheated unvented greenhouse (control), or b) one heated and cooled by a phase change material (PCM) energy storage unit, but unvented for the period 29 Oct to 4 Dec 1992. Data expressed are means of plants destructively harvested 4 Dec. 1992.

Cultivar	Plants (no.)	Greenhouse	Ht (cm)	Main	Lateral	Flowers (no.)	Bud (no.)	Leaf area (cm ²)		Total top dry matter (mg)
				leaves (no.)	shoots (no.)			Main	Total	
Yellow Blotch	10	PCM	15	15	6	3.5	2.6	223	478	2.7
					**					
	10	Control	16	13	6	2.8	3.6	240	510	2.9
Blue Blotch	10	PCM	13	13	6	3.3	1.7	169	389	2.0
				**						
	10	Control	17	14	7	2.4	2.6	186	471	2.4
Yellow Blotch	20	---	16	14	6	3.2	3.1	230	494	2.8
				*				***		*
Blue Blotch	20	---	15	14	6	2.9	2.2	177	430	2.2
Both cultivars	20	PCM	14	14	6	3.4	2.1	196	433	2.3
				****						*
Both cultivars	20	Control	16	14	6	2.6	3.1	213	491	2.7

*, **, ***, **** Significant difference at the 5%, 1%, 0.1%, or 0.01% levels, respectively, as determined by an analysis of variance F-test.

A PCM unit can cool and heat greenhouses and other plant growing structures if sufficient solar energy is available, backup heating and ventilation systems are in place, and the plant species are capable of being grown under the temperature conditions described in this study. Cost of the PCM is another factor. This unit, if commercially constructed, would cost about \$2000 for a 124-m³ greenhouse. The economics of using a PCM unit has not been determined.

This study demonstrates that a PCM system can reduce air temperatures during high solar energy periods

and can raise air temperatures during the night period to create an acceptable growing environment for bedding plants. A modified PCM system could also be used to produce other horticultural crops (vegetables, small fruits, herbs, nursery, and floricultural) in geographic areas with low ambient air temperatures and sunny fall–winter–spring seasons found in many regions in the northern hemisphere.

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