CONSIDERATIONS FOR PASSIVELY COOLING A POLYETHYLENE-COVERED RAINSHELTER IN HAWAII

B.A. Kratky
University of Hawaii, 461 W. Lanikaula St.
Hilo, HI 96720

Abstract: Rainshelters consist of steel or wooden framed structures covered with polyethylene on the top and screen on the sides and ends. Vegetable, flower and foliage crops are grown in these structures. A reasonable goal is to maintain bench level temperatures within 10°F of ambient temperature without utilizing fans in the rainshelters. Incoming radiation may be determined by measuring temperature rise of colored water in an insulated beaker. Solar radiation may be reduced by shading the roof or by utilizing white-colored surfaces to increase reflectivity. Evapotranspiration absorbs much solar energy and is affected by type and stage of crop, growing method and irrigation program. Misting promotes additional evaporation. Replacing the warmed air in the rainshelter with cooler, ambient air-cools the rainshelter. Proper location of the rainshelter and removal of obstructions to air movement promote air movement. Replacing upper, warmer air in the rainshelter with ambient air provides more efficient cooling than bench level air so taller buildings and upper vents are recommended.

Keywords: Air movement, cooling, evapotranspiration, greenhouse, irrigation, rainshelter, reflectivity, solar radiation

Introduction

Rainshelters consist of steel or wooden framed structures covered with polyethylene on the top and screen on the sides and ends. Vegetable, flower and foliage crops are grown in these structures by various cultural methods including soil beds, container culture and hydroponic methods.

Short wave visible solar radiation passes through the polyethylene roof. Most is absorbed by inside surfaces and emitted as long wave radiation, which does not pass through the polyethylene roof. Much of this captured energy becomes evident as heat. The maximum heat buildup in these structures typically occurs on a sunny day from noon to 2 PM. Rainshelters are commonly cooled by fans, but the electrical power plus mechanical equipment increase production costs. Ambient high air temperatures on the Island of Hawaii are usually in the 80s and rarely exceed 90°F. A reasonable goal is to maintain bench level temperature in the rainshelter within 10°F of ambient temperature without utilizing fans. This paper discusses strategies and considerations for passively cooling rainshelters.

Incoming Radiation. It is first necessary to determine the amount of incoming radiation or the amount of heat generated in the rainshelter during one hour. Although precise instruments exist for measuring radiation, a rather crude home-made model may be sufficient for most growers.

A 400 ml glass beaker filled with dark colored water (250 ml) was placed in a clear polyethylene bag. Liquid polyurethane intermediate expanding foam sealant was sprayed around the plastic bag such that the beaker had a layer of insulation foam on all sides except the top. One side of the plastic bag was stretched over the top of the beaker and secured. The beaker was placed on a flat surface in the rainshelter. The diameter of the beaker was 7.5 cm and its surface area was 44 cm^2. A temperature rise of 1°C in the liquid calculates to an energy gain of 5.68 cal/cm^2 (250 ml x 1°C/44 cm^2).

PROC. Nat. Agr. Plastics Congress 28 : 158-163

For example, the temperature of the liquid rose 6.5°C from 12:40PM to 1:40PM on 11/1/98 in a 6 x 29 m Quonset-type rainshelter which was recently recovered with new polyethylene. This calculated to an energy gain of 36.9 cal/cm^2/hr as compared to an energy gain of 39.8 cal/cm^2/hr in a nearby outside location. The energy received during this hour was amongst the highest of the day and was actually equal to 14.1% of the total energy for 11/1/98 (1). This proportion will vary with seasons and locations. The average of 2 radiation readings taken during this hour was 1425 umol/m^2/s in the rainshelter and 1625 umol/m^2/s outside.

The energy capture of this 6 x 29 m rainshelter for one hour was 64,206,000 cal or 254,785 BTU (1 BTU = 252 cal). This energy was used to evaporate water (evapotranspiration), heat the air and solid materials such as the plants, benches and soil.

Shading the rainshelter reduces incoming radiation, and thus decreases the need for cooling. Shading can occur from trees or even a large hill as well as coating the roof with a shading compound or covering the roof with a shade screen or reflective cover. Unfortunately, crop growth may also be reduced when the rainshelter is shaded.

A fraction of the incoming solar radiation is lost by reflectivity. For example, typical fields have a short-wave albedo of 0.20, which means they reflect 20 per cent of the energy (6). Some of the reflected radiation will be absorbed by various matters in the rainshelter and be emitted as heat. However, that proportion of incoming radiation that is truly reflected will reduce the net solar radiation captured in the rainshelter. The computation of reflective heat loss in a rainshelter is quite complex.

Since white colored objects are very reflective, an attempt should be made to have as much white color as possible in a rainshelter. A grower could increase reflectivity in a rainshelter by such practical measures as replacing black weedcloth with white-colored material on walkways, installing white mulches and top covers for hydroponic tanks and painting trellis posts and bench structural material white. As a general rule, everything in the structure should either evapotranspire or to be white-colored and reflect radiation!

Energy Absorption by Evapotranspiration. Approximately 581 cal (2.31 BTU) are required to evaporate 1 g of water from an initial temperature of 30°C (6). The relative humidity of the ambient air in Hawaii is relatively high in Hawaii as compared to arid desert locations. The evapotranspiration rate is lower in moist climates than in arid climates. Consequently, plants growing in a rainshelter located in a moist climate will cool the air less than those growing in a climate with a low humidity.

Lettuce was grown by a non-circulating hydroponic method at a plant density of 19 plants/m^2 and 60% of a rainshelter was utilized for the crop. Water consumption was 72 liters/crop/m^2 of bench space or 14.4 liters/m^2 /wk or 2.06 liters/m^2/day. Because the hottest hour of the day represented 14% of the incoming radiation for Hawaii's situation, it is reasonable that 288 g/m^2 (2.06 liters x 14%) of water were evapotranspired during the warmest hour of the day which would absorb 167,328 cal/m^2 . This calculates to 16.7 cal/cm^2 of bench space/hr or 10.0 cal/cm^2 of the whole rainshelter area/hr and represented 27% of the incoming radiation on 11/1/98.

If the rainshelter floor were covered with grass, and if it evapotranspired at the same rate as lettuce, the energy required for evapotranspiration could be increased to 16.7 cal/cm^2 for the whole rainshelter/hr. Thus, live foliage in the walkways provides some cooling of the rainshelter. Yes, even weeds growing on the rainshelter floor will help to cool the structure!

Water use and energy consumption data are shown for 2-cluster non-circulating hydroponic tomatoes (Table 1) and for tomatoes grown in a soil bed (Table 2.) A small portion of the water from the soil bed crop in Table 2 may have been lost from the soil bed by deep drainage. Nevertheless, more energy was dissipated when tomatoes were grown in a soil bed than when growing by a non-circulating hydroponic method. Our enthusiasm for saving water was dampened upon learning that a high water efficiency of the cropping system decreases the cooling potential in the rainshelter.

Table 1. Water use and evapotranspiration energy for 4 crops of tomatoes grown in a rainshelter[z].

Crop	Months Grown	Water Use Liters/ m^2/day	 Liters/m^2/warmest hr[a]	Energy cal/cm^2/warmest hr[b]
1	Sept-Dec	1.35	0.19	11.0
2	Dec-Mar	0.95	0.13	7.6
3	Apr-July	1.33	0.19	11.0
4	July-Oct	1.77	0.25	14.5

[a] Liters/ m^2/day x 14%

[b] Liters/m^2/warmest hr x 1000 g/liter x 581 cal/g x 0.0001 cm^2/m^2

[z] Plants were pruned such that only 2 clusters were harvested. They were grown by a non-circulating hydroponic method. The plant density was 4.03 plants/m^2 and the plants produced 0.8 to 1.4 kg tomatoes/plant in a 13 week growing period.

Table 2. Water use and evapotranspiration energy for tomatoes grown in soil beds and drip irrigated to a tension of 0.2 bar in a rainshelter[z].

Age Weeks after Transplanting	Water Use Liters/ m^2/day	 Liters/m^2/warmest hr[a]	Energy cal/cm^2/warmest hr[b]
3 to 11	1.97	0.28	16.3
11 to 15	2.42	0.34	19.8
15 to 26	2.03	0.28	16.3

[a] Liters/ m^2/day x 14%

[b] Liters/m^2/warmest hr x 1000 g/liter x 581 cal/g x 0.0001 cm^2/m^2

[z] The plant density was 2.78 plants/m^2 and the tomatoes produced 5.1 kg/plant in a 26 week growing period (2).

Cooling by Misting. It would be reasonable to cool the plants by misting with water during the hottest time of day. Misting should be terminated by mid-afternoon to allow plants to dry by evening in order to discourage bacterial and fungal diseases. Simple mist systems only require pressurized water (25 to 100 psi), PVC pipe, mist nozzles, a timer and a solenoid. Fog nozzles are more efficient, but they are more costly to set up and maintain.

How much evapotranspiration occurs from misting a rainshelter? Most models which can answer this question are very complex, but the Hargreaves Model is relatively simple because it only requires temperature and incident radiation data (7) and works well for Hawaii's outdoor conditions. It is being suggested that the Hargreaves Model will also provide a ballpark estimate of total evapotranspiration inside a rainshelter which would include plant evapotranspiration and evaporation of mist. It probably would underestimate evapotranspiration in drier climates because the model does not directly account for relative humidity. The model is:

$$ET_o = 0.0135\ (\text{temperature in } {}^\circ C + 17.78)\ Rs\ (10/595.5 - 0.55T)$$

where ET_o = potential daily evapotranspiration in mm/hr and
Rs = incident solar radiation in cal/cm^2/hr

In our previous example where the incident radiation was 37 cal/cm^2/hr and the temperature was 34°C (93 °F) the equation becomes:

$$ET_o = 0.0135\ (34^\circ C + 17.78)\ 37(10/576.8)$$
$$ET_o = 0.448 \text{ mm/hr} = 0.0448 \text{cm}^3/\text{cm}^2 = 0.0448 \text{ g/cm}^2$$
$$ET_o = 0.0448 \text{ g/cm}^2 \times 581 \text{ cal/g} = 26.0 \text{ cal/cm}^2/\text{hr}$$

This includes the crop evapotranspiration. Let us review the situation for July - Oct tomatoes (Table 1). Assume the incident radiation was 37 cal/cm^2/hr. The crop evapotranspiration was 14.5 cal/cm^2/hr, but this figure could be increased to 26 cal/cm^2/hr if the crop were misted. There remains 11 cal/cm^2/hr which will mostly accumulate as heat.

Conductive Heat Loss. The conductive heat loss in a tight greenhouse where there is a large difference between inside and ambient temperatures may account for more than 90% of the total heat loss (3). However, the proportion of conductive heat loss would be much smaller in tropical rainshelters, because rainshelters have a great deal of ventilation and the goal is to maintain a relatively small difference (10 °F) between inside and outside temperatures. Heat loss by air exchange should greatly supercede conductive heat loss in a midday tropical rainshelter situation.

Cooling the Rainshelter with Air. The rainshelter is cooled when cooler outside ambient air replaces warmer air in the rainshelter. Let us now change over to English units where 1 cal/cm^2/hour = 3.69 BTU/ft^2/hr. An equation for cooling a structure (5) is:

$$\text{cfm} = \frac{\text{BTU/hr}}{1.08\ (\text{rainshelter temp} - \text{ambient temp } \{{}^\circ F\})}$$

where cfm = cubic feet of air per minute exchanging into rainshelter

Consider a 96 x 20 ft rainshelter (1920 ft^2) and an incident solar radiation of 37 cal/cm^2/hour. How many cfm of air are needed to maintain the rainshelter temperature at 10°F above ambient temperature?

Case 1. Dec - Mar tomatoes have an evapotranspiration loss of 7.6 cal/cm^2/hour (Table 1).

$$(37 - 7.6) \text{ cal/cm}^2/\text{hour} \times 3.69 \text{ BTU/ft}^2/\text{hr} = 108.5 \text{ BTU/ft}^2/\text{hr}$$

$$\text{cfm} = \frac{108.5 \text{ BTU/ft}^2/\text{hr} \times 1920 \text{ ft}^2}{1.08 \times 10^\circ F} = 19{,}289 \text{ cfm}$$

Case 2. A crop is misted such that the energy loss for evapotranspiration is 26 cal/cm^2/hour.

$$(37 - 26)\ \text{cal/cm}^2\text{/hour} \times 3.69\ \text{BTU/ft}^2\text{/hr} = 40.6\ \text{BTU/ft}^2\text{/hr}$$

$$\text{cfm} = \frac{40.6\ \text{BTU/ft}^2\text{/hr} \times 1920\ \text{ft}^2}{1.08 \times 10\,^\circ\text{F}} = 7218\ \text{cfm}$$

Environmental control technicians frequently refer to the concept of air changes/minute. If the average height of the rainshelter is 10 ft, there are 19,200 ft^3 of space in the rainshelter. The number of air changes per minute for cases 1 and 2 are 1.00 and 0.38, respectively.

Consider that this is a quonset-shaped rainshelter which is covered by shade screen on both ends and to a 6 ft. height on the sides and the structure is placed lengthwise parallel to wind direction. If there are no obstructions in the rainshelter, and if the ends are 200 ft^2, then 1 air change/minute could be accomplished by an air movement of 1.1 mph (96 ft. long/88 ft/min/mph). If the rainshelter is half obstructed with crops, it would likely require a 2.2 mph air movement rate.

Screen hinders movement of air. For example, a 2 mph breeze was slowed to 1.2 mph by a 35% shade screen and a 10 mph wind was slowed to 1 mph by a 79% shade screen (Table 3). Fine screens that eliminate insects from rainshelters also restrict air movement, and thus, hinder the cooling process. Therefore, in a non-obstructed 20 x 96 ft quonset-shaped rainshelter where the sides and ends were covered with 35% shade screen, ambient air velocities of 1.9 and 1.0 mph would be needed for the above 2 cases, respectively, to maintain the inside rainshelter air temperatures at 10°F above ambient temperature.

Table 3. Effect of shade screen on air velocity as determined with a hand-held electrical anemometer.

No Screen	35% Shade Screen 2.5 mm openings	79% Shade screen 0.5 mm openings
	Air Velocity - mph	
1.0	0.4	0.0
2.0	1.2	0.0
4.0	3.2	0.0
10.0	8.0	1.0

When 1 cubic ft of ambient air (85 °F, 70% RH) replaces 1 cubic ft of 95°F air in the rainshelter, approximately 0.18 BTU is removed from the rainshelter. When 1 cubic ft of 100°F air is replaced by this ambient air, approximately 0.27 BTU is removed. Thus, for these conditions, 1 cfm of ambient air removes about 0.018 BTU for every 1°F difference between inside and ambient temperature.

The upper air in a 11 ft high Quonset-shaped structure is at least 3 to 5°F warmer than bench-level air at midday. Because our goal is to maintain bench level air temperatures at +10°F above ambient temperature, it is reasonable to expect that the air temperatures above the bench range from 95°F to 100°F when the ambient temperature is 85°F. Air exhausting from the peak of the building removes 50 per cent more BTU's than air exhausting at bench level. Thus, our calculations of air replacement for

Cases 1 and 2 are overestimates, because they did not account for the increasing temperature gradient with increasing building height.

Growers in warm climates are advised to increase the height of their structures, because tall structures provide a reservoir for hot air. However, tall structures are more costly to construct and maintain than short structures. Saw-tooth and top-vented rainshelters have been popular, because they effectively utilize convective cooling principles and vent out the warmest air in the structure, ie. the air at the peak. Thus, top vents are more efficient and effective in exhausting warm air than side or end vents placed at lower heights.

Growers like the ease of replacing the roof covering on quonset-shaped structures, because they can attach the plastic covering on the sides of the rainshelter from ground level. In tropical conditions like Hawaii where freezing is not a possibility, it is useful to place 4 x 6 ft screened vents at the top of the rainshelter. Three such vents in a 20 x 96 ft x 11 ft high rainshelter provide 72 ft^2 of venting area with the equivalent cooling capability of about 108 ft^2 at bench level. Top vents encourage convective cooling such that ambient air comes through the side and end screens, heats up and vents outside. In rainy climates like Hilo, it is advisable to arrange the cropping pattern such that rain falling through the vents will not harm the plants.

When designing rainshelters, attention should be given to wind direction, normal wind speeds and obstructions for wind such as trees and shrubs. Also, it is useful to limit the width of the structure (4) and ensure that there is at least 15 ft. of space between buildings. This greatly improves the cooling potential of the screened sides.

Conclusion

Rainshelters covered with polyethylene on the top and screen on the sides and ends may be passively cooled such that bench level temperatures are maintained within 10°F of ambient temperature. Increasing reflectivity by employing white-colored surfaces such as white mulches and shading the roof reduce solar radiation in the rainshelter. Evapotranspiration absorbs much solar energy and it is affected by the type and stage of crop, growing method, irrigation program, cropped proportion of the rainshelter and misting of the crop. The rainshelter is cooled when cooler outside ambient air replaces warmer air in the rainshelter. Taller buildings provide a reservoir for hot air and upper vents exhaust more heat per volume of air than lower vents. Air movement into and through the structure should not be obstructed. Fine side screens with small openings restrict air movement into the rainshelter.

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