COLORADO FLOWER GROWERS ASSOCIATION, INC.

IN COOPERATION WITH COLORADO STATE UNIVERSITY
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Temperature Observations in the CSU Bay Farm Greenhouse

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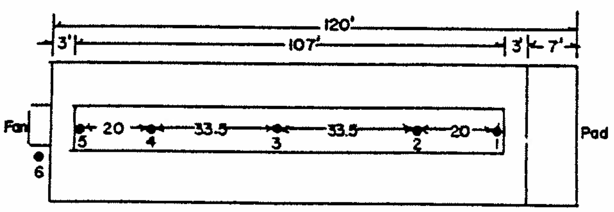
During September 1970, temperature measurements were undertaken at the 120-foot Bay Farm fiberglass-covered greenhouse to determine the inside temperature rise and the amount of cooling under high heat conditions. Figure 1 is a diagram of the house. Aspen evaporative pads are located on the outside wall, with water flowing when the wet bulb temperature is sufficiently high to avoid freezing. Under Colorado conditions, the dry bulb temperature may be as high as 50 to 55 F when wet bulb temperature is near the freezing point. Modulating dampers are located on an inside wall, programmed to operate in conjunction with the four exhaust fans. When one fan is on, moist cool air is distributed through an overhead plastic tube. As additional fans come on, the louvers step open; these are fully open when all fans are operating. Benches are approximately 107 feet long. Aspirated, shielded thermocouples were located at the ends, the middle, and 20 feet from each end (Figure 1). The outside wet and dry bulbs were unfortunately located for convenience, close to the ground, and at the exhaust end of the house. This tended to raise both wet and dry bulb temperatures above real outside values. Measurements were made every ten minutes on September 8, 9, 11, and 12, and the data subjected to a moving mean smoothing process.

Figure 2 is an example of the results. The weather was not considered "dry" for Colorado. Based on wet bulb depression, the percent relative humidity was always below 60% between 10:00 a.m. and 3:00 p.m., with occasional values below 40%. On all four days, the inside dry bulb temperature at position 1 (Figure 1) was nearly equal to the outside wet bulb temperature. The inside wet bulb temperature generally ran one to two degrees below the outside wet bulb.



Date	%	°F/10'	%	°F/10'	%	°F/10'	%	°F/10'	→ N Total
8/8	21	0.65	19	0.36	25	0.48	35	1.1	6.3°
8/9	22	1.0	23	0.63	20	0.54	35	1.6	9.1
8/11	17	0.70	25	0.60	21	0.51	37	1.5	8.1
8/12	21	0.90	20	0.54	16	0.40	43	1.9	8.9

Figure 1. Floor plan of the Bay Farm range with location of thermocouples. Figures below the diagram give the mean percent of total temperature rise between thermocouples, and the mean rise per ten feet of distance between the same positions.

These results are remarkable since they suggest 100% cooling efficiency, and that the air passing through the pad actually contained less water, i.e., a lower wet bulb temperature. This would indicate errors in the outside wet bulb temperature (Position 6, Figure 1). In spite of this, 14 to 16 degrees of cooling were often obtained during the measurement periods. The results do emphasize the fact that the higher relative humidity inside the greenhouse, 80 to 95%, resulted more from a lowering of the dry bulb temperature than from an actual increase in the quantity of water in the air. It is probable, with proper pads, that we should normally obtain cooling in excess of 20 degrees under usual Colorado conditions.

The major part of the cooling comes from evaporation of water on the pads; this process requires over 16,000 calories for every ounce of water evaporated. The real outside wet bulb temperature was probably one or more degrees below the inside wet bulb reading. The amount of water actually evaporated may be much less than generally suspected. For example, if we have a wet bulb temperature of 68 F, the evaporation of one ounce of water into 35 cubic feet of air would raise the wet bulb temperature to 98 F, a very improbable event. More likely, we may have a situation where the temperature of the incoming air is reduced by 20°. For 35 cubic feet, this requires the evaporation of roughly 0.16 ounces of water, which would effectively raise the wet bulb temperature a few degrees. The wet bulb temperature cannot exceed the dry bulb reading since this would give a ridiculous relative humidity value in excess of 100%.

There are two other means of cooling air as it passes through the evaporative pad that are usually considered insignificant. If we assume, due to pad restriction, that a suction of two inches of water is being maintained in the house, the air will expand as it passes to the interior. If we also assume that heat is neither gained nor lost in the expansion process, the temperature of a cubic foot of air will be reduced by 3.2° F. For 100 cu. ft. of air this represents a capacity of about 600 calories that can be absorbed by the air without change in temperature. A second method of cooling is heat transfer between the transient warm air and cold water in the pad. The water in the pad is probably always close to the outside wet bulb temperature. Between 90° air and 60° water, there would be a rapid flow of heat, with only 7 calories needing to be removed from each cubic foot of air to reduce its temperature by 2°. A corresponding temperature rise of less than 0.3 ounces of water would be sufficient to absorb the 7 calories. The longer the air is in contact with the water, the more heat will be exchanged. Tight, small pads are inefficient both for evaporation and heat exchange by conduction.

As would be expected, the temperature rises as the air flows from pad to exhaust fans. Figure 3 gives an example of readings obtained for positions 1, 3, 5, and 6 (Figure 1). Figure 4 plots the differences

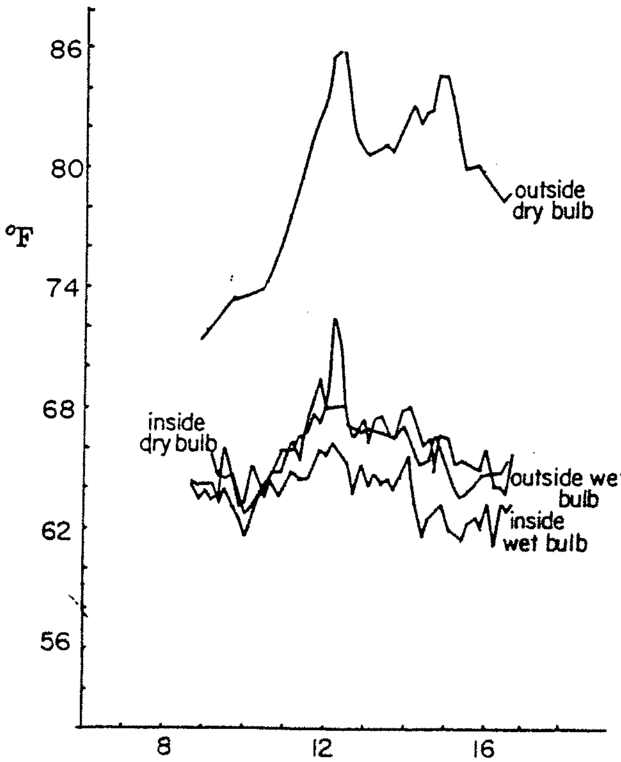


Figure 2. Inside and outside wet and dry bulb temperatures for Sept. 8.

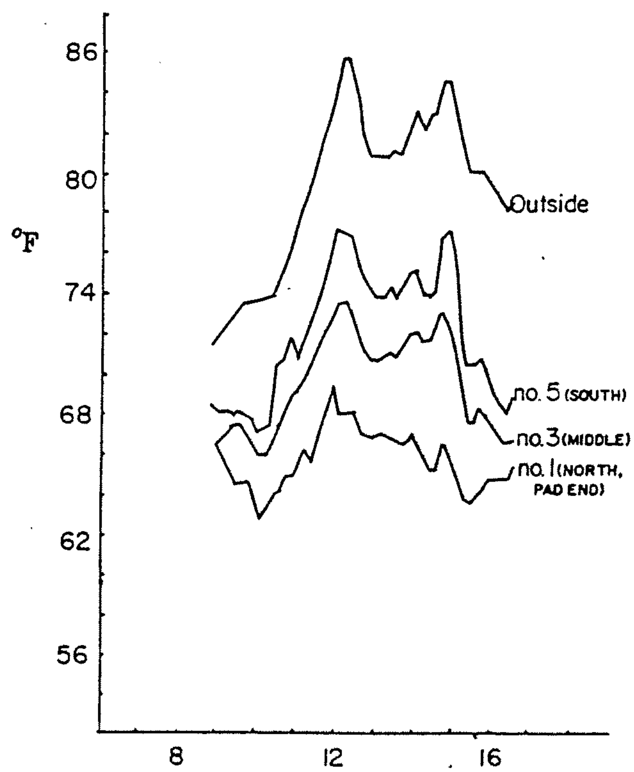


Figure 3. Inside and outside dry bulb temperatures for Sept. 8.

between positions 3 (middle) and 1, 2, 4, and 5 for September 8th and 9th. The temperature rise from one end of the bench to the other occasionally exceeded 10°. Remarkably, the variation between bench positions did not vary as much as might be expected but was relatively constant, even though radiation and air temperature outside the greenhouse were constantly increasing or decreasing. As heat load increased in the morning, additional fan operation compensated for the increased heat by moving more air. Conversely, decreasing heat load resulted in fewer fans operating.

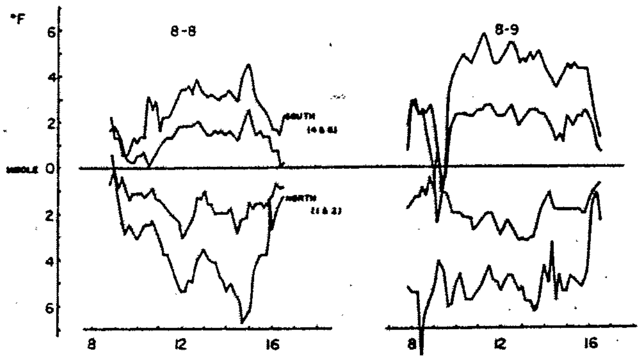


Figure 4. Differences in temperature between locations on a 107-foot greenhouse bench and the middle for Sept. 8 and 9.

Air is a relatively poor heat transfer agent. For every 1.8° change in temperature, 28 calories are released or absorbed for an ounce of water, whereas less than 8 calories may be exchanged by a similar weight of air. A portion of heat load is also utilized to evaporate water from the plants. The latter will unavoidably raise the wet bulb temperature in the house. Unless this additional water is condensed on cold surfaces in some fashion to reduce the wet bulb temperature, there will always be a significant rise in temperature from one end of the house to the other with present cooling systems. Increasing the air velocity will obviously reduce the temperature rise since it removes more heat. But, increased air velocity also brings the plant closer to the air temperature, and may tend to reduce evaporation during periods of high light. However, beyond wind speeds of 100 feet per minute, the change in plant temperature does not appear to warrant the increase in fan horsepower to move the air. Increased air movement also means a larger investment in pads, and greater danger of undercooling plants next to the pads. If the air is not close to saturation, faster movement may tend to increase water loss, thereby reducing growth due to higher stress.

The temperature rise was not uniform from one end of the bench to the other. The mean temperature rises between thermocouple positions for the four days of record are given below Figure 1. Over 1/3 of the total temperature rise occurred in the first 20 feet of the 107-foot bench. For example, on the 12th, the temperature rose 1.9° per ten feet in the first 20 feet, but only 0.58° per ten feet in the remaining 87 feet. As the air continued to move down the house, the rate of rise began to increase until, in the last 20 feet, it exceeded 0.65° /10 ft. The reason for this variation is not clear. It possibly had something to do with initial mixing and fast air velocity at the pad end, or the mixing of upper warm air near fans.