Colorado Flower Growers Association Inc.

IN COOPERATION WITH COLORADO STATE UNIVERSITY
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GREENHOUSE TEMPERATURE CONTROL WITH FORCED AIR CIRCULATION

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Heating of greenhouses has been accomplished for many years by radiation from heating pipes. Gray (5) states that one of the biggest problems with warm air heating is having adequate air distribution to insure uniform temperature. He states further that it is conceivable that someone may develop a warm air heating system for greenhouses readily adapted to a wide range of conditions. In recent years unit heat exchangers with blowers have been used successfully, especially where periphery heating pipes were installed to prevent cold spots near sides and ends of houses. A forced air system would eliminate the labor and expense of piping a greenhouse. Since cooling and ventilating of greenhouses is now mostly done by fans, any piece of equipment accomplishing the jobs of heating, air circulation, ventilating, and cooling could be of definite advantage over present methods.

A large installation of heat exchangers, centrifugal fans, and plastic ductwork was installed in the Cherry Creek Greenhouses at Parker, Colorado, in 1962, for the purpose of heating, ventilating, and some degree of cooling. At the time this installation was made, there was considerable information lacking for the design of greenhouse heating and ventilation with this equipment. This investigation was designed to supply some of the missing information in order that industrial heating tables and formulas can be adapted to greenhouses. The main objective of this study was to determine if warm air could be distributed through a plastic tube to provide an evenly controlled greenhouse temperature environment. To accomplish this objective it was necessary to find the tube diameter, size, and number of outlets required to evenly heat the test greenhouse. The amount of air to flow through the tube was partially determined by the heating load and the tube diameter.

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[1] *This is a part of the work completed by Frank E. Edlin, Jr. in partial fulfillment of the requirements for the Master of Science Degree in Horticulture at Colorado State University.*

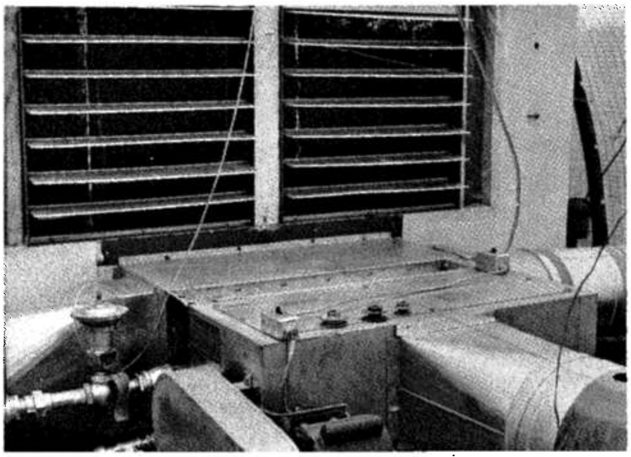

Fig. 1--Heating and ventilating unit showing automatic louver bypass.

METHODS AND MATERIALS

The polyvinyl film-covered greenhouse used in this investigation is 42' long, semicircular shaped with a 7' radius. A heating and ventilating unit with a forward curved centrifugal fan and a steam coil was used as the heating system. The unit, powered by a 1/2 hp motor, was capable of producing 175,500 BTU/hr. Low pressure steam (5-10 psi) was supplied from a boiler. The heating and ventilating unit (Fig. 1) was placed several feet from the pad end of the house and connected to the pads by a plenum. An automatic damper was built into the plenum and two automatically controlled louvers were placed above the unit to form a by-pass for cooling. Connected to this unit was a 2 mil polyethylene tube (Fig. 2) running the length of the greenhouse. The tube was supported by an internal wire and tied shut at the end away from the unit. The outlet holes in the tube were circular and 1 3/4'' in diameter. An exhaust fan was located in the far end of the greenhouse.

DUCT AIR FLOW CHARACTERISTICS

The purpose of this phase of the investigation was to determine the basic flow characteristics of air in plastic tubes which have outlet holes at regular intervals along their length. Holes were punched in 3 sizes of tubes and data taken at different fan speeds. The following tabulation shows the parts of this phase:

Tube diameters (inches)	No. holes in tube	Fan speeds (rpm)
8	36	510
12.5	53	675
18.6	71	875
	88	1075
	105	

Fig. 2--Polyethylene tube in center of the quonset-shaped experimental greenhouse.

The velocity and pressure of air was measured by a Velometer to find the following:

1. Velocity from discharge holes,
2. Velocity in the tube, and
3. Static pressure of air in the tube.

These measurements were taken at 7 locations (V) along the tube, as shown in Figure 3. The first 6 locations were spaced 6' apart and the last one was at the end of the tube furthest from the heating and ventilating unit and 4 feet from the next hole.

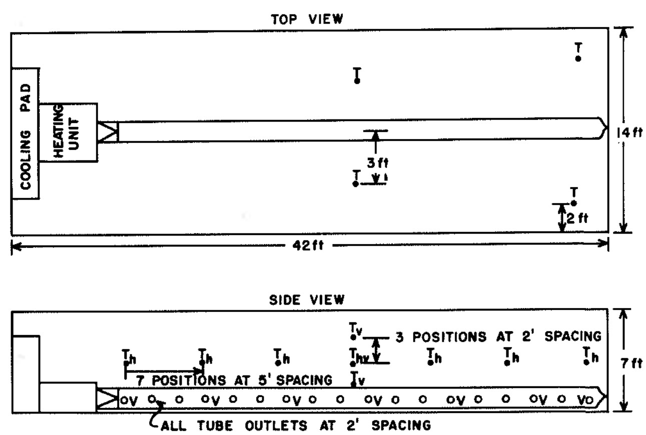

Fig. 3--Location of velocity (V) and temperature (T) measurements.

Outlet velocities vary considerably with tube diameter (Fig. 4). Velocities at the outlets were uniform throughout the length of the 18.6'' tube, and increased with distance from the fan for the 12.5'' tube. Outlet velocities of the 8'' tube dropped for the first quarter of the tube length.

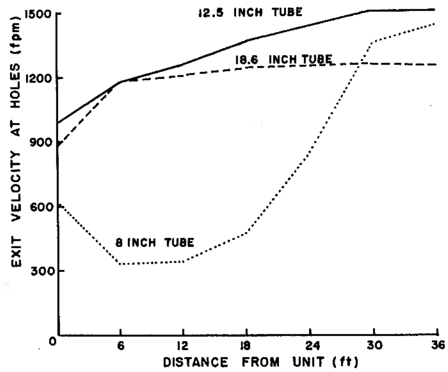

Fig. 4--Exit velocities at outlet holes of 3 tube diameters.

HEATING

This phase of the investigation was divided into 4 parts:

1. Determining variance in air temperature throughout the greenhouse,
2. Determining changes in temperature from one end of a plastic tube to the other,
3. Determining the thermal conduction coefficient for plastic tubes, and
4. Determining effect of cold air returns.

Copper-constantan thermocouples were used for temperature sensing in all of these investigations. To measure temperature differences inside a plastic tube thermocouples were placed at each end of the tube and connected to a potentiometer. All measurements taken inside the tube were done with the maximum input from the heating unit.

To find temperature variation throughout the greenhouse, 13 thermocouples were arranged in two horizontal rows (T_h) (side to side and end to end) and one vertical (T_V) row as shown in Figure 3. Two additional thermocouples were located in shelters, one outside the greenhouse and the other centrally located within. A small fan was used to draw air across the thermocouple and other instruments in the shelter within the house. All 15 thermocouples were connected to a 24-point recorder so that a complete set of readings could be taken within minutes.

The extremes of the temperature variances within the greenhouse caused by tube size, fan speed and number of outlets are shown in Table 1. The 18.6'' tube had large temperature variances and considerable differences between them. The 8'' tube varied more than the 12.5'', which gave the most uniform temperatures. Temperature differences increased for the 8'' tube with 71 holes as negative pressures started to develop.

Horizontal temperature gradients throughout the greenhouse were measured for 3 tube sizes and are shown in Figure 5. The 12.5'' tube provided the most uniform temperatures. The highest temperature readings were obtained at the unit end of the house when using the 18.6'' tube, with a gradual drop in temperature toward the terminal end. The reverse was obtained when using the 8'' tube, the higher temperature being at the terminal end.

Table 1. -- Means[1] of temperature differences in degrees F between the high and low readings of 13 thermocouples.

Tube size (inches)	No. holes	Fan speed (rpm) 510	675	875	1075
18.6	36	8.0	6.0	4.5	3.5
	53	10.8	13.0	11.3	10.0
	71	12.5	11.0	11.3	11.3
	88	8.5	10.0	9.0	8.5
	105	9.3	7.0	7.8	7.5
12.5	36	9.5	7.5	5.5	3.8
	53	6.8	8.3	7.5	6.5
	71	6.3	6.3	6.8	7.0
	88	5.3	5.8	5.8	5.3
	105	5.8	5.3	4.8	4.3
8.0	36	4.3	2.3	4.8	2.8
	53	4.8	4.0	3.0	3.5
	71	5.6	8.8	10.5	10.5

[1] Means of 4 replications.

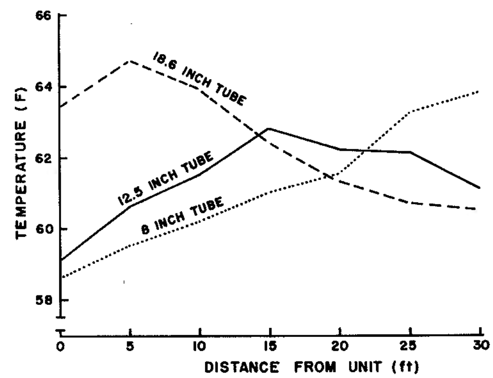

Fig. 5--Comparison of greenhouse temperature uniformity for 3 tube diameters. Measurements made by the horizontal network of thermocouples.

The differences in house temperature from unit to terminal end at 4 fan speeds and with different numbers of outlet holes are shown in Table 2. The temperature difference decreased with an increase in both number of holes and fan speed for each tube with one exception. The temperature difference found using the 8'' tube increased with the number of holes. This tube developed wrinkles from uneven expansion caused by the seam sewn on one side.

Table 2. -- Temperature difference in degrees F from the unit end of the plastic tube to the terminal end with full steam.

Tube size (inches)	No. holes	Fan speed (rpm) 510	675	875	1075
18.6	36	41.2	38.1	34.9	32.3
	53	40.8	37.8	32.2	28.0
	71	38.5	36.5	29.9	25.3
	88	37.5	36.1	29.9	24.8
	105	34.8	30.8	24.8	24.2
12.5	36	38.3	33.3	26.3	21.9
	53	41.0	34.4	23.0	18.5
	71	33.8	26.6	21.3	17.7
	88	31.0	23.2	21.1	15.3
	105	29.4	20.0	16.0	10.5
8.0	36	40.0	33.7	24.5	22.0
	53	41.5	37.5	29.1	27.3
	71	57.7	54.2	42.3	28.5

At this point in the investigation the optimum tube diameter for application to this greenhouse was reached by the process of elimination. The 18.6'' tubes were eliminated because of high temperature variations throughout the greenhouse. The 8'' tubes were not large enough for the volume of air needed to heat the greenhouse when outside temperatures were low (Figures 6, 7, and 8). The 12.5'' tube with 105 outlet holes would wear out rapidly due to flutter. The extremes of the temperature variances were erratic when different fan speeds were used with the 12.5'' tube with 36 outlets. The remaining three 12.5'' tubes with 88, 71, and 53 holes were selected for further tests.

U VALUE FOR POLYETHYLENE TUBES

Temperature differences between the inlet and outlet ends were measured at 4 velocities. By calculating the heat loss in BTU/pound of air, the weight of the air passing through the tube, and the surface area of the tube, it was possible to determine the U value with Gray's (5) formula. The temperature differences and the corresponding U values are shown in Table 3. With the exception of 875 rpm fan speed the U values increased as fan speed increased.

Table 3. -- Temperature differences in degrees F and corresponding U values found in a 2 mil polyethylene tube with no outlets.

Fan speed (rpm)	Velocities (fpm)	difference (inlet-outlet)	U value
510	900	19.0	1.2
675	1200	15.0	1.3
875	1600	10.5	1.5
1075	1900	10.0	1.4

THE USE OF TUBE RETURNS

Tube returns were installed along the outside of the house and temperatures measured with and without the returns. The use of returns did not change the uniformity of the greenhouse air temperatures as compared to operation without the cold air returns (Table 4). With the optimum number of holes (88), a change in fan speed caused no change in temperature differences. With fewer holes the higher fan speed produced more uniform temperatures. Where longer tubes are used, cold returns are probably necessary. The design of these to get minimum temperature variance remains to be worked out.

Table 4. -- Means[1] of the greenhouse temperature differences in degrees F for the heating system with and without cold air returns (12.5 inch diameter tube).

Fan speed (rpm)	No. of holes 53	71	88
		With Returns	
510	9.5	6.3	5.5
1075	4.5	6.0	5.0
		Without Returns	
510	9.0	7.3	5.8
1075	4.3	5.0	5.0

[1]Means of 4 replications.

DISCUSSION

Heating, cooling and ventilating with forced air has advantages over heating with pipe. Several investigators (1, 3, 4, 9) have found that forced warm air heating has eliminated excessive relative humidity and therefore reduces disease. Others (2, 6, 8, 10) have shown that in direct sunlight the temperature of a leaf in quiet air is much higher than when there is brisk air movement. Part of the cooling load should be relieved by keeping the leaf temperature close to that of the surrounding air. From the results of this investigation it was concluded that uniform temperature can be maintained by forced air heating, cooling and ventilating through a polyethylene tube.

The greenhouse used in this investigation would have required 4,116 cfm of air moving through it to satisfy the 7 cfm per sq. ft. figure used in cooling calculations. This amount of air was within the capacity of the exhaust fan, but it was too large a volume to be moved through the 12.5'' tube under optimum conditions. Therefore, adequate cooling through tubes was possible only as outside temperatures were not excessive. The cooling phase of this study will be published in a later bulletin.

HEATING AND VENTILATING THE DESIGN OF FORCED AIR

The first decision to be made in the installation of a forced air heating and ventilating system is the number and capacity of units. Most units are rated in BTU/hr output when moving a known volume of air. After calculating the heat loss with Gray's (5) formulas and converting this loss into warm air volumes, the velocity of air required for different tube sizes can be determined (Figures 6, 7 and 8). In this investigation a tube with a cross-sectional area equal to the outlet area of the heating unit fan was found best. This relationship will generally hold true for units with larger or smaller capacities.

Using a maximum tube velocity of 2200 fpm (7) it is possible to determine the number of tubes of a particular size needed to fill the heat requirement of a greenhouse. The number of units and the appropriate capacities can be found by reviewing the characteristics of the available units and deciding which tube size is most desirable for a particular house. The maximum amount of cooling to be obtained from a system can be determined by converting from velocity for a tube (fpm) to heat requirement BTU with Figures 6, 7, and 8, using the temperature difference for cooling in Figure 6.

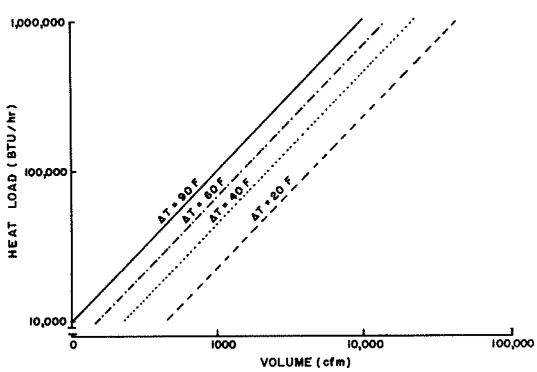

Fig. 6--Curves indicating air volumes required from the heating unit for various greenhouse heating loads.

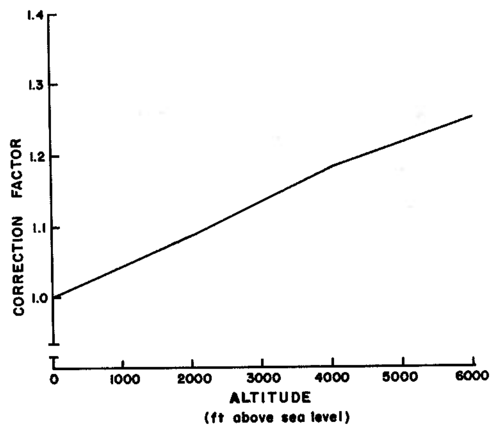

Fig. 7--Correction factors used to convert volumes from Fig. 6 to altitudes above sea level.

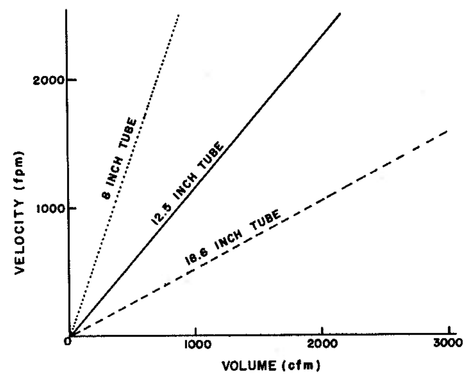

Fig. 8--Curves indicating the velocities required in 3 tube sizes for various volumes of air.

The size of the tube outlet holes was not studied in this investigation since the total area of the outlets was considered more significant. Plastic tubes developed flutter when the total area of the outlets was larger than 1.7 times the cross-sectional area of the tube. This fluttering could cause the tubes to wear out in a short time. Since uniform heating and cooling can be obtained with a constant distance between outlet holes, it would be best to start with a uniform distribution of holes, Additional outlet holes could be added to alleviate the cold spots that develop.

Since the maximum velocity is used in calculating the heat load, it would be best to use a variable speed motor. The following speeds should make a good system:

1. Low speed for minimum recirculation,
2. Medium speed for one half heat load, and
3. High speed for full heat load.

The variable speed fan would make regulation of the steam valve more accurately controllable at any heat load less than full.

Since the temperature of the area adjacent to the unit is hard to control, the unit should be placed outside the growing area of the greenhouse.

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