The successful heating of a greenhouse is dependent on two things: 1) providing a sufficient quantity of heat to maintain the greenhouse at the desired temperature; and 2) distributing this heat uniformly throughout the house. The design or selection of a heating unit of adequate capacity is a relatively simple and straightforward procedure. However, much more is involved in the design and installation of a system which uniformly distributes the heat and maintains an even temperature throughout the house.

Heated air has a high capacity for receiving and holding moisture. Thus, particular care must be exercised to prevent hot, dry air from coming in immediate contact with either the plants or the soil. If it does, high transpiration and/or evaporation will occur, resulting in problems of maintaining adequate moisture levels. On the other hand, cold spots within the house will result in uneven growth, increased problems with disease and, if severely cold, plant death due to freezing.

A satisfactory heating system for general greenhouse use and for small commercial ranges should possess a number of essential characteristics. These are:

1. The system should provide adequate heating capacity. The system must maintain the desired inside temperature regardless of the outside temperature (down to the designed minimum outside temperature).

2. The system should uniformly distribute the heat. The temperature should be the same throughout the crop growth zone.

3. The system should be automatic. Once the desired temperature is selected and set, the system should maintain the inside temperature (as outside environmental conditions change) without further operator attention. Normally, it should be possible to select different day and night temperatures.

4. The system should be reliable and simple. The system must operate day and night throughout the heating season with little or no maintenance. Any repairs or necessary maintenance should be simple and not require special training or talent unless the range is large enough to have trained maintenance personnel.

5. The system should be inexpensive. Consistent with performance, the system should be as low in cost as possible.

6. The system should utilize available fuel. A greenhouse heating system must be capable of constant operation with those fuels available now and in the future.

Unfortunately, many of the systems for controlling temperature are designed and set up to only fulfill a portion of these functions or characteristics.

DETERMINATION OF HEATING SYSTEM CAPACITY

As suggested earlier, the determination of heating capacity is a relatively simple and straightforward procedure. A number of graphs, tables and formulas to determine heat requirements have been published in various literature. The publication of this Extension series AEN-8, "Estimating Greenhouse Heating Requirements and Fuel Costs", presents one
method of determining the required greenhouse heating capacity. There are many factors affecting the heat requirements of a particular greenhouse, but only the major ones are generally included in the charts and graphs. These major factors and how they affect your greenhouse design and choice of heating system are discussed below.

Number of Coverings:

Theoretical analysis and experimental test results show that the number of coverings used has a very marked effect on the heat requirement. This is due to the resistance to heat flow created by the air space between multiple glazings. Ideally, an air space should be approximately 1 1/2 inches thick, but air spaces from 3/4 to 8 inches are all reasonably effective and are commonly used. Below 3/4 of an inch, the effectiveness of the air space is rapidly lost.

![Diagram showing heat loss for single and multiple glazings of polyethylene.](image)

Figure 1 shows the heat requirement for a typical house with one, two and three layers of glazing. The curves show that the addition of a second layer of glazing with the dead air space between reduces the heat loss for the double-covered house by approximately 46% when compared to a single-covered structure. The addition of a third layer results in only an additional 16 percent savings in the heat requirement when compared to the single-covered structure. Since each additional covering results in a decrease in available light, and since light is often the factor limiting growth, it is doubtful if triple glazing can be justified in most areas. Only when fuel prices are extremely high would such construction merit consideration. Double-covering, on the other hand, due to very significant reductions in fuel costs, has proven desirable in most areas of the United States. Double-covering also results in a reduction of condensation on the interior greenhouse surfaces. This reduction is due to the higher interior surface temperature which is a result of the insulating value of the air space.

Type of Covering:

The type of covering material is also very important. Some plastic film, notably polyethylene, allows heat in the form of radiation to pass through it rather freely as warm objects inside the greenhouse radiate heat to colder outside objects. Other types of plastics and covering materials have very low heat radiation transparency and effectively trap heat within the house. Polyethylene film, in the absence of water condensation, will allow 71 to 80% of the thermal radiation striking it to pass through it. Tests have shown this would result in a potential increase in heat loss on a cold clear night of 28 to 39% for a single-covered structure and 39% for a double-covered structure when compared to similar houses covered with thermally opaque materials (fiberglass, glass, etc.). In actual practice, however, heavy condensation can occur on all single-layer glazing materials during cold weather, and the water droplets significantly reduce the radiant heat loss. Water droplets will cover 68% of the surface area if heavy condensation occurs and about 25% if only light condensation occurs. For conditions where heavy condensation occurs, double-covered polyethylene houses would then have only a 12.5% higher heating requirement than greenhouses double-covered with a thermally opaque material.

Air Leakage:

Air leakage around cracks in vents, doors, and between glass panes also represents an increased heat loss. The actual magnitude of this infiltration loss depends largely upon the condition of the greenhouse. To account for this air leakage, a 10 to 15% increase in the theoretical heat loss is commonly made with single-layer glass-covered greenhouses. This is approximately equal to the radiant loss from polyethylene houses. Since the radiation loss in a polyethylene house occurs directly from the leaf surfaces, the leaves may be a degree or more cooler than in a glass covered greenhouse with the same air temperature. If a glass greenhouse is double-covered, particularly if it is lined with...
polyethylene film, the infiltration loss is largely eliminated. For houses covered with polyvinyl or polyester film plastics, little radiation loss occurs and infiltration is also kept to a minimum.

House Volume and Surface Area:

In determining the heat loss from a greenhouse, volume is thought by some to be an important factor. This is not true. The most important feature of the house shape is the amount of exposed surface area per unit of usable plant space. To minimize exposed surface area, some growers build greenhouses with low eaves. Though this does reduce the wall area, it often creates difficulty in effectively distributing heat or ventilating such houses.

If either ventilation air or heated air are directed upon plants without first intermixing with the air already within the greenhouse, plant growth will be adversely affected. In many greenhouses the space above the crop is used for this mixing, but if the crop is tall and near the roof, inadequate space is available. As a general rule, at least 1/3 of the total house volume should be unoccupied if it is intended to use this space for the introduction and intermixing of ventilation or heated air with the greenhouse air. Thus, house shape and exposed surface area are important factors to consider in heat requirement determination and heat distribution.

GREENHOUSE HEATING SYSTEMS

Once the heating capacity has been determined for a particular greenhouse, the next important step is determining a proper heating system or method of producing heat and distributing it in the house. Schematic drawings of common greenhouse heating systems are shown in the following pages. Each of these systems has some definite advantages and some definite weaknesses. An understanding of these advantages and/or weaknesses is necessary for a greenhouse operator who is selecting a heating system.

Finned or Radiant Sidewall Pipe:

The use of either finned pipe or plain steel pipe along the sidewall, as shown in Fig. 2 and Fig. 3, has been a commonly accepted heating system in glasshouses. It is the old standby method and has proven to provide uniform heat distribution if properly installed. In particular, with forced-circulation hot water systems, temperature variations along the pipe can be kept small and few problems with heat distribution are normally encountered. If steam is used, obtaining uniform steam distribution along the full length of the pipe during low heat requirement periods often is a problem. For this reason steam pipes are generally looped along the sidewall (trombone coil arrangement).
draft of cold air along the roof will not be fully intercepted with the side coils and uneven temperatures in the crop zone will occur. For maximum uniformity, it is recommended that one-third of the total piping be placed overhead with a uniform spacing of the pipes. If benches are used, it is desirable to place one pipe directly over or underneath each bench, providing the 1/3 pipe requirement is met. The remaining 2/3 of the piping is placed along the sidewalls. For narrow-span ridge-and-furrow houses, piping is usually concentrated along the outside sidewalls and below the valleys between house sections. Pipes under the valleys not only intercept the cold downdraft along the underside of the roof, they also provide extra heat to aid in the melting of snow which might accumulate in the valleys.

The main disadvantage of radiant pipe systems is their high cost. Not only is the piping expensive, a central boiler facility is also required. For large ranges, this boiler facility must conform to rigid safety requirements and must be operated by a man knowledgeable in the operation of such systems. Overhead piping has an added disadvantage of causing some shade, though this is not normally critical. With radiant pipe systems, strong winds can adversely affect interior temperature patterns more than with heating systems which have forced air circulation.

The use of overhead circulating fans (Turbulators or Dutch Mill fans) to improve temperature patterns in houses with sidewall pipes has not proved successful. A cold spot is created below the fan and the hot air mass in the ridge is intensified. The hot air rising from the sidewall pipes is also directed back towards the floor or onto the top of the benches, resulting in a concentration of warm air along the sidewalls. Since the air circulation pattern created by the fan is, in effect, working in direct opposition to the pattern being developed by the heating pipes, increased temperature variation is expected. Other, better, air circulation methods are described in Extension publication AEN-18, "Air Circulation in Greenhouses."

Radiant Pipe Across House Floor:

Many operators, particularly European greenhouse owners, prefer to place 1/3 or more of the piping low along the ground or under plant benches, as shown in Fig. 5. Their reasoning is to bring the heat close to the plants when they are small and to provide a slight increase in soil temperature. For tomato culture, the ground pipes would be placed between alternate rows of plants. With this system a definite upward convection of heat between the plants occurs. This concentration of heat near the plants is not generally sufficient to cause problems with excessive transpiration. In terms of uniformity of temperature profiles, this system is comparable to the sidewall system with dispersed overhead piping. It actually is generally considered superior when the plants are very small and slightly inferior when the plants are tall (at least in terms of uniformity of temperature at the tops of the plants). As with the previous system, the temperature profiles are easily affected by strong winds, but this is not a significant problem with well-constructed houses having tight-fitting ventilators.

The same disadvantages of cost and complexity exist with this arrangement as with the preceding system and, in addition, the ground pipes are in the way during soil preparation operations. Normally they must be removed, either by hanging them up out of the way or completely disconnecting them.

Overhead Vertical Discharge Unit Heaters:

Vertical downward-discharge unit heaters, as shown in Fig. 6 and Fig. 7, are available with either hot water or steam coils. These unit heaters have a circulation fan which normally is thermostatically controlled to operate when the coil becomes hot. The house thermostat controls a steam or hot-water valve or pump which controls the fluid flow to the coil. The circulation fan can be wired to run continuously if induced air movement is desired. However, since the fan would tend to pull cold air off the roof and dis-
charge it down into the crop when the unit heater coil is unheated, continuous fan operation is not a normal practice. The temperature profiles created within the house with such heaters are not very uniform, as shown in Figure 8. There is a relatively rapid temperature change vertically during a heating cycle. In addition, there is a cold spot directly below the heater and a hot ring at the point where the air discharge enters the plant zone. On occasion, such units are used in conjunction with sidewall pipes to supplement the heat output of the sidewall pipes. This generally results in the two induced air flow patterns opposing one another and unevenness of temperature patterns persists.

This system is less expensive than radiant pipe systems, and, where less precise temperature control is acceptable, such systems have merit. The system does require a boiler or hot water furnace like the previous two systems.

**Overhead Horizontal Discharge Unit Heaters:**

Unit heaters which discharge air horizontally, as shown in Fig. 9 and 10, can be obtained with hot water, steam, or gas-fired heat exchange coils. The gas-fired units, in particular, are very versatile and relatively inexpensive when compared to other heating units. However, the restricted availability of gas fuel seriously limits their use. The fan in the unit heaters can, in most instances, be wired to run continuously. The heater fans alone are usually not adequate to horizontally induce air flow throughout the greenhouse for houses 60 ft. or longer. Where uniform air movement is desired everywhere in the house, additional horizontally discharging fans can be added. Usually, two unit heaters are used for houses 60 to 120 ft. long and two additional circulation fans should be provided. The heaters should be placed at the center of the house and should be aimed to direct air toward opposite ends.
Since a large quantity of hot air is discharged horizontally with this system, difficulty is encountered with uneven temperatures, particularly in the upper crop zone. If this air is directed upward against the ceiling, this problem can be minimized, but then extra heat loss occurs. For bedding plant production operations, where the plants are on the ground and a relatively large house volume exists for air mixing, the system works fairly well; particularly if the required extra fans are provided for full development of a horizontal air circulation pattern and heat is circulated to ground level.

The main advantages of the system are its simplicity and its relatively low cost. When using any gas-fired heating equipment, it is very important to use only well-ventilated equipment. Combustion fumes are quite toxic to plants and, even with the cleanest burning type units, problems are generally encountered with plant injury if the products of combustion are released into the house.

Perforated Ground Polyethylene Tubes:

6 to 8 inch polyethylene tubing with holes punched 1/2 to 2 feet apart to distribute hot air along the ground of a greenhouse, as shown in Fig. 11, has been used in plastic covered houses for a number of years and is now being evaluated in Europe in glasshouses. The system is relatively inexpensive and can easily be removed at the end of the heating season. Uniformity of heat distribution, however, is a problem. With polyethylene tube systems more air is generally discharged out of a hole near the closed end of the tube (furthest away from the air inlet) and, at the same time, heat loss by conduction through the walls of the tube results in a decrease in air temperature within the tube. Fortunately, these two characteristics tend to compensate for each other. However, a variation in hole spacing is generally necessary for maximum uniformity.

For tomato or other ground row crop culture, the tubes are generally spaced between alternate rows. Some problem occurs if a blast of air directly strikes a young transplant. Care must be taken when working within the house to avoid tearing the tubes or laying some form of material on a tube which will prevent its inflation when the heating system operates. If induced air circulation is desired, the heat distribution fan can be operated continuously.

The main disadvantages with this system are the difficulty of properly designing the perforated tubes and of constructing the main air distribution heater to which the tubes are connected. For large houses, this heater becomes very large and can be an obstacle in the house.

Any type of forced hot air heater can be used with the system—coal, gas, oil, hot water, steam, etc. Normally, the main distribution header is run across the house at mid-length and the perforated tubes are then run in each direction from the header towards the two ends. For houses less than 60 ft. long, the header would normally be placed at one end of the house and the tubes run only one way.

Overhead Perforated Polyethylene Tubes:

Commercial development and marketing of perforated polyethylene tubes for heating and air circulation, as shown in Fig. 12 and Fig. 13, has expanded rapidly in

Fig. 10.—Overhead horizontal discharge unit heaters.

Fig. 11.—Ground-level perforated polyethylene tubes.

Fig. 12.—A perforated plastic tube system used for air circulation, heat distribution, and first stages of ventilation.
recent years. The perforated polyethylene tubes are placed overhead. With houses less than 30 ft. wide, one tube is commonly used, with two tubes for wider houses. Normally, the holes are uniformly spaced; but, for optimum temperature distribution, the hole spacing should be varied. A fan is connected to the tube at one end of the house to circulate air through the tube. Heat is then introduced behind the fan.

Good distribution can be achieved throughout the length of the house with proper tube size and hole spacing. However, since hot air tends to rise and since the air velocity rapidly slows down after exiting from the tube, vertical temperature stratification can be a problem. This is particularly true in a greenhouse with ground beds. Not only will cool temperatures exist near the ground surface, the humidity can be near saturation levels, thereby intensifying problems with diseases. For more details on overhead perforated tube systems see publication AEN-7 of this series, "Poly-tube Heating-Ventilation Systems and Equipment."

**Sidewall Heating and Recirculating System:**

The placement of a recirculating fan and hot air heating system, as shown in Fig. 14 and Fig. 15, at spaced intervals along the side of a greenhouse has proven successful for research and production houses of moderate size. A baffle is placed in front of the air circulation fan to direct the air up along the underside of the greenhouse roof, across the house, and then down the far side and back along the floor. The recirculation fan runs continuously and heat is added as necessary behind the fan. Since mixing of heated air and greenhouse air occurs in the fan and along the ceiling, relatively uniform temperatures are achieved. The baffle in front of the fan should be triangularly shaped to direct more air towards the corner of the house than directly across the house.

The heating system can be any hot air heating system—coal, gas, oil, etc. As with the other systems, any fuel burning equipment should be vented to the outside to avoid the danger of plant injury due to the products of combustion. The fan capacity in CFM for heat distribution needs to be 3/8 to 1/2 the house volume. If the same fan is to be used for ventilation, the fan capacity should be 3/4 to 1 times the house volume. Further details on this system are available from the Agricultural Engineering Department at the University of Kentucky.

**Radiant Heating System:**

The use of radiant heating systems in greenhouses, as shown in Fig. 16, has been evaluated by several investigators. As a general rule, leaf temperatures were higher than air temperatures. Soil surfaces which were exposed to radiation were as warm or slightly warmer than the air tempera-
ture. When the plant canopy became closed and shaded the soil, soil temperatures were lowered and generally were considered below optimum. Also, leaf temperature further increased and could be detrimental to good plant growth if radiant energy sources were too close to plants. Generally, some form of air heating system is considered necessary even when using radiant heating. Though the capacity of this air heating system would be less than that required if no radiant heating were used, the basic cost of an air heating system is still a necessary factor. Due to the cost and complexity of designing and installing two different heating systems, very few commercial greenhouses utilize radiant heat.

**DESIGN AND SELECTION OF A SPECIFIC HEATING SYSTEM**

The actual design of a heating system thus involves two factors: 1) a determination of the system capacity; and 2) the selection of a heat distribution system which will provide uniform temperatures throughout the greenhouse. Several systems can be used. The size and type of house will determine the exact type of system that is best for a particular house. Details of recommended and widely used systems are too extensive to be covered in this publication, but other literature is available for your use. In addition to commercial literature, a publication of this greenhouse series on the overhead polytube system (AEN-7, "Poly-tube Heating-Ventilation Systems and Equipment") and a blueprint from the Agricultural Engineering Plan Service entitled "Unit Heater and Fan Greenhouse Heating and Ventilation System" (No. 811-7) are available through your local Kentucky Cooperative Extension office.

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