Greenhouse Glazing Effects on Heat Transfer for Winter Heating and Summer Cooling

David R. Mears, Ph.D.
Bioresource Engineering
Department of Plant Biology and Pathology
Rutgers University
20 Ag Extension Way
New Brunswick, NJ 08901

I. Energy (heat) transfer in the context of greenhouse environmental and its control occurs in a combination of four different ways: Conduction/Convection, Radiation, Latent heat transfer, and Infiltration.
Knowledge of these methods of heat loss will bring the understanding that for thin film continuous glazings, radiation may be the most important of the four, and that the formulation and manufacture of the film will determine its transmission of heat by radiation. The others, especially infiltration and latent, can be minimized only by the design and management of the greenhouse operation.
Light is the only form of radiation that is visible to humans, but all radiation is energy, and energy is synonymous with heat. Since the amount of heat within an object determines its temperature, we must be concerned with the input/output flows of heat from the greenhouse, or from the plant itself, as this will determine the temperature of the air of the greenhouse, or the plant leaf surface.

The thermal environment (air temperature) of the greenhouse is based on the proportion of the radiant energy transmitted into the greenhouse, to that re-emitted through the glazing (solar energy "in" compared to heat energy "out"), as well as, infiltration losses (uncontrolled air exchange from greenhouse to outside), and conductive/convective heat loss directly through the glazing. If more heat enters than leaves, the greenhouse air temperature will tend to rise. If more heat leaves than enters, the air temperature will fall.

Although we are primarily concerned with the radiation heat loss and gain, it is valuable to review the other heat loss mechanisms.

Conduction and Convection heat gain and losses are practically the same for all plastic single film glazing materials, and there is little that can be done to reduce them, except increase the number of layers. Multiple layers such as air-inflated double-polyethylene glazing will have increased insulation value and therefore reduce heat loss from the greenhouse. However, additional layers will also reduce the transmission of incoming solar radiation used for photosynthesis.

Conduction is defined as the transfer of energy through materials and can be envisioned as the transfer of heat from molecule to molecule across the material. The rate of heat transfer is proportional to the surface area of the material, multiplied by the conductivity coefficient multiplied by the difference in temperature across the material. As an example, heat transfer across a glazing material is surface area of the glazing multiplied by the conductivity for the thickness of glazing multiplied by the temperature difference between the inner/outer surfaces. Note that the resistance to heat transfer can be considered the insulation value for a material.

Convection is the transfer of energy by movement of a fluid from location to location, or by movement of the fluid across another layer of fluid. The rate of heat transfer is proportional to the area across which heat is being transferred, multiplied by the convection coefficient, multiplied by the temperature difference. As with conduction, the convective resistance is the reciprocal (opposite) of the convection coefficient. This concept is particularly useful when considering heat transfer from one glazing surface to another across an air space. The total convective resistance is the sum of the three resistances: (1) from one surface to the air, (2) across the air space and (3) from the air to the other surface. The reciprocal (inverse) of the sum of the resistances is the total convection coefficient for the air space. In a natural convection situation (ie no circulation fan/pump), the coefficient is strongly dependent upon the temperature differences between the two locations of the fluid movement. Where forced convection using a fan to blow air, or a pump to move water, the coefficient is also strongly dependent on the flow rate of the fluid.

Energy losses by radiation in the greenhouse are primarily dependent upon the emissivity and the transmissivity (in the infrared waveband) of the greenhouse covering material. The emissivity is a material property which defines its ability to emit energy which it has absorbed. The net radiation, that is, the difference of the energy received and lost by radiation, is important for determining the greenhouse air temperature. During the day, solar radiation generally assures a net gain of energy, with a subsequent greenhouse air temperature rise. At night, the warm plants and components within the greenhouse lose energy by transmission of long wave (infrared) radiation to the cold sky above. The rate of this loss depends, not only on the temperature of the plants, and the atmospheric conditions (cloud cover, carbon dioxide, and ozone content), but also on the properties of the glazing. The capability of the glazing to transmit long wave radiation, directly affects radiation energy losses. It is therefore important to consider the transmission properties of the glazing material in the long wave radiation region (wavelengths greater than 850 nm).

Radiation heat transfer in the context of greenhouse environmental control is usually the net result of heat transfers to and from an object by radiation. This energy transfer can be conceptualized as photons transporting energy from the object to its environment and other photons transporting energy from the environment to the object. Net radiation heat transfer is proportional to the area of the object, multiplied by a coefficient depending upon the geometry of the object and its environment, multiplied by another coefficient which depends upon the thermal emissivities of the object and its environment, multiplied by the difference in the fourth powers of the absolute temperatures of the object and its environment. The thermal emissivity of most materials is dependent upon the material temperature, as well as, the material physical properties.

Infiltration and ventilation involve the transfer of heat by the movement of air from the greenhouse to the outside environment. The heat transfer involved in the movement of air is the volume of air multiplied by the density of the air, multiplied by the specific heat of the air, multiplied by the temperature difference. This temperature difference is usually the difference between inside and outside air temperatures. In addition, the difference in latent heat of the air between inside and outside the greenhouse must be considered.

Latent heat loss is related to the amount of moisture in the air. As moist air is lost to infiltration across the greenhouse glazing, the energy (heat) that was consumed during the process of evaporation of the liquid water to form the gaseous vapor is also lost. In the process, the greenhouse air was cooled. Latent heat loss also occurs when water vapor in the air condenses to liquid water on a cold surface (such as the glazing), and thus releases its heat directly to the glazing and then out to the environment.

II. Radiation fundamentals related to greenhouse environmental control

In conceptualizing radiation heat transfer as the movement of photons to and from an object the characteristics of the photons need to be considered. The energy of a photon is directly related (proportional) to the characteristic frequency of that photon [Planck's law]. The frequency of the photon is related to its wavelength, which is the practical way to measure and describe the photon of light. Photons travel at the speed of light. The frequency of the photon is the speed of light divided by the equivalent wavelength of the photon.

The human eye can visualize only those photons with wavelengths between 400 and 700 nm. These represent the various colors ranging from blue (400 nm) to red (700 nm). The eye cannot "see" other wavelengths such as the ultraviolet (UV) or infrared (IR). It is the IR and longer wavelengths that are important for heat loss from an object by radiation.

Objects emit photons of wavelength and energy level which is dependent on the temperature of the object. The peak of the distribution of energy of photons emitted by an object [Wein's law] have a wavelength equal to a constant divided by the object's absolute temperature. Thus the sun, which has a surface temperature of over 10,000ºF, emits photons with a wavelength peak at 500 nm. A greenhouse plant at a typical temperature for proper growth may emit photons with a wavelength peak at 1,000 nm. Note that the typical photon coming into a greenhouse from the sun during the day has 20 times as much energy as one leaving a warm plant in the greenhouse at night and passing outward through the glazing [Planck's law].

Important points:

- In conceptualizing radiation heat transfer as the movement of photons to and from an object, the characteristics of the photons need to be considered. The energy of a photon is directly related (proportional) to the frequency of that photon.
- The practical way to measure and describe a photon of light is by its wavelength.
- The wavelength of a photon can be determined by dividing its frequency by the speed of light.
- The human eye can visualize only those photons with wavelengths between 380 (violet) and 770 nm (red). The eye cannot "see" other wavelengths such as the ultraviolet (UV) or infrared (IR).
- It is the IR and longer wavelengths that are important for heat loss from an object by radiation.

III. Examples for Discussion

In order to discuss the fundamentals of energy transfer in the context of greenhouse environmental control and the effect of glazing, it is important to examine the night time and the day time situation separately, as one represents a net loss of energy, and the other a net gain of energy through the greenhouse glazing. Next, it is important to consider the effects of common types of glazing, within single and double layer configurations, as they directly affect the energy gain or loss due to their different radiation transmission properties. Finally, the option of curtain systems for energy conservation is considered, as the interaction of the properties and effects of a curtain with those of glazing is important. A complete explanation of all aspects of energy exchange through greenhouse glazing is complex, thus the following discussions are simplified to emphasize some important aspects of the total subject.

IIIa. Energy transfer at night requires heat to maintain greenhouse temperature
To summarize, the greenhouse air will lose heat to the environment by transfer through the glazing, the insulating curtain system, and by infiltration, all which are directly proportional to the inside to outside air temperature difference.

Consider first the transmission of heat from a greenhouse to outdoors on a cold night. Heat is transferred from warm objects within the greenhouse, including the heating system, to the greenhouse air and from the greenhouse air to the glazing and then to outdoors. Also, objects in the greenhouse radiate directly to and/or through the glazing. The plants transpire some water, but far less than during the daytime and exchange heat with their surroundings by convection and radiation. For most heating systems there will be a net loss in terms of radiation heat exchange and the plants will receive heat by convection from the warmer greenhouse air to compensate for the net radiation loss and the loss of latent heat due to transpiration. The greater the net radiative heat loss the lower will be the plant temperature relative to the air. The type of heat distribution system within the greenhouse can have a significant effect on the relationship between plant and average air temperature. There is no photosynthesis in the dark, but there is plant respiration which produces some heat, but very little compared to what a greenhouse is losing to the outside on a cold night.

Single glazing
In greenhouses with a single layer of glazing and no curtain insulation system, the balance of energy flows to keep the greenhouse air at a constant temperature requires that the heating system provide energy at the same rate as the total of the heat loss. The major losses are due to air infiltration plus that lost by radiation and that lost through the glazing. Heat transfer through the glazing is proportional to the temperature difference between inside and outside. The resistance to heat loss is the sum of the resistance to heat transfer from the warm air to the inner surface of the glazing plus the resistance through the glazing and plus the resistance from the outer surface of the glazing to the outside air. Generally the resistance through the glazing itself is negligible compared to the other two resistances. The external resistance depends on wind velocity and is reduced as wind increases. The resistance from the still, interior air to the interior glazing surface depends strongly on the difference between the air temperature and the glazing temperature but is not significantly influenced directly by the outside wind speed except for the effect that the wind has on lowering the glazing temperature.

On cold nights the glazing will be colder than the plants and the greenhouse air but warmer than the outside air. As the plants are respiring at a low rate the moisture added to the air has to be removed by a combination of infiltration and condensation on the underside of the glazing. In a tightly constructed greenhouse infiltration heat losses should be relatively low. Note that the coefficient of heat transfer for condensing moisture on a cold surface is on the order of 1,000 times the natural convection heat transfer coefficient so any energy put into the evaporation of water within the greenhouse is transferred directly to the glazing.

Long wave infrared heat transmission: plain polyethylene glazing
An important property of plain polyethylene is its very high rate of transmission of long wave infrared radiation. If the glazing is essentially transparent to thermal radiation then the warm plants, (and warm structural components and heating pipes etc.), radiate directly to the outside sky. Radiation exchange with the sky is a complex phenomenon as the emmissivity of the sky and sky temperature, are both difficult to determine. However, if one considers the emmissivity to be unity and measures actual net outgoing radiation an apparent sky temperature can be determined. When it is raining or completely overcast with fog or low clouds the effective sky temperature is the outside ambient temperature. The

clearer the sky the lower the effective sky temperature. When the sky is very clear as on a crisp, clear winter night the heat loss by radiation is maximum.

Under clear sky conditions it is possible for plants under dry polyethylene glazing to be substantially colder, on the order of 7 ^{o}F, than the air temperature. This is due to the large rate of heat loss from the plant by radiation, which is being replaced by convection from the air, which requires a significant temperature difference to effectuate. Plants can freeze under such conditions even when air temperatures are substantially above freezing. Note that this problem can be substantially alleviated if enough moisture is evaporated to induce a layer of condensation on the film as the water itself reduces the infrared transparency of the polyethylene film, making it more like glass or other long wave absorptive glazing as discussed next.

Long wave infrared heat absorption: glass glazing, IR absorbing film, or wet film

If the glazing is completely opaque to long wave infrared radiation then warm plants and other objects within the greenhouse no longer radiate directly to the outside sky as discussed above. Instead, radiation exchange is with the glazing itself. As the glazing is warmer than the outside sky, net radiation loss to the glazing is significantly less than radiation loss to cold sky directly through IR transparent glazing. The radiative energy the glazing receives from the plants and other warm objects in the greenhouse is then lost to the outside by convection to the outside air and onward radiation to the cold sky. Radiation heat transfer depends upon the differences in the fourth powers of the temperatures of the radiating and receiving bodies. Therefore there is a greater reduction in the heat loss from the plant when the glazing is the receiving body instead of the colder outside sky than would be the case if radiation losses were linearly dependant upon temperature differences as are conduction, convection and infiltration.

The comparison between single layer glazing which is IR transparent and IR absorptive will show that less energy input is required to maintain internal temperature under a given weather condition with the absorptive film and also, that the plant temperature will be somewhat warmer relative to inside air temperature. This effect is most pronounced when the sky is clear and the outside temperature is coldest. As the IR absorptance of a polyethylene film depends upon the thickness of the water film on it or the amount of IR absorbing additive in the film radiative heat losses will range between values for completely transmissive and completely absorptive films.

Multiple layers of glazing

Double layer glazing and multiple layers beyond two have a major impact on heat loss at night by reducing heat loss through the glazing by conduction and convection. The conductive resistance of thin films is relatively insignificant and the reduction in heat loss is not due to the added resistance of the thickness of the glazing. However, adding a layer of glazing with an air space substantially increases the total convective resistance. Heat must be transferred from the greenhouse air to the inner surface of the inner glazing then from the outer surface of the inner glazing to the air space between the glazing layers. Next it must be transferred by convection across the air space, then from the air space to the inner surface of the outer glazing. Finally, if there are two layers of glazing, it must be transferred from the outer layer of the outer glazing to the outside air. The major resistance is the sum of the four surface to air resistances and only the outer one is significantly influenced by outside wind speed. Thus multiple layer glazing systems are far less influenced by wind than single layer glazing.

Double layer polyethylene without IR absorption
Due to the insulating effect of the trapped air space and the additional resistances to heat transfer between air and glazing described above, the convective heat loss through a double layer glazing system is far less than a single layer. However, total heat loss from the greenhouse is not reduced to the same proportional degree as infiltration loss and direct radiation losses are relatively unaffected. With the reduction of the convective loss the relative importance of direct radiation loss and infiltration loss are substantially increased. With double layer glazing the inner layer will be much warmer than a single layer glazing which substantially reduces the potential for condensation. However, as there is some transpiration at night the interior humidity will increase and as the inner glazing temperature is less than the air there is likely to be some condensation, which, if present, will provide some IR absorption for the inner layer. The rate of condensation accumulation will be significantly less than would be the case for a single layer. Reduction of condensation and drip on the crop below was a strong incentive for the introduction of the double layer system for polyethylene greenhouses in the early years.

Double layers with IR absorption such as glass and IR absorbing polyethylene film
The net loss of radiation from the greenhouse is greatly reduced when the glazing is IR absorptive rather than IR transmissive. The plants are exchanging radiation with the interior layer of glazing which is warmer than the outer layer and far warmer than would be a single layer glazing. The inner layer loses net radiation with the outer layer, which, in turn, loses net radiation to the cold sky. Radiation heat transfer varies with the differences in the fourth powers of the temperature. Therefore there is a marked reduction in net loss as the temperature difference between the plants and the outside sky is divided into several intermediate temperatures with the radiation loss from one to the next in series.

Different materials in combination
If a double-glazing system utilizes two layers with different IR transmission properties the total reduction in net heat loss by radiation will not be as great as if both are completely IR absorptive. It is significant here to note that most IR absorption additives to polyethylene film do not make the film completely IR absorptive. In glazing a greenhouse with two layers of film with different IR absorption properties the differences in performance due to the relative placement of the two films are not very substantial. The greatest impact on night radiation loss is the use of at least one IR absorbing film for either the inner or outer layer with a significant improvement if both layers are IR absorbing. In a fully cropped greenhouse on a cold night there is generally enough transpiration to cause some condensation on the inner layer giving that layer some IR absorptancy leading to a slight benefit of putting the IR absorbing layer on the outside in a mixed system.

Curtains for heat retention
While internal curtain systems used for heat conservation are not part of the glazing system, the properties of the curtain do have a substantial effect on the performance of the glazing. This is particularly the case relative to heat loss by radiation. In a single layer glass greenhouse the curtain system conserves heat energy at night primarily by reducing heat loss through the glazing by adding a trapped air space and convective resistances to and from the curtain. In a double layer polyethylene house where there are already the added convective resistances the major contribution of the curtain is likely to depend on its radiative properties. A curtain of plain polyethylene will add convective resistance for some benefit but make little reduction in the radiation loss. Any opaque, IR absorbing curtain will have a marked effect on the radiation heat loss which is relatively more important for a double polyethylene glazing.

An opaque curtain reduces radiation loss by dividing the temperature difference between the plant and the night sky. Any curtain, which is reflective of IR radiation, has the added benefit of further reducing radiation heat loss. A reflective material also does not emit heat radiation so an internal curtain, which is reflective on top, will not emit to the outer glazing or the cold sky. The reflective property is less important for the bottom of the curtain as the curtain itself will receive heat from the warm air under the curtain by convection and radiation from crop to curtain is relatively less important. Thus a curtain with different properties on both sides will generally be more effective with the reflective side up. A good application would be a curtain silver on top and black underneath used for photoperiod control as well as night heat retention. Such a curtain would not, however, be helpful as a summer shade.

Important points:

- The plant constantly gains and loses heat while attempting to maintain a balance with its surrounding environment. A cooler leaf will gain heat from the warmer air.
- Transpiration will transfer latent heat by evaporation from the plant to the air.
- The plant may receive net radiation from warmer portions of its environment such as heating pipes, radiant heaters, and possibly a warm floor or bench top. It will lose heat by radiation to the colder glazing, or lose heat by radiation directly to the cold outside sky.
- If the glazing is not transparent to radiation at the wavelengths being emitted by the plant (i.e., it is an infrared barrier film), then this heat loss will be reduced, and the leaf temperature will be warmer.

IIIb. Energy transfer during the day requires cooling to maintain greenhouse temperature

There are significant differences between the energy balance of the plant and greenhouse in the daytime and at night. With sunlight, the plant is actively engaged in photosynthesis and transpiration becomes a major mechanism for moving latent heat from the plant to the greenhouse air, which then will normally be expelled from the greenhouse by ventilation. The plant receives radiation transmitted by the glazing system over a much larger wavelength spectrum than it will actually use. The PAR is a portion of the total light spectrum, which is necessary for photosynthesis. Of the PAR, less than 5% of its energy is converted to stored chemical energy by photosynthesis, therefore, at least 95% of the PAR and all of the other non-PAR radiation (shorter [less than 400nm] and longer wavelengths [greater than 700nm]) have only to contribute to raising the plant leaf and air temperatures.

It should be noted that for reasonably well-designed greenhouses in cold climates, the rate of energy input to a greenhouse during a sunny day is on the order of 10 times the rate of heat loss during a cold night. Given that only 44% of the incoming radiation from the sun is in the PAR waveband, a glazing, which reflects or absorbs energy in the non-PAR range does reduce the direct thermal radiation energy unneeded by the plant. Thus the greenhouse system air temperature would be less with a selective glazing.

During a sunny day the energy transfer situation is far different than that of a cold night, even though the basic laws of energy transfer are the same. As noted in earlier discussions, the incoming solar radiation is absorbed by the plants and of that amount a small fraction is converted by the plant by photosynthesis. Most of the energy absorbed by the plant is converted to heat and that has to be removed from the plant by transpiration and by convection to the greenhouse air. The plant will therefore be warmer than the surrounding air. It is important to understand that the total rates of energy exchange on a sunny day are far higher than on a cold night. When the internal greenhouse temperature is somewhat warmer than outside there will be some heat loss through the glazing but this is very small relative to the net incoming radiation. Heat loss from the greenhouse must be primarily by ventilation which removes both latent and sensible heat if the internal temperature is to be maintained near outside ambient.

The incoming solar radiation may not all be transmitted by the glazing and any energy, which is reflected or absorbed by the glazing, does not have to be removed by ventilation. To the degree that the plants do not need incoming UV and short wave IR radiation, a glazing, which does not transmit these wavelengths, reduces the greenhouse-cooling load. More importantly, the total radiation load on the plants is reduced if the energy is not transmitted into the greenhouse and this energy need not then be removed from the plant by transpiration and convection to the greenhouse air. Energy absorbed by the glazing tends to increase its temperature reducing the likelihood of condensation when outside temperature is very cold relative to inside as on a sunny winter day.

Long wave infrared heat transmission: plain polyethylene glazing
Plain polyethylene is essentially transparent to all incoming solar radiation including UV, visible and short wave IR as well as long wave IR. While it does represent no barrier to outgoing long wave IR, radiative cooling is not very helpful in reducing plant temperature. To lose heat by outgoing radiation equivalent to the rate of gain from the incoming solar radiation the plant temperature would have to be extremely high. For the plant to maintain temperature only slightly above the ambient air transpiration must be the primary means of heat loss. If the plant is slightly warmer than the ambient air there will be some transfer of heat to the air by convection. The heat added to the greenhouse air by the plant must be removed by ventilation. As heat exchange by long wave radiation is very small relative to total solar heat gain the IR absorbing properties of the glazing have very little effect on the total heat balance of a fully cropped and ventilated greenhouse. However, if the greenhouse is not vented interior temperatures will rise substantially and radiation loss can then become significant and the IR property of the glazing becomes important, increasing temperature as absorptancy increases.

Long wave infrared heat absorptive: glass glazing
Most glass is not only absorptive of long wave IR but also some short wave IR and UV radiation. To the degree that glass absorbs non-PAR energy, it reduces the heat load on the plant that must be removed by convection and transpiration. As PAR represents less than half the incoming solar radiation, a glazing material that would absorb or reflect all non PAR would have a substantial benefit in reducing the heat load on the plant. However, as noted above, plant cooling cannot depend substantially on outgoing long wave radiation, as plant temperature cannot be allowed to rise to very high levels. During the day, there is IR exchange between the plant and the glazing but the glazing cannot be cold enough to adequately remove incoming solar radiation.

Partially absorptive water condensation or IR absorber added to transmissive film glazing
As noted under the previous section on heating at night, adding IR absorbers or a thin water layer to otherwise IR transmitting plastic film effects heat transfer by radiation but to a lesser degree than is the case for completely IR opaque or reflective materials. Under hot summer daytime conditions when heat stress on plants is most important, water condensation on the film is not likely. Again, the IR absorbing characteristic of the glazing has little relative importance on the total removal of heat from a well-ventilated greenhouse but may have a notable impact on the energy balance of the plant. To the degree that the glazing absorbs incoming energy rather than transmitting it to the plant, the cooling load for the plant is reduced. The plant temperature elevation relative to the greenhouse air may thus be slightly reduced as heat stress on the plant is lessened. This factor may be particularly important for plants with a limited potential for transpiration, as is the case with rooted cuttings.

In one experiment evaluating the features of IR versus non IR absorbing polyethylene recently rooted poinsettia cuttings were placed in all the research greenhouses on a clear, hot August day. All greenhouses were similarly ventilated but the root systems of the cuttings were not fully developed so the ability of the plants to transpire water was limited. The IR absorbing film did block some incoming IR resulting in very slight reduction of plant temperature relative to the greenhouse air. The plants in the non-IR covered greenhouse perished while those under the IR film survived. The environmental difference was not very great but it was significant. All houses were double film covered and without shade curtains.

Multiple layers of glazing
Multiple layers of glazing under daytime conditions do substantially influence the total energy balance. The major impact of multiple layers is the reduction of incoming energy in all wavelengths due to absorption and reflection. Partial reflection from glazing materials is primarily a surface phenomenon so adding multiple layers increases the probability of reflection for each incoming photon. Total energy transfer is further complicated as there can be multiple reflections between surfaces and reflectivity is highly dependent upon the incident angle of the incoming radiation. Energy absorption by multiple layers can also be complex. Frequently it is assumed that the transmissivity of two layers of glazing is simply the product of the transmissivities of each. This is not always the case. If one layer of glazing is highly absorptive in a certain waveband, the second layer will appear to have lower total absorptivity as that portion of the incoming wavebands has already been deleted.

The situation is somewhat different when the additional layer is a shading material. Most shading curtain materials have a percentage of their area transmittive and other area either absorptive or reflective of all portions of the incoming spectrum. Reflective shade materials will reduce heat stress on plants more than absorptive materials as the reflective material will be cooler and will not radiate back to the plant.

Comparative adjectives have generally been used to describe the relative effects on energy transfer rather than example values in the above discussions. Measurements can be made under research conditions of both environmental parameters and plant response. Calculations can be done for a wide variety of greenhouse designs and external environments if all relevant material properties are known. Engineering measurements of environmental parameters are far more useful when the greenhouse is filled with plants. Empty greenhouses can give very misleading empirical results, especially when considering greenhouse cooling issues. Plant response information without comprehensive data on the environmental conditions being achieved by the test greenhouse contribute less to understanding than when that information is also analyzed.

Important points:

- There are significant differences between the energy balance of the plant and greenhouse in the daytime and at night. With sunlight, the plant is actively engaged in photosynthesis and transpiration becomes a major mechanism for moving latent heat from the plant to the greenhouse air.
- The plant receives radiation over a much larger waveband than it will actually use for photosynthesis.
- The PAR is a portion of the total radiation spectrum, which is necessary for photosynthesis. Less than 5% of the PAR energy is converted to stored chemical energy by photosynthesis. Therefore, at

least 95% of the PAR and all of the other non-PAR radiation (shorter [less than 400 nm] and longer wavelengths [greater than 700 nm]) contributes to raising the plant leaf and air temperatures.

- Given that approximately 44% of the incoming radiation from the sun is in the PAR waveband, the remaining 56% contributes to heating the greenhouse and the plant leaf surface.

Definitions

Conduction heat transfer *-- transfer of energy through materials by heat movement from molecule to adjacent molecule across the material.*

Conductivity coefficient *-- property of a material directly related to its ability to transfer heat; reciprocal of insulation (resistance, R) value.*

Convection heat transfer *-- transfer of energy by movement of a fluid (e.g., air, water) from location to location, or by movement of the fluid across another layer of fluid.*

Convection coefficient *-- physical property of the fluid to transfer heat through physically moving from one position to another; reciprocal of the convective resistance.*

Convective resistance *-- the sum of the resistance to heat movement by convection; the reciprocal of the convection coefficient.*

Condensation *-- the change of vapor to liquid water; heat is given off during condensation.*
Evaporation *-- the change of liquid to vapor; heat is consumed during evaporation.*

Natural convection heat transfer *-- movement of heat by fluid flow without the use of a fan or pump.*
Forced convection heat transfer *-- movement of heat by fluid flow with the use of a fan or pump.*

Infiltration *-- unwanted heat loss through air exchange across the greenhouse structure and glazing.*

Insulation *-- resistance (R value) to heat flow; reciprocal of conductivity.*

Latent heat *-- energy associated with the amount of moisture contained in air; energy associated with the change of liquid to vapor; evaporation is an example of latent heat exchange.*

Net radiation *-- the difference of the energy (heat) received to that lost by radiation.*

Radiation heat transfer *-- energy lost through the greenhouse glazing that is primarily dependent upon the emissivity and the transmissivity of the glazing; there is no movement of air mass.*

Reciprocal *-- mathematically the inverse; to determine the inverse, divide the value into one.*

Transpiration *-- loss of plant moisture through openings in the leaves; it is an evaporative process which cools the leaves.*

Reference

Hanan, J.J. 1997. Greenhouses – Advanced Technology for Protected Horticulture. CRC Press.