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X - Air and Ventilation in Passive Solar Greenhouses

This chapter explains what air is (its composition and properties), how it behaves, and why its proper management is important to the success of growing plants in your greenhouse. All greenhouses require ventilation to exhaust warm, moist, CO_2 poor air and pull in fresh air. SunCatcher PSGs primarily manage airflow naturally rather than mechanically as standard greenhouses do. The second part of this chapter explains the how and why of effective ventilation and air movement practices for climate regulation in PSGs.

The Composition and Weight of Air

Like natural air, the air inside a greenhouse is composed of nitrogen (78%) and oxygen (21%), with the remainder being water vapor, CO_2, and trace gases. Among these, CO_2 and O_2 are most important for plant growth. Not all gas molecules weigh the same (measured in Atomic Mass Units or AMU):

- Water (H_2O) = 18 AMU (lightest)
- Nitrogen (N_2) = 28 AMU
- Oxygen (O_2) = 32 AMU
- Carbon dioxide (CO_2) = 44 AMU (heaviest)

At first glance, you might think moist air is heavier than dry air because water is heavier than air, but gas laws tell us otherwise. The equation (relationship) **PV = nRT** is known as the ideal gas (Charles' or Boyle's) law, where

P = Pressure
V = Volume
T = Temperature
n = number of molecules (how many)
R = a constant needed for numerical calculations

When adding lighter water vapor molecules to air at the same pressure, volume, and temperature, heavier nitrogen, carbon-dioxide and oxygen molecules will be displaced, making moist air less dense than dry air. This is why moist air rises. Similarly, warm air is less dense than cool air because heating causes molecules to spread apart. Together, these principles explain why CO_2, the heaviest common gas, tends to sink and accumulates in a layer close to the ground surface, while moist, warm air rises.

Another way to explain this is using car tires as an example. If we have two identical imaginary tires of exactly the same size (V), pressure (P), and temperature (T) (R is a constant, so remains the same, regardless), then the tires will contain the same number (n) of air molecules (mostly oxygen and nitrogen). If any of these variables change, it will change at least one of the other variables. If you increase the temperature (T) of the air in one tire, either the tire must increase in size (V) or the pressure (P) of the air in the tire will increase. If you increase the pressure, the size of the tire must increase or the temperature will go up. So, if we don't want to change the pressure, temperature, tire size or the number of molecules in the tire (in other words, keep everything exactly the same), then when we add some new molecules (n) we must take the same number of molecules already in the tire out so the overall number of molecules in the tire stays

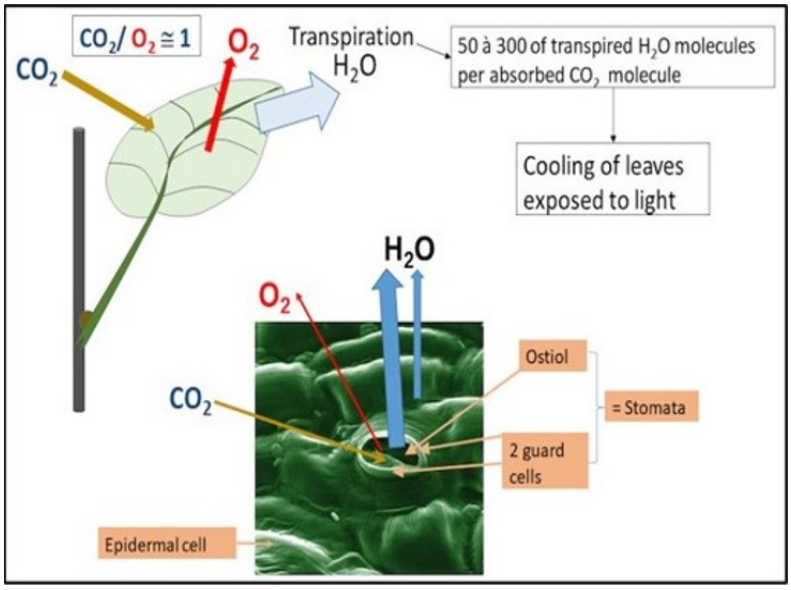
the same. When lighter water vapor molecules replace heavier nitrogen and oxygen molecules, the overall weight of the tire is lighter! From this hopefully we can see that a chuck of moist air (containing lots of light water vapor molecules to replace heavier air molecules) is *lighter* than an equivalent chuck of dry air! **Moist air rises** - causing a low pressure area in the atmosphere.

So, can the Gas Laws also explain why warm air rises while cool air sinks? Yes!

Again, let's use the twin tire analogy from above with each tire containing the same gas. If the air in one tire is heated (ex., by putting it in the sun) either the pressure goes up or the tire volume increases (i.e., the tire walls expand like a balloon does when you blow air into it). What our equation tells us is that we must remove some of the molecules in the tire in order to keep the pressure and volume constant as the temperature increases.

Cool air, devoid of its lighter water molecules (precipitation) sinks as it now contains mostly heavier molecules, causing a high pressure area in the atmosphere. If we would put our second tire in the freezer, its pressure or volume will drop and we must add some molecules to maintain tire volume and pressure.

The Role of CO_2 and O_2 in Plant Growth



As noted in the table above, carbon dioxide (CO_2) is the heaviest of the main atmospheric gases. If left undisturbed (i.e., if the air is not mixed by fans or natural ventilation), CO_2 will settle at lower levels within a greenhouse, which will benefit plants growing in the ground or in raised beds. During photosynthesis, plants take in CO_2 through the stomata in their leaves and release an equal number of oxygen molecules as a byproduct ($6\ H_2O + 6\ CO_2 \rightarrow C_6H_{12}O_6 + 6\ O_2$). Depending on plant species and their life-cycle, the stomata also release 50-300 molecules of water per absorbed CO_2 molecule as a way to cool themselves, thereby raising the humidity of the air. If air is not circulated, CO_2 can settle near the ground while water vapor and oxygen accumulate at higher levels, disrupting the balance. Good air circulation and ventilation keep gases mixed, to provide optimal conditions for plant growth ensuring plants have access to sufficient CO_2 and preventing excessive oxygen and humidity to build up. The air vented out the top of a greenhouse during the day is usually warm, moist, oxygen-rich but carbon-dioxide poor air.

Plants, however, do need oxygen for respiration (primarily at night) to "digest" sugars produced during the day as a source of energy and as building blocks for cell and tissue growth (roots,

stems, leaves, flowers, seed/fruits, …), releasing CO_2 in the process. The "law of the minimum" tells us that plant growth is limited by the resource in shortest supply, whether CO_2, light, nutrients, temperature or water. Plant requirements for these elements change over the course of the growing season. A well-designed, built and managed PSG works in sync with nature allowing plant growth year-round, even though the amount of sunlight during the winter period may be the element in shortest supply given fewer hours of sun during the day. The 60^0-angle of the south-facing glazing maximizes solar gain on clear, sunny winter days to maximize solar heating of the SunCatcher even with ambient temperatures well below freezing. The angle of the north-facing roof and its white interior surface reflect much of the low winter sun onto the plants and thermal mass. The combination of glazing and roof angles allows interior light and temperature to reach optimal levels for photosynthesis for plants to absorb CO_2 for photosynthesis while releasing water vapor and oxygen. Ventilation may then be necessary to balance heat retention with CO_2 intake (even though our instinct tells us to keep windows closed in the winter in order not to lose heat).

The Importance of Ventilation and Air Circulation

Ventilation serves multiple purposes in a greenhouse:

- Prevents overheating during sunny days.
- Maintains a healthy balance of O_2 and CO_2. Too much oxygen, a byproduct of photosynthesis, can harm plants, while adequate CO_2 is critical for photosynthesis.
- Reduces excess moisture that may foster fungal diseases and insect pests (fungus gnats).
- Prevents the development of "microclimates" around plants by mixing the air so that all plants photosynthesize more evenly and efficiently.
- Encourages stronger plant growth by simulating natural breezes that reduce leggy-ness and promote sturdier stems.
- Minimize any cold or hot spots developing within the greenhouse.

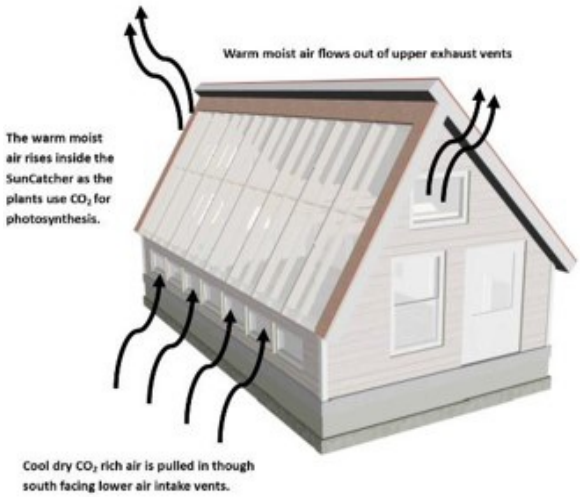
Conventional high tunnels use drop-down or roll-up side curtains for ventilation, while glass warehouses rely on roof windows. In both types, large exhaust fans in side and/or end walls pull in outside air while smaller "squirrel fans" circulate it inside. A PSG, however, is built to be insulated and sealed, and depends heavily on natural convection and air circulation through carefully designed vent placement.

Natural Ventilation in SunCatchers

SunCatcher PSGs primarily use natural convection, or the "chimney effect," to move air. Warm air rises and exits through high vents, while cooler, denser air is drawn in through lower vents. By opening or closing vents, the grower regulates how much air is exchanged.

Lower vents: The windows in the front south-facing knee wall serve not only to allow more light in but also to serve as air intake points for fresh CO_2-rich and dry outside air.
Upper vents: Awning windows above the east and west doors serve as exhaust outlets of warm, humid, oxigen-rich air. When opened together with lower vents, they create a steady, convective flow.

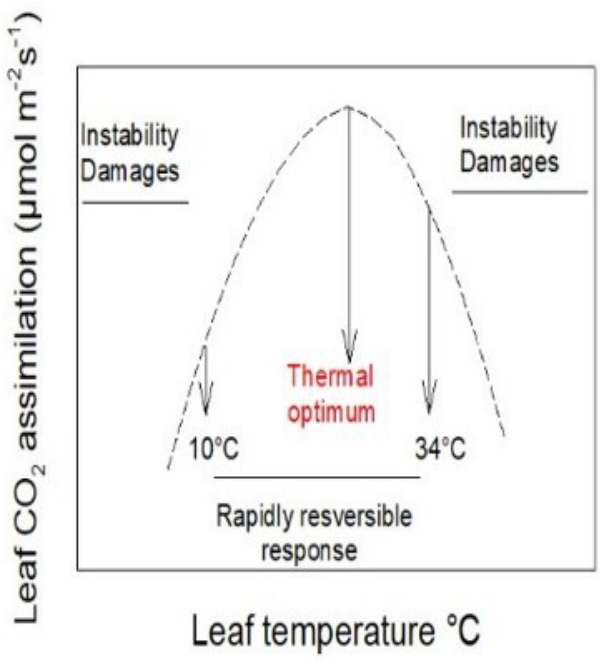
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On sunny days, vents are typically opened once the greenhouse warms to about 20°C (68°F). The extent of opening controls the air exchange rate. Ceiling fans can supplement convection, pulling warm air up and out or mixing cooler air down onto plants as needed.

On cloudy days, with less solar gain, less venting is required. Vents are generally closed before interior temperatures fall below 20°C to preserve heat. With experience, operators learn to use weather forecasts to anticipate when and how much venting will be needed.

Managing Interior Temperature



As shown in the diagram (left), optimum temperature for photosynthesis is around 77^0F (25^0C). Most crops do best with temperatures of 70-80^0F (21-27°C) during the day and 60-68°F (15-20°C) at night. Maintaining this day/night temperature differential is crucial for good plant development. For cool season crops (lettuce, spinach, cabbage family), the optimum day/night temperatures are 10^0F (5.5^0C) lower than those given above. In Summer, opening north vents can be helpful to lower night-time temperatures for best performance.



Partly sunny day with four lower inlet vents open and side exhaust vents open on both sides.



All vents closed at the end of a winter day.

North Wall Vents and Seasonal Adjustments

North wall vents are not critical to the design but can be very helpful for passively cooling the SunCatcher between late Spring and early Fall when outside nighttime temperatures are above the mid-40s. By leaving these vents open day and night, the thermal mass can release more heat stored during the day, giving the SunCatcher a cooler start the following day. To maintain good air flow, thermal mass barrels should be placed at least 20-30 cm (8-12 inches) apart directly in front of the north wall vents.

To retain warmth and capture CO_2 from plant respiration, a good closing temperature for north vents would be $5^0C/41^0F$ for cold-season crops, and $10^0C/50^0F$ for warm-season ones. A lower temperature through nighttime venting in Spring helps "harden" seedlings before transplanting them into the garden, getting them used to the variable conditions outside. In winter, all vents should be closed before sunset or earlier if interior temperatures fall below $20°C/68^0F$.



Managing CO_2 Levels

In conventional greenhouses, CO_2 levels often drop on sunny winter days when photosynthesis is rapid, but cold outside air discourages venting. Some growers use burners, boilers, or compost piles for CO_2 enrichment, but these can add cost, complexity, and excess humidity. SunCatchers

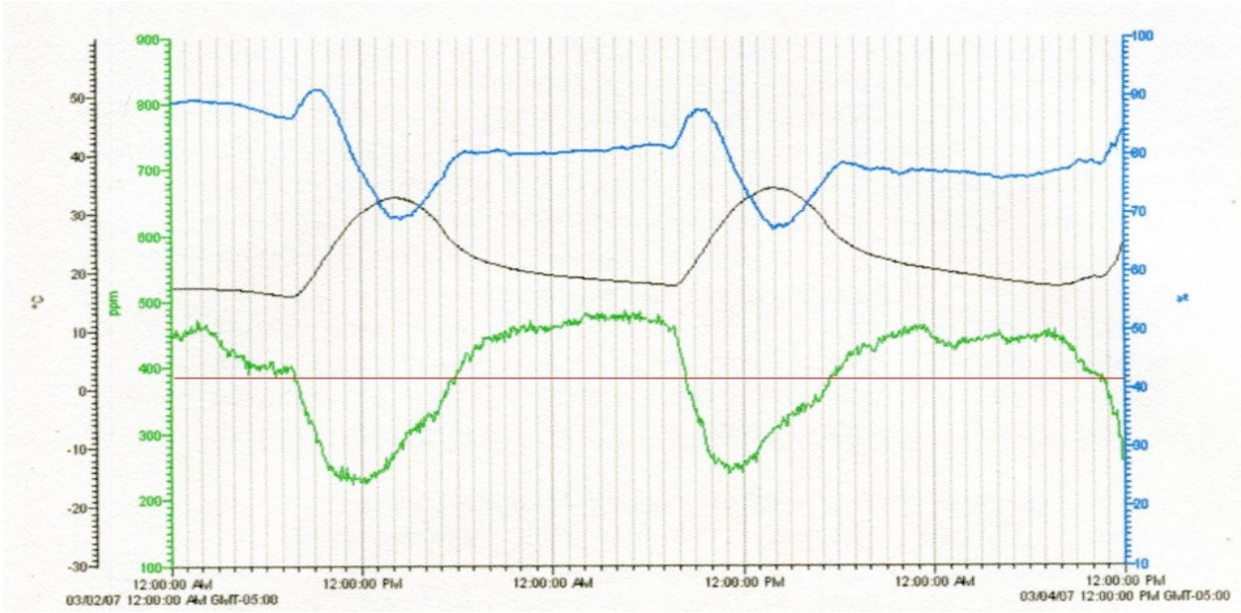


Figure X.1 Relationship between temperature (^{0}C, black line), relative humidity (%, blue line) and carbon dioxide (ppm, green line) for a two-day sample (March 2, 2007 12 AM through March 4, 2007 12PM) in the Parkway PSG. The red line indicates the global average CO_2 level (384 ppm) in 2007 (source: https://www.statista.com/statistics/1091926/atmospheric-concentration-of-co2-historic/).

avoid this by using their tight construction and a venting strategy based on 'banking' nighttime CO_2, ensuring plants begin the day with higher-than-ambient levels before fresh air is brought in.

CO_2-banking was a serendipitous discovery in the Parkway PSG during research by Duus (2007) as shown in Figure X.1. As the day warms and photosynthesis accelerates, vents can be opened to bring in fresh air and maintain balance between indoor temperature and CO_2 levels. This natural cycle makes CO_2 enrichment strategies, such as burning fuel or composting inside the greenhouse, unnecessary in most cases. SunCatchers recycle what plants produce, maintaining healthy levels without added cost or complexity.

Managing for Temperature or CO_2?

There is a delicate balance between maintaining proper CO_2 concentrations and adequate temperatures for plant growth within the greenhouse. During the day (during maximum photosynthesis), plants will generally use twice as much CO_2 than they give off from cellular metabolism. In many greenhouses, CO_2 levels can be depressed on a cold sunny day when lots of photosynthesis is going on, but the air outside is too cold to bring in fresh air. A popular way to compensate for this drop in greenhouse CO_2 levels is enrichment from combustion gases from small burners (oil, wood, gas) placed within the greenhouse, or from a central boiler used to heat the greenhouse in winter. Compost "cooked" or raising animals (rabbits, chickens) inside a greenhouse can produce extra CO_2 but also increase humidity levels (and odors!). These methods can be expensive, time consuming, and wasteful.

The SunCatcher's unique venting system coupled with the tightness of the construction allows the SunCatcher to capture and store the CO_2 plants respire at night when all vents are closed. This provides above ambient CO_2 at the start of photosynthesis the next morning. As the SunCatcher warms and the excess CO_2 is consumed by the plants, the vents can then be opened to release the excess humidity and heat building inside, while bringing in cooler, fresh CO_2-rich air from the outside. This venting procedure (when properly operated) provides excess CO_2 in the mornings until the vents are opened, and maintains ambient CO_2 level of inside the SunCatcher through the afternoon! Thus, SunCatcher PSGs can provide a low/no carbon energy structure that can grow plants in cold climates possibly faster than predicted times for normal growing conditions outside in the summer.

Fans and Mechanical Support

Although designed to work passively, SunCatchers can be enhanced with ceiling fans; properly placed, fans serve three roles:

1. Push warm air down onto plants on (very) cold nights or overcast days.
2. Pull warm air up and out on hot, sunny days.
3. Mix air within the greenhouse to prevent stratification of CO_2, O_2 and humidity levels, reducing fungal risks and strengthening plant stems.

In USDA zones 5 and warmer, builders may want to mount fans directly behind the two upper window vents to handle summer cooling, with their blades located between the bottom of the upper vent and the top of the door way on the east and west side of the greenhouse. The upper windows still have to seal tightly during cold weather. To help with good internal air circulation and air mixing (especially during the winter), one or more central fans can be hung from the ridge board with the blades 30 cm (1 ft) above the cross-ties (option 1) or hung from the cross-ies (option 2). Ideally, fans are controlled separately with bi-directional (up and down), variable speed switches for flexibility. Fans should be outdoor (waterproof) rated given the high humidity levels inside a greeenhouse.



East & West fans



Central fan option 1



Central fan option 2



Do not use louvered fans in the upper windows. A closed louver almost never seals tightly enough for cold weather PSG operation. Use awning windows with a fan mounted behind them: closed, the window forms a tight seal; open, the windows vent passively with the fan available if convection alone is not enough. See photo on the next page of the New Zealand SunCatcher with upper vent box fan in the upper vent.

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A Typical Day of Venting

On a clear winter day, venting may begin around 11:00 a.m. to release heat, humidity and oxygen and admit fresh, dryer air and CO_2. Lower intake vents are cracked open, followed by upper exhaust vents. As the day progresses, the number of vents opened and by how much can be adjusted to maintain a balance between temperature, humidity, oxygen and carbon-dioxide levels. By late afternoon, as photosynthesis slows, vents are closed to trap the CO_2 released overnight. This cycle ensures that each morning begins with CO_2-rich air and that plants can maximize growth during peak sunlight hours.

Enhancing Performance

Several strategies can further optimize SunCatcher ventilation and performance:

- Use light-colored (white or silver) shade cloth in spring and fall to reduce excess sunlight to keep the greenhouse cooler.
- During the winter months, cover glazing at night with insulating blankets to reduce radiative heat loss.
- Automate venting with low-voltage (12/24 VDC) window openers powered by solar panels or other renewable sources.
- Install 12/24V DC variable speed bi-directional fans for reliable air mixing.
- For greenhouses over 500 sq. ft., or in consistently warm regions, add insulated exhaust fans to help manage hot conditions.

Air management is one of the most subtle but essential aspects of PSG design. By working with natural convection, gas laws, and plant physiology, the SunCatcher creates a balanced internal environment without constant reliance on mechanical systems. When managed well, the greenhouse captures CO_2 at night, provides fresh air by day, regulates humidity, and protects plants from extremes. This thoughtful approach ensures that the SunCatcher not only conserves energy but also supports healthy, vigorous plant growth year-round.

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Further Reading

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