Solar tunnel food dryer

version 7/2014f (corrected the '11/2009e' Figure 11 description of wind speed and added summary notes demarcated by # #); original version 3/2008

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Summary
This solar food dryer design is a scale down version of the solar tunnel food dryer developed at Hohenheim University, Stuttgart, Germany (www. innotech-ing.de). Food product is exposed to direct sunlight (not shaded under a stack of trays in a cabinet) and has low resistance to airflow. The solar dryer tilt angle is horizontal and point in the direction of the prevailing wind to achieve a minimum of 10 ft/s (3 m/s). If there is no wind, then point the dryer south in the northern hemisphere (north in the southern hemisphere), tilted to achieve a minimum of 10 ft/s (3 m/s or 6.7 m/hr) airflow rate. Operate the solar dryer at less than 50% relative humidity. If the moisture exiting the dryer is greater than 50%RH, reduce the amount of products placed in the dryer.

The criteria for optimizing solar dryers in any climatic conditions are based on a crop evapotranspiration equation. Water evaporation from a solar food dryer, crop canopy, bare soil, lake surface, or animal skin (sweating) is driven by solar radiation, wind speed, relative humidity and air temperature. Meteorological conditions that maximize crop evapotranspiration or lake surface evaporation also maximize evaporation in a solar food dryer. An equation was developed to predict evaporation from a grass canopy, bare soil, lake or open tank of water by Penman (1) and modified by Monteith (2). By extension, the Penman-Monteith equation can be used to compare the relative evaporation potential of any solar food dryer by measuring solar radiation, wind speed, relative humidity and air temperature in the solar dryer at different tilt angles, airflow rate or size of inlet and exhaust openings. For normal operating conditions of a solar food dryer, the Penman-Monteith equation predicts the relative importance for water evaporation from a surface as follows: solar radiation > air temperature <=> wind speed <=> relative humidity.

- Solar radiation is the most important contributor to water evaporation in a solar dryer. You sweat a lot more standing in direct sunlight than in the shade. For the same reason, a sliced tomato will evaporate a lot faster in direct sunlight of a solar tunnel dryer than in the shaded compartment of a solar cabinet dryer.
- Air temperature is more important than wind speed in direct sunlight and in humid conditions. In humid conditions, design the solar dryer with a pre heater section to increase air temperature before the air passes over the product being dried.
- Wind speed is more important than air temperature at night or in shaded conditions with less than 70% relative humidity (temperate and arid climates). In hot dry conditions, you cool off in the wind or by turning on a fan to facilitate evaporative cooling; while humid conditions provide less evaporative cooling. For the same reason, a sliced tomato will evaporate more by increasing the wind speed; 10 ft/s (3 m/s) minimum.
- The general 'rule-of thumb': minimum wind speed in the solar dryer is 10 ft/s (3 m/s); operate the solar dryer with air exiting the dryer at less than 50% relative humidity.
- # This solar food dryer design maximizes the exposure of products to sunlight with unobstructed air flow to remove water vapor. It does not maximize air temperature

inside the solar dryer. Evaporation by solar radiation is more important than evaporation by air temperature, i.e. photons outperform molecular vibration. #

I. Solar food dryer design

The solar dryer dimensions are 4 ft wide x 16 ft long x 12 to 19 inches tall (1.2 m x 4.9 m x 0.3 to 0.48 m); constructed with materials readily available in US (Figures 1 to 4). The frame consists of two 4 x 8 ft plywood sheets on the bottom and 1 x 4 inch side boards (Figure 3). Hoops made of 9 gauge (3.8 mm) wires support a clear polyethylene film cover (Figures 2, 5 and 6). The peak height of the polyethylene cover is 8 to 16 inches (20 to 41 cm) above the drying trays. One edge of the polyethylene film is securely attached to the side of the frame while the other is attached to a 1 inch (25.4 mm) polyvinyl chloride (PVC) pipe. The PVC pipe allows easy removal of the cover and drying tray access (Figures 1 and 2). The bottom of the dryer is insulated with 3/4 inch (19 mm) thick foil faced insulation board (Figures 4 and 5). The entire solar dryer frame is supported on a swivel and tilt bracket (Figures 8 and 9), allowing the dryer to rotate and tilt for maximum sunlight exposure or point in the direction of the prevailing wind.

A smaller version of this dryer, 4 ft wide x 8 ft long x 10 inches tall (1.2 x 2.4 x 0.254 m) can be constructed using one 4 ft x 8 ft (1.2 x 2.4 m) plywood sheet and one 3/4 inch x 4 ft x 8 ft (0.019 x 1.2 x 2.4 m) insulation board (Figure 4).

Drying trays have knitted polypropylene shade cloth attached to the bottom of 3/4 x 1 1/8 inch (19 x 29 mm) wood frames (Figures 5 and 6). The drying tray is supported on tracks that raise the tray ~2 inches (51 mm) above the bottom insulation board. Trays are held in place by top braces (Figure 3) to prevent the trays from sliding. Air ducts convey heated air from the solar collector section to below the drying trays, allowing heated air to rise through the bottom of the polypropylene shade cloth (Figures 6 and 7).

For daylight conditions of 70-90F (21-32C), 15-50% relative humidity and a variable 0 to 10 mph (0 - 4.5 m/s) wind speed, the temperature inside the solar dryer ranged from 90-120F (32-49C) with a relative humidity between 15-30%. After 6 hours of drying, 40 pounds (18 kg) of fresh tomatoes were reduced to 22.5 pounds (10.2 kg), a 43% weight reduction. The partly dried tomatoes were used to make tomato sauce.

Figure 1. Solar tunnel dryer, 4 ft x 16 ft (1.2 x 4.9 m).

Figure 2. Solar tunnel dryer with tomatoes in drying trays.

Figure 3. Solar tunnel dryer frame, 4 ft x 16 ft (1.2 x 4.9 m).

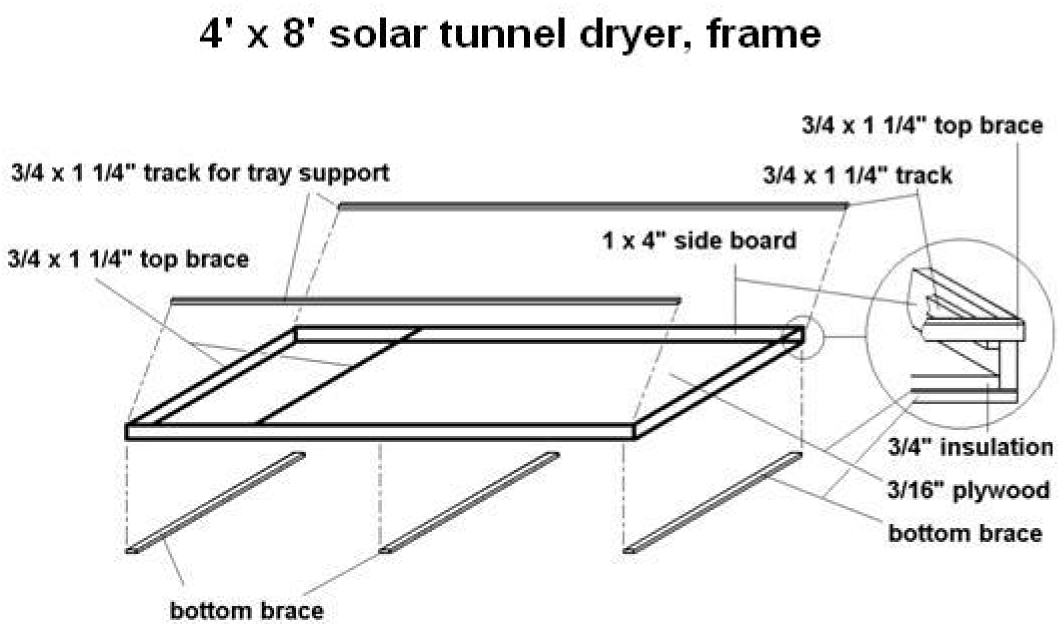

Figure 4. Solar tunnel dryer frame 4 ft x 8 ft (1.2 x 2.4 m), double length for 4 ft x 16 ft dryer.

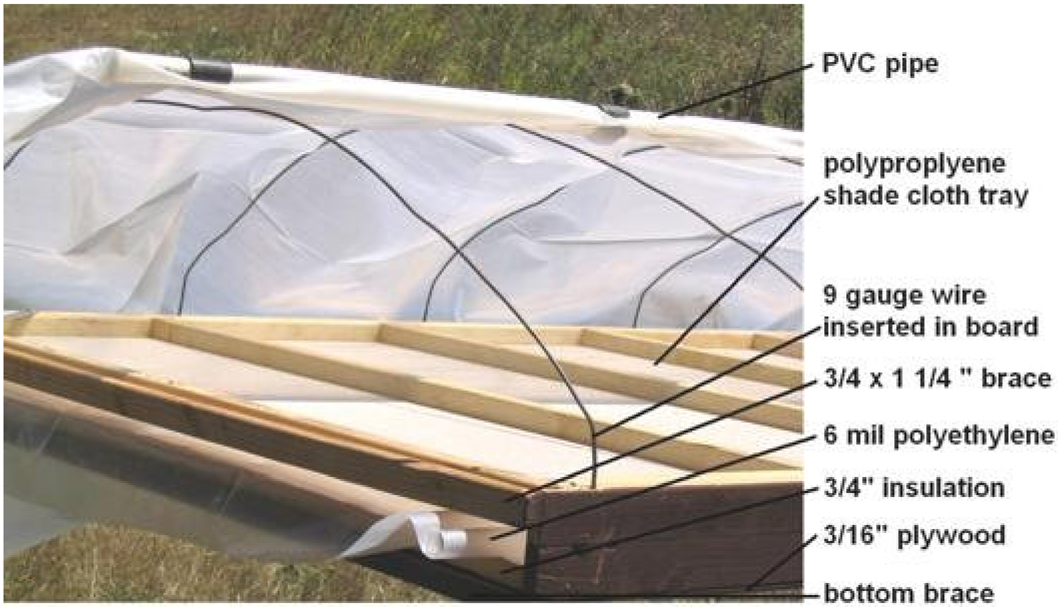

Figure 5. End view of solar tunnel dryer and drying trays. Peak height in this photo is 14 inches (33 cm) above the trays; the height was later reset to 10 inches (25 cm) above the trays.

Figure 6. Air ducts convey heat under drying trays.

Figure 7. Another view of the air ducts shown without drying trays

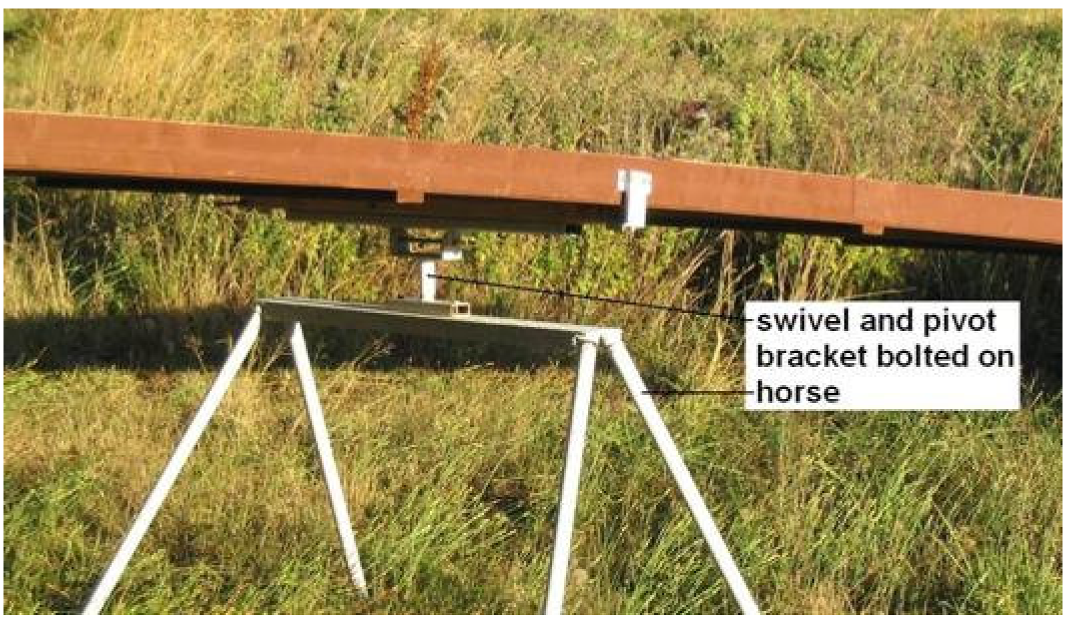

Figure 8. Solar tunnel dryer supported on swivel and pivot bracket.

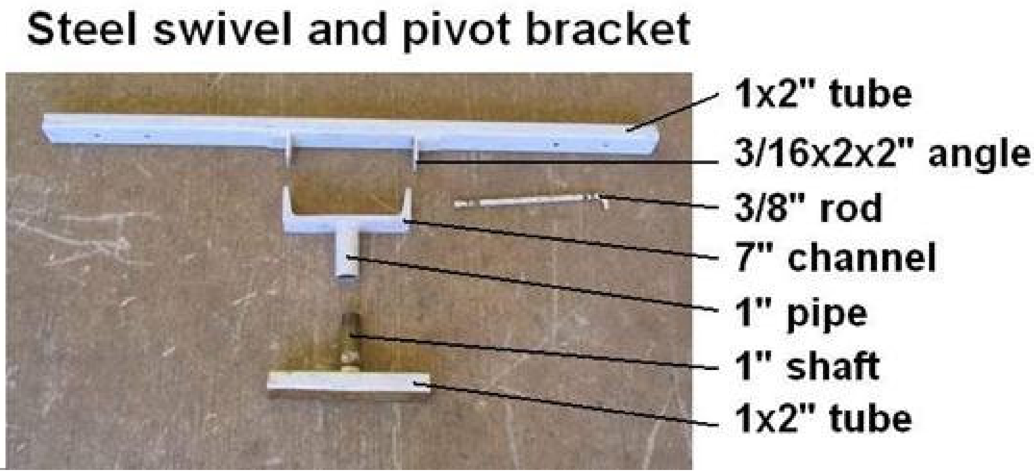

Figure 9. Welded swivel and pivot bracket for supporting the solar tunnel dryer.

List of materials for a 4 x 8 ft solar tunnel dryer; double the materials for a 4 x 16 ft dryer

- 7 pieces 1 x 4 inch x 8 ft length board (or cut four 2 x 4 inch x 8 ft lumber into eight 1 x 4 inch x 8 ft board) to make the following:

  (2) side boards
  (1) cut into 3 pieces ~1 1/4" x 8'; use 2 for tracks and 1 for making two top braces
  (1 1/2) cut into 3 pieces 1" x 4" x 4' length bottom brace
  (2 1/2) cut into 1 1/8" x 4' to make two 3 x 4 ft trays and one top brace

- 1 sheet 6 mil 6 x 8 ft clear polyethylene film, greenhouse film or suitable transparent film for the top of the solar tunnel dryer
- 1 sheet 6 mil 4 x 8 ft clear polyethylene film to cover the insulation board
- 1 sheet 4 x 6 ft (1.2 x 1.8 m) knitted polypropylene shade cloth for drying trays
- 1 sheet 3/4 inch x 4 x 8 ft (19 mm x 19 x 1.2 x 2.4 m) foil-faced rigid board insulation
- 1 sheet 3/16" x 4 x 8 ft (4.8 mm x 1.2 x 2.4 m) plywood
- 9 gauge (3.8mm) wire 25-35 ft (7.6 – 11 m), cut to ~5 ft (1.5 m) length for hoops to support polyethylene film 8-16 inch (0.20 -0.41 m) above the tray; hoop spacing is 16-24 inches (0.41 – 0.61 m) apart.
- 3 sheets of 24 gauge x 14 x 30 inch (0.53mm x 0.36 x 0.76 m) aluminum roof flashing, painted black for air ducts to convey heated air below the drying tray.

Fasteners

Steel to make a swivel and pivot bracket, see Figure 9 above

II. Solar dryer adjustments

- The ideal peak height of the polyethylene cover is site specific, affected by wind direction and wind speed. The peak height ranges between 8 to 16 inches (20-41 cm) above the drying trays; the length of the 9 gauge (3.8mm) wire hoops is 52 to 60 inches (132-152 cm). A solar tunnel dryer with taller peak height has a larger air volume to absorb water vapor but it takes longer to heat the larger volume of air. The taller peak height also has less wind resistance allowing faster airflow, but the path of airflow is higher above the drying trays with less mixing of moisture-laden air at the drying tray. A shallow peak height has a smaller volume to absorb water vapor but the smaller volume heats up faster and the airflow is directed closer to the drying tray to remove the moisture from the products.
- The tilt angle should be horizontal, and the solar dryer pointed in the direction of the prevailing wind if the prevailing wind speed is greater than 10 ft/s (3 m/s or 6.8 miles/hour). Otherwise, point the solar dryer south in the northern hemisphere (point north in the southern hemisphere) and tilt the dryer to achieve a minimum of 10 ft/s (3 m/s) airflow.
- The amount of products placed in the dryer depends on the ambient humidity. In low humidity conditions, the entire drying surface can be loaded with products. If the ambient humidity is high, partition the solar dryer into 2 sections. The front section serves as a pre heater to raise the air temperature before air passes over the drying products. Load products in the back section for drying.
- As drying progresses, the evaporation rate decreases. With less evaporative cooling, the product's internal temperature increases. Discoloration and formation of off-flavor may occur with high internal temperature toward the end of the drying period. Increase the airflow rate to lower the air temperature. Alternatively, move the partly dried product to the exhaust end of the dryer and place fresh product with greater moisture content near the inlet of the dryer. The fresh product provides evaporative cooling and lowers the air temperature before the air passes over the partly dried product at the exhaust end of the dryer. Commercial dehydrators use a similar parallel flow system where fresh product is placed at the inlet, and then moves progressively toward the exhaust end. The product moves in parallel with the direction of airflow.
- The minimum wind speed in the solar dryer is 10 ft/s (3 m/s), flowing through the immediate neighborhood of the drying product. This is based on the ASTM (3) recommended tip speed for a wet bulb thermometer on a sling psychrometer; 3 to10 m/s (9.8 -32.8 ft/s) whirled in the shade regardless of the ambient humidity. The wet bulb thermometer measures the heat gain (heat extracted from the air) minus the heat loss (through evaporative cooling) on the wet wick. As the tip speed of the wet bulb thermometer increases from 3 m/s to 10 m/s, the rate of heat extracted from the air increases and is equal to the rate of heat removed by water evaporation from the wet wick. Heat extraction and evaporative cooling are in equilibrium, water evaporation and heat extraction increase with increasing tip speed of the thermometer but the temperature on the wet bulb thermometer remains constant. However, below 3 m/s, the wet bulb thermometer has not reach equilibrium between heat extracted from the air and evaporative cooling. Below 3 m/s tip speed, water vapor in the immediate neighborhood surrounding the wet wick impedes water evaporation from the wick to the ambient air. Evaporation on a wet wick of a wet bulb thermometer is equivalent to evaporation on a 'nearly' wet leaf (100% relative humidity) or the wet surface of a sliced tomato. Thus, the minimum wind speed for

removing free surface water from wet products is the same as the minimum wet bulb thermometer tip speed, 3 m/s (9.8 ft/s). Below 3 m/s, the water vapor in the immediate neighborhood surrounding the sliced tomato suppresses water evaporation from the surface of the sliced tomato to the overlying air in the solar dryer.

- After removal of free surface water, the sliced tomato forms a dry skin and water diffusion across the skin become rate limiting. When the skin is at less than 100% relative humidity, it is no longer equivalent to the wet wick on the wet bulb thermometer. The minimum 3 m/s wind speed no longer applies when a dry skin forms over the sliced tomato; reduce the airflow rate to increase the temperature and contact time for heat to transfer from air to drying product.
- Case hardening can occur if the product with high soluble solids dries too fast. As drying occurs, the soluble solids migrate to the outer surface and form a hard skin. This hard skin acts as a barrier retarding interior water from reaching the outside surface and thus decreases the evaporation rate. If this occurs, slow the drying rate by adjusting the airflow rate to reduce the air temperature or by increasing the amount of products placed in the dryer.
- Drying rate is affected by size and shape of the product. Slicing and dicing exposes more surface area for evaporation, and may resolve the problem of case hardening.

III. Supplemental notes: Applying the Penman-Monteith evapotranspiration equation to solar food drying

Penman (1) developed an equation to calculate the evaporation potential from a grass canopy, bare soil, lake surface or open tank of water; the equation was modified by Monteith (2). The Penman-Monteith equation uses an energy budget method to calculate evaporation potential, with a solar radiation component (net energy input from solar radiation minus soil heat storage (Rn-G) multiplied by a weighting function) plus an aerodynamic component (heat extracted from the air as a function of wind speed, vapor pressure deficit and air temperature). Inputs for the Penman-Monteith equation includes net solar radiation, air temperature, wind speed, vapor pressure deficit, and leaf stomata resistance and bulk surface resistance to water vapor transfer to the ambient air. The FAO Penman-Monteith (4) version of the equation uses a hypothetical 12 cm (4.7 inches) tall adequately watered grass canopy as the standard reference crop for measuring evapotranspiration, ETo. Evaporation from bare soil, open pan of water, or different crop canopy surfaces is determined by applying suitable coefficients to the reference crop ETo (reference to 12 cm grass canopy).

The contribution of radiation, sensible and latent heat exchange and vapor pressure to evaporation are based on fundamental principles of physics. However, the wind function (surface resistance to vapor transfer from soil, leaf stomata, and leaf area; and aerodynamic resistance to vapor transfer from air turbulence and canopy roughness, i.e. very complex relationships) is based on empirical observation, not fundamental principles of physics; the wind function is the weak link in the Penman-Monteith equation.

Proposal:

- As a first approximation, use the ASTM (3) sling psychrometer criteria of 3 m/s as the minimum wind speed in the solar dryer. The wind function in both the ASTM sling psychrometer operation and the Penman-Monteith equation was empirically derived; both are backed by extensive experimental data for their respective application, but the data were not from solar food dryers. The ASTM wind function (3 m/s minimum) was selected for first approximation based on simplicity, not on its performance over the Penman Monteith equation. The 3 m/s criteria for the sling psychrometer is conservative, with built-in tolerance for operator error, ease of counting (1 whirl per second), repeatability, and a one-size-fits-all humidity condition. Less than 3 m/s is permissible but ASTM (3) did not provide raw data for assessing the 'less than 3 m/s' number.
- Use the Penman-Monteith equation for an overview of relative contribution by the 4 meteorological factors to evaporation: solar radiation, air temperature, vapor pressure and wind speed; and how changes in one parameter affect the evaporation potential of other parameters (discussion follows).
- Use ETo as a proxy for computing the relative evaporation potential in a solar food dryer at different settings or in different meteorological conditions. The solar dryer is optimized with settings that achieve the maximum ETo value inside the solar dryer (tilt angle, peak height, direction of air intake, size of air intake and exhaust). The computed ETo values are for relative comparisons, not the actual evaporation potentials in the solar dryer because basic criteria for using the equation are not met.

The FAO Penman-Monteith (4) version is used here because the equation was tested in diverse meteorological conditions and is applicable worldwide. Free software to calculate ETo is available, at http://biomet.ucdavis.edu. To use the FAO Penman-Monteith equation in optimizing the solar food dryer, first determine the ambient outside air temperature and relative humidity. Use a reasonable (Rn-G) value for the local area, for example 1.5 MJ/m2.hr. Convert relative humidity to vapor pressure and hold vapor pressure constant while computing ETo with increasing air temperature obtainable by the solar dryer; compute ETo at varying wind speed obtainable in the solar dryer, 3 m/s minimum. The parcel of air with the highest ETo value will have the highest evaporation potential; the parcel of air with the lowest ETo value will have the lowest evaporation potential. Adjust the solar food dryer settings to achieve maximum. ETo.

1. Figure 10 shows the plot of the ETo as a function of wind, humidity and temperature with adequate wind speed (3 m/s minimum). ETo (green triangles) is the potential to evaporate water from a 12 cm tall (4.7 inches) grass canopy, measured in mm of water evaporated per hour on a unit surface area. The radiation component (blue diamonds) is 'solar radiation minus soil heat flux' held constant, 'Rn-G' = 1.5 MJ/m2.hr, equivalent to clear sky condition and sun angle at 3 hours before or after solar noon. The aerodynamic component with varying wind speed (open red squares) is with 3, 5, 7 and 9 m/s (9.8 to 29.5 ft/s or 6.7 to 20.1 miles/hr) at constant 30C (86 F) temperature. Variations in air temperature (solid red squares) is 30, 40, 50, and 60C (86-140F) at constant 3 m/s (9.8 ft/s or 6.7 miles/hr) wind speed. The constant 3 m/s wind speed is the ASTM (3) recommended minimum tip speed for a sling psychrometer. Initial relative humidity conditions of 90%, 70%, 50%, 30% and 10% RH are at 30C temperature. The relative humidity values are converted to vapor pressure and the vapor pressures are held constant so that as air temperature increases the relative humidity decreases. The water holding capacity of a parcel of air increases with air temperature at constant vapor pressure.

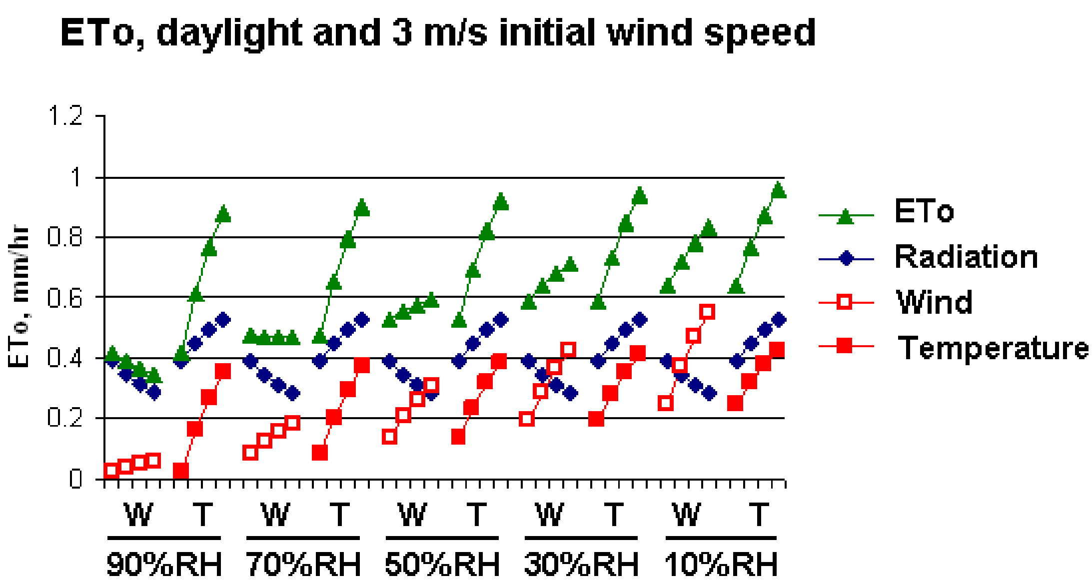

Figure 10. Contribution to evapotranspiration, ETo from radiation, wind and air temperature. ETo is measured in mm of water evaporated/hour from a unit surface area. Radiation input, (Rn-G) is held constant at 1.5 MJ/m2.hr, equivalent to clear sky at 3 hour before or after solar noon. Wind speeds are 3, 5, 7 and 9 m/s (6.7 to 20.1 miles/hr) at 30C (86 F). Air temperatures are 30, 40, 50, and 60C (86-140F) at 3 m/s (6.7 miles/hour). There are five sets of wind and temperature data,

corresponding to five vapor pressures equivalent to 90%, 70% 50%, 30% and 10%RH at 30C.

2. ETo (green triangles, in mm/hr) is greater with increasing air temperature (solid red triangle) than with increasing wind speed (open red triangles) in each of the 5 sets of relative humidity conditions (Figure 10), thus air temperature is more important than wind speed (using 3 m/s minimum wind speed). When examining the effect of increasing air temperature on ETo, the solar radiation component contributes more to ETo than air temperature (mm/hr of the blue diamonds are greater than the solid red squares). Thus, the order of contribution to evapotranspiration (ETo, green triangles) is solar radiation component ('Rn-G', blue diamonds) > air temperature (solid red squares) > wind speed (open red squares), when using a 3 m/s minimum wind speed. This is the main reason for using direct solar radiation in a solar tunnel food dryer; instead of indirect solar radiation in a cabinet solar food dryer with drying trays in a shaded compartment.
3. Increasing the air temperature (solid red squares) causes the radiation component (blue diamonds) to increase; slope of blue diamonds increase with increasing temperature. As air temperature increases, a higher fraction of the solar radiation component (Rn-G) goes to evaporation and less goes to heating the air.
4. Increasing wind speed (open red squares) causes the radiation component (blue diamonds) to decreases; slope of blue diamonds decrease with increasing wind speed (Figure 10). As wind speed increase while air temperature is held constant at 30C, a higher fraction of the solar radiation component (Rn-G) goes to sensible heat and less to evaporation. However, increasing wind speed also increases the transport of water vapor away from the system resulting in an increase in the aerodynamic component of ETo (Figure 10, slope of the open red squares increases with increasing wind speed). The crossover point where decreasing solar radiation component equals the increasing aerodynamic component is 69%RH at 30C. There is a net decrease in ETo with increasing wind speed at 30C, and 70% and 90% RH; the slope of the green triangle is negative for 70% and 90% RH. Whereas, there is a net increase in ETo with increasing wind speed at 30C and 10% to 50% RH; the slope of the green triangles is positive for 10% to 50%RH. As a general 'rule of thumb' operate a solar food below 50%RH, in the positive-slope-territory of ETo. The '50%RH' number is conservative, allowing for changes in ambient conditions and for conditions other than those used in Figure 10, which computed a crossover point at 69%RH. For humid climates, use the front part of the solar dryer to increase the air temperature and decrease the RH to <50%RH before passing the air over product to be dried at the back end of the dryer (no products in the front part of the solar dryer)
5. In temperate and arid conditions, high wind speed can contribute more to evaporation than solar radiation at (Rn-G) =1.5 MJ/m2.hr. In Figure 10, the open red square line intersects the blue diamond line at 8.5 m/s (18.9 miles/hr) for 50%RH at 30C conditions; at 6 m/s (13.5 miles/hr) wind speed for 30%RH at 30C; and at 4.7 m/s (10.5 mph) for 10%RH at 30C.
6. If the ASTM (3) recommended sling psychrometer tip speed of 3 m/s is not achieved, then wind speed can be more important than air temperature at low humidity (Figure 11) and when 'Rn-G' =0 ('night', or 'shaded condition'; actually, nighttime is typically negative with heat radiating out into space, and shaded condition is typically positive with scattered and infra red radiation input).

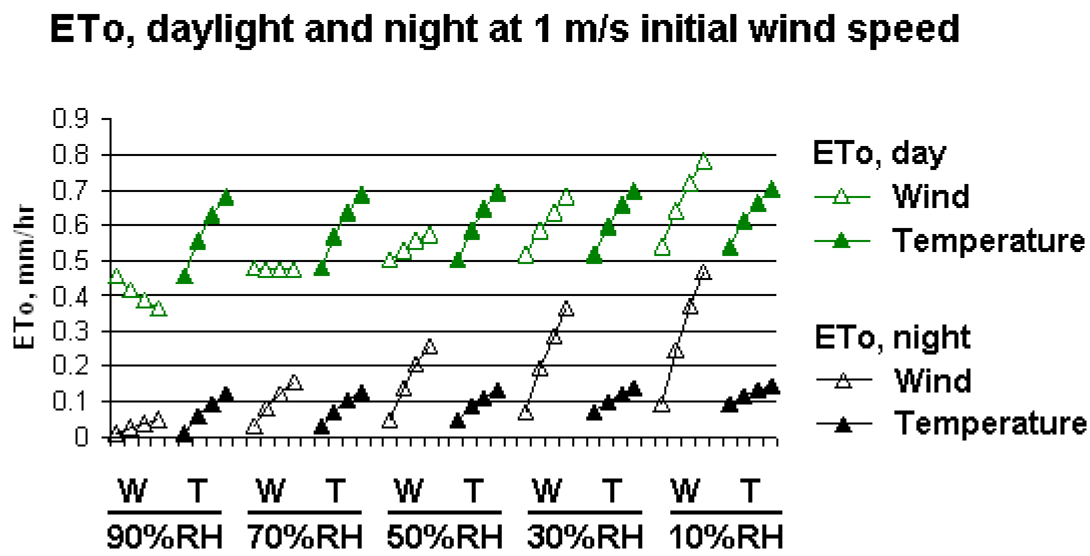

Figure 11. Effect of low (inadequate) airflow rate on evapotranspiration (ETo). Wind speeds are 1, 3, 5, and 7 m/s (2.2 to 15.6 miles/hr) with constant 30C (86F). Air temperatures are 30, 40, 50, and 60C (86 to 140F) with constant 1 m/s (2.2 miles/hr). There are five sets of wind and temperature data, corresponding to five vapor pressures equivalent to 90%, 70% 50%, 30% and 10%RH at 30C.

7. The advantage of increasing air temperature over wind speed with adequate wind (Figure 10) is diminished in low wind conditions (Figure 11). For daylight (Rn-G =1.5 MJ/m2.hr), 30% to 90%RH and 1 m/s initial wind speed, increasing air temperature contributes more to evapotranspiration than increasing wind speed (Figure 11, mm/hr of solid green triangles are greater than the mm/hr of open green triangles). At 10%RH, increasing wind speed contributes more to evapotranspiration than increasing air temperature.
8. For conditions with 'Rn-G' =0 ('night' or 'shaded'), 10% to 70%RH and low wind (1 m/s initial wind speed), increasing wind speed contributes more to evapotranspiration than increasing air temperature (Figure 11, mm/hr of open black triangles are greater than solid black triangles). This is the opposite of daylight exposure and adequate wind. Increase the wind speed to a minimum of 3 m/s even if it lowers the air temperature in the dryer
9. In the above discussion, 3 of the meteorological parameters were held constant as 1 of the parameter varied. A more complex situation is where 2 of the meteorological parameters are held constant and 2 parameters varied. For example, in daylight (Rn-G) =1.5 MJ/m2.hr and 30% RH, the decreasing order of ETo is 30C, 7m/s (0.68 mm/hr) > 40C, 2 m/s (0.64 mm/hr) > 50C, 1 m/s (0.63 mm/hr) > 60C, 0.5 m/s (0.62 mm/hr). An even more complex situation is where 3 of the parameters are allowed to vary. For example, with daylight (Rn-G) =1.5MJ/m2.hr, the decreasing order of ETo is 30C, 30%RH, 7 m/s wind (0.68 mm/hr) > 40C, 40%RH, 3.5 m/s wind (0.67 mm/hr) >50C, 50%RH, 2 m/s wind (0.65 mm/hr) > 60C, 60%RH, 1.0 m/s wind (0.62

mm/hr). These are not typical environmental conditions because as temperature increases, the RH should decrease. However, these conditions can occur inside a solar dryer with inadequate airflow to remove water vapor from the dryer.

10. It should be noted that comparisons made in Figure 10 and 11 assume the ease and ability to change the wind speed from 3 m/s to 9 m/s are equal to the ease and ability to change air temperature from 30C to 60C. The ease and ability to shift air temperature and wind speed are site specific, use the Penman-Monteith equation for site specific conditions.
11. Limitations on using the Penman Monteith equation to analyze solar dryers
    - ETo is a potential measurement, it provides no information on how long it takes to saturate the parcel of air inside the solar dryer or how long it takes to dry a tray of tomatoes. This is similar to a tank of water with an evaporation potential of 1 mm/hr; there is no information on how much water is in the tank or how long evaporation will occur before the tank empties.
    - The Penman Monteith equation assumes an extensive boundary layer, horizontally, and there is no advection, the horizontal flow for air with significantly different temperature and humidity conditions. These criteria are not met in a solar food dryer; the polyethylene film and bottom board are abrupt boundaries resulting in advection. # The restricting boundaries cause humidity to builds up quickly inside the solar dryer. Use a humidity sensor at the exhaust end of the solar dryer, and operate the dryer below 50% relative humidity. #
    - #The wind function is the weak link in the Penman Monteith equation, and when applied to a solar food dryer, it will underestimate the importance of wind speed due to the boundary layers and advection into the solar dryer. Operate the solar dryer at 3 m/s wind speed minimum as suggested by ASTM for operating a sling psychrometer. #
    - Air temperature is measured at 2 ft above the canopy layer; criteria not met inside the solar food dryer.
    - The relative humidity at the canopy surface of adequately watered grass is 100%; equivalent to freshly sliced tomato with tomato juice on the surface, but the criteria is not met when the sliced tomato forms a dry skin with <100% RH.

IV. References

1. Monteith, JL (1973). Principles of Environmental Physics, Chapter 11, Partitioning of heat (ii) Wet Systems. Edward Arnold, London (pp 171-189)

2. Penman, HL 1948: Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society. A, 193, 120-45.

3. ASTM (2005). Standard Test Method for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures). Annual Book of ASTM Standards, Section 11 Volume 11.03 designation E337-02. American Society for Testing and Materials, International, West Conshohocken, PA. (pp 1226-1249).

4. Allen, RG, LS Pereira, D Raes, M Smith 1998. Crop evapotranspiration, guideline for computing crop water requirement. FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization, UN, Rome, Italy. http://www.kimberly.uidaho.edu/water/fao56

The FAO Penman-Monteith version of the Penman equation is:

ETo = [0.408*delta*(Rn-G) + gamma*f(u)*(e'-e)]/(delta+gamma*(1+0.34U) , where

- ETo = 0.12 m tall reference crop (grass) evapotranspiration, in mm of water/day
- 0.408 converts MJ/m2.day to mm of water/day
- delta = change in saturated vapor pressure (e') with temperature.
- gamma = psychrometric constant.
- Rn = net solar radiation, in MJ /m2.day.
- G = soil heat flux, sensible heat going into the soil, in MJ/m2.day
- f(u) = wind related function ([900/(T+273)]*U) where U= average wind speed (m/s) during the day, measured at 2 m elevation and temperature T (C) also measured at 2 m elevation. The coefficient for this wind function is for a reference grass canopy 0.12 m height, a surface resistance of 70 s/m, albedo of 0.23 and aerodynamic resistance of 208 s/m. The '900' incorporates seconds per day, the gas constant, and molecular weight ratio of water to air. For hourly calculation, replace '900' with '37' (=900/24).
- (e'-e) = vapor pressure deficit (kPa), difference between e' the saturated vapor pressure at air temperature and e the saturated vapor pressure at dew point temperature, both measured at 2 m elevation .

Parenthetically, another commonly used evaporation equation is the 'Dalton mass transfer equation' (Satori, 2000): E = (a + b*v) (e' - e), where E is the evaporation rate; v is wind speed, (e' - e) is the vapor pressure deficit and a, b are empirical coefficients. Specifically, the Carrier (1921) version of the Dalton equation W = 0.093(1 + v/230) (e'-e) have been used in food dehydration literatures (Cruess, 1958; Desrosier 1963); W = pounds of water evaporated, v = wind speed in ft/min, and e' and e = vapor pressure in inches of mercury. It should be noted that e' is the saturated vapor pressure at the surface water and at the surface water temperature. For a sliced tomato in a solar food dryer, e' is measured at the surface water temperature of the tomato juice on the sliced tomato. The surface water temperature includes evaporative cooling and solar radiation received at the surface. There is no solar radiation component in the Dalton equation. Whereas, the Penman-Monteith equation has a solar radiation component, and uses air temperature, not the surface water temperature. In a solar food dryer, air temperature is easier to measure than the surface water temperature (of the tomato juice on the sliced tomato).

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