Energy Balance of Apples Under Evaporative Cooling

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ABSTRACT: Sunburn (or sun scald) of fruit surfaces exposed to direct sun is a major economic problem of fresh apples and other important horticultural crops. There is a critical need to maximize evaporative efficiency and avoid excessive water use. A process-based energy balance model has been developed and compared with field data for apple skin temperatures during evaporative cooling to reduce sunburn on apples in the Pacific Northwest. The model worked well although it tended to slightly over-predict during times with high advective heat energy. Automated control of evaporative cooling by cycling based on fruit core temperatures worked well in a controlled test stand and minimized total water use. Model results support the management of overtree evaporative cooling systems based on pulsing water applications at sufficiently high rates so that sufficient free water evaporating from the fruit surface will maintain core temperatures of exposed fruit in the 30° to 32°C range. Results indicated that the model could potentially be used with sensor (e.g., thermocouples) feedback for the initiation, management and control of overtree evaporative cooling systems to reduce sunburn and conserve water.

Keywords: Evaporation, irrigation systems, sprinklers, orchards

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INTRODUCTION

Sunburn (discoloration or burning of fruit surfaces exposed to direct sun) can discolor the skin and negatively affect the appearance of several important crops including fresh apples, pears, grapes and other fruits as well as vegetables, such as peppers and tomatoes. This paper has focused on sunburn on apples since it is a serious economic problem in many fruit growing areas in the Pacific Northwest of the USA and around the world. The surface blemished fruit cannot be sold for fresh market consumption which receives the highest prices.

Many orchardists are utilizing overtree evaporative cooling to control temperature of exposed fruit by the use of sprinklers applying water over the tree during the warmest times of the day to minimize sunburn (also called sun scald). As this applied water evaporates, it directly cools the leaves, fruit and the orchard air depending on local climatic conditions and the rate water is applied. The avoidance of excessive leaf and fruit temperatures during the hottest part of the day can greatly reduce the incidence of sunburn. Use of evaporative cooling just prior to and for about an hour after sundown and sometimes around sunrise has also been found to improve color development on red and red-striped apples (especially early varieties) prior to harvest.

In some areas, orchardists may be using evaporative cooling for 35-75 days or more per season. Consequently, evaporative cooling activities potentially impact several major areas of total orchard management including pest and disease control, fruit maturity, fruit storage characteristics, fruit color development, seasonal irrigation water requirements, and irrigation scheduling. In addition, expensive investments in water treatment facilities in the orchards and packing sheds due to poor water quality (primarily calcium carbonates) are often necessary to remove surface deposits on fruit. Scientifically-based irrigation scheduling programs with actual measurements of soil and or plant parameters are mandated when these evaporative cooling systems are used since they will somewhat suppress transpiration. In addition, evaporative cooling is a very inefficient use of water (e.g., amount of water applied per total amount needed by plant) since most of the water is lost by intent. Evaporative cooling requires large amounts of water and water conservation and minimizing water logging of soils is critical in both arid and humid areas. All of these factors cause increases in system installation and operating costs which must be recovered through higher prices from improved fruit grade.

However, orchardists are experiencing several problems with evaporative cooling as a result of one or a combination of the following: a) existing irrigation systems are used which were not designed to meet the higher hydraulic and operational requirements of evaporative cooling; b) there is an inadequate supply of water for both irrigation and cooling, evaporative cooling water application rates are too low and soils may become too dry; c) water applications cannot be cycled to maximize evaporative efficiency and avoid excessive water use; and d) poor water quality causing deposits on fruit and/or leaf burn from salt accumulations. This paper reports on research addressing the third issue.

Almost all apples can sunburn regardless of fruit color. Some red varieties of apple may color over burned areas so the damage may not be visually evident, but these apples often have storage problems due to the internal damage. The physiological mechanisms and causes of sunburn are not well understood and much work remains to be done by plant physiologists on this subject. Data on the threshold conditions where burn begins to occur are not available for any variety, however, it is well known that there are big differences between varieties in their susceptibility to sunburn. Some of the more sunburn susceptible apple varieties are ‘hJonagold’, ‘Braeburn’, ‘Golden Supreme’, ‘Ginger Gold’ and ‘Fuji’.

Limited past research on evaporative cooling of apples has been associated only with improving red color development ranging from about 3.9 L s^{-1} ha^{-1} continuous applications to around 10.9 L s^{-1} ha^{-1} pulsed on 15 minute cycles (Unrath, 1972a, 1972b; Unrath and Sneed, 1974; Griffin, 1974). These studies were all successful at improving red color development on 'Red Delicious' apples.

Evans et al. (1995) found that applications at about 6.25 L s^{-1} ha^{-1} were sufficient to hold core temperatures close to the selected temperature range during a 40°C day under sunny conditions. They also found that evaporative cooling systems should pulse water applications on and off so that water is continually evaporating, hydro-cooling is minimized, and water is conserved.

Surprisingly, there are very few data on the design, management and operation of overtree evaporative cooling systems for sunburn reduction. Little information exists on critical plant tissue temperatures for initiation of evaporative cooling although work by Unrath (1972a, 1972b) on apples, Chesness and Braud (1970) on strawberries, and Gilbert et al. (1971) on grapes suggest that temperature ranges of 30-32.2°C may be appropriate for temperate zone crops. Available information shows that starting evaporative cooling based on air temperatures is a very poor procedure (Middleton and Proebsting, 1971; Thorpe, 1974; Parchomchuk, 1991). Our data (not presented) showed that the side of nonsprinkled fruit directly exposed to the sun (where scald occurs) can warm much more quickly (e.g., 10°C to 14°C warmer) and cool off more slowly than shaded fruit and/or ambient air temperatures.

Available information on the design, management and operation of overtree evaporative cooling systems for sunburn reduction is mostly anecdotal experiences by innovative orchardists who are experimenting under the low-humidity and hot summer temperatures typical of many

USA Pacific Northwest fruit growing districts. Satisfactory criteria for evaluating these experiences and concerns, as well as the long-term horticultural impacts of evaporative cooling techniques, are not presently available. Consequently, a research project was initiated by Washington State University and the Washington State Tree Fruit Research Commission to develop knowledge on design and operation of evaporative cooling systems for apples where the primary emphasis is on reducing the temperature of exposed fruit tissue (skin) to reduce sunburn.

This ongoing research effort has shown that the most appropriate control of evaporative cooling is based on direct measurement of exposed fruit temperatures. However, suitable, high capacity commercially available controllers to accomplish this are not available, and growers are not interested in building and maintaining their own control systems. Consequently, orchardists are most interested in control systems based on easily measured climatic variables, but skin temperatures are not linearly related to air temperatures or any other single environmental parameter. Thus, since skin temperature is related to several variables, one approach would be the development of a simple physical model to predict skin temperatures of fruit exposed to direct sun during cooling, and then use the results to propose management criteria for effective, efficient evaporative cooling.

The objectives of this research were to develop a simple, climatological process-based energy balance model to predict fruit skin temperatures of individual, exposed uncooled apples under overtree sprinkling and required water application rates for evaporative cooling under various conditions to minimize sunburn. Model results are compared with field data collected under controlled conditions.

MATERIALS AND METHODS

In order to help validate the simple energy balance model, a special test stand was constructed at the Washington State University Irrigated Agriculture Research and Extension Center near Prosser, WA (latitude :46.2°N; longitude: 119.7° W; elevation: 257 m.) to monitor skin and interior or core temperatures of two cooled and two uncooled ‘Fuji’ apples. The test stand provided conditions where shading by other trees and branches was not a problem throughout the daylight hours and variables could be more precisely measured. It was erected adjacent to a complete agricultural weather station where electrical power and pressurized water were available. Fruit was suspended from a support arm (towards the south to avoid shading by the support) so that one hemisphere would always be fully exposed to the sun throughout the day (worst case). This was done since sunburn damage typically occurs on the upper, south facing quadrant of the fruit surface in the Pacific Northwest. All four apples were replaced every week using sun exposed fruit picked from trees in a nearby orchard so that size and color would closely follow fruit development in an orchard. It was assumed that small differences in heat transfer due to mass fluid flow through the tree to the apple (which mostly occurs at night) or from the the fruit to the tree was negligible and could be neglected for the picked test apples.

Field data collected in commercial orchards were also collected but not used in this stage of model comparisons. Data on the size and mass of the test fruit were also collected. Values of the various parameters used in the modeling process are listed in Table 1 (it should be noted that even though some values change slightly with temperature and humidity, the variation from 30°C levels are small in the ranges used and outside the sensitivity of the model).

Thermocouples (K type, 22 ga.) were inserted into the apples to measure skin and core (interior) temperatures. The “skin” thermocouples were inserted from the back or non-sun exposed side of the apple until it was just under the skin on the exposed side of the fruit. Infrared thermocouple sensors (Exergen, IRt/c.5) were also used to monitor average skin temperatures (data not presented) on the sun exposed surface, and although more variable, their averages closely followed the readings of the regular "skin" thermocouples.

The goal of this set of experiments was to maintain exposed skin temperatures at an maximum arbitrary value of 38°C or less using direct evaporative cooling of water from the fruit surface (measured with infrared thermocouple sensors). This value was chosen because adequate physiologically-based threshold temperatures where surface tissues are damaged by sunburn were not available. This was a conservative criterion, and sunburn of the test fruit was not observed under these conditions.

However, for this experiment, sprays were initiated based on core temperatures (near center interior) since surface (skin) temperatures are much more variable, and are therefore more difficult for a grower to implement. Water applications were pulsed on for about 30 seconds when core temperatures of 33°C were measured and turned off at 32°C, in order to keep the exposed skin temperature near the 38°C value. These values were based on several years of field data measuring the thermal gradient between exposed skin and the center of the fruit.

Thus, once the core temperature of the apple reached 33°C, a fine spray of water was applied directly to the fruit surface by small spray nozzles about 15cm away until the core temperature dropped one degree to 32°C. These sprays seldom lasted more than a few minutes, but could be on almost continuously during the warmest periods of the hottest days. The sprays were pulsed (equivalent to 6.25 L s^{-1} ha^{-1}) to reduce runoff and keep the fruit surface wet most of the time .The applied water temperatures (at nozzle) were typically around 12°C during these experiments, but rapidly cooled towards wet bulb temperatures by evaporation during the spray process.

Table 1. Identification of symbols and other related values of interest (T_a is about 30°C).

Definition	Symbol	Value	Units	Reference
Thermal Conductivity of Green Apples	k_f	0.422	W/m°C	Sweat, 1974
Thermal Conductivity of Red Apples	k_f	0.513	W/m°C	Sweat, 1974
Specific heat of apples	C_f	3660	J/kg°C	Sweat, 1974
Emissivity of apples	ϵ_f	0.97	--	(estimated)
Density of Red apples	ρ_f	850	kg/m^3	Sweat, 1974
Density of Green apples	ρ_f	790	kg/m^3	Sweat, 1974
Radiative Resistance	r_r	~185	s/m	Campbell, 1977
Apple Surface Cond.	h_c	≈32	W/m^2°C	Thorpe, 1974
Heat transfer coeff. for radiation (apples)	h_r	5	W/m^2°C	Thorpe, 1974
Heat transfer coeff. for wet apples	h_w	≈80	W/m^2°C	Hamer, 1986
Stephan-Boltzmann constant	σ	5.67E-08	W/m^2°K^4	Campbell, 1977
Density of dry air at T_a	ρ_a	1.1352	kg/m^3	Campbell, 1977
Specific heat of water	C_w	4185.5	J/kg°C	Campbell, 1977
Specific heat of air	C_p	1010	J/kg°C	Campbell, 1977
Atm. Pressure, sea level	P_o	101.3	kPa	Campbell, 1977
Atm. Pressure at site	P	99.53	kPa	(estimated)
Emissivity, soil surface	ϵ_g	0.97	--	Campbell, 1993
Atm. Transmission Coeff.	a	0.70	--	Campbell, 1977
Slope, Sat. Vapor Curve	Δ	2.16	g/m^3°C	Campbell, 1977
Psychometric Constant	γ	0.6653	kPa/°C	Campbell, 1977
Latent heat of vaporization at T_a	λ λ	2480 191.4	J/g W s/m^3	Campbell, 1977
Short wave absorptivity	a_S	0.40	--	Campbell, 1977
Long wave absorptivity	a_L	0.95	--	Campbell, 1977

The cooling on-off criteria were based on observations that once the core temperature started decreasing, the skin temperature had dropped to at least 32°C, there was sufficient liquid water evaporating on the fruit surface to continue cooling and additional spraying was not needed. Applied water volumes could be conserved since evaporative cooling is, by design and intent, very inefficient from a crop water requirement standpoint.

A Campbell Scientific CR10X datalogger was used to collect the data and to initiate water spray events. Tests were conducted from early August through the harvest period in late September. Supporting climatic data (e.g., air temperature, humidity, solar radiation, wind speed) were also monitored using the adjacent Washington Public Agricultural Weather System station (PAWS: http://www.paws.prosser.wsu.edu/).

Observation indicates that sunburn is a progressive phenomenon and accumulates over time. Some varieties appear to become more susceptible as they begin to approach maturity. Darker (e.g., more red colored) fruit also tend to absorb heat faster than green fruit which may contribute to the increase in varietal sensitivity to sunburn as season progresses. There is no question that the albedo changes as the fruit darkens and more heat is absorbed causing higher temperatures in the fruit. Since the fruit is also increasing in size during this period, there is an increase in thermal mass as the season progresses and the fruit does not cool as quickly.

THEORETICAL CONSIDERATIONS

For sunburn protection, it is desirable to reduce fruit surface temperatures during the warmest parts of the day. To cool fruit, all sources of incoming heat energy "loads" that cause the exposed fruits' temperatures to rise must be countered. If the amount of heat extracted is greater than the total incoming heat energy, the temperature of the fruit will decrease. If the amount of heat extracted is less than the incoming energy, fruit temperature will increase. The heat "load" on fruit that is exposed to the sun has two principal components: 1) direct radiative heating from the sun; and, 2) advective heating from hot air originating from outside the block moving through the orchard.

There are basically three ways of using water to reduce crop temperatures. In order of increasing effectiveness, these are:

1.) evaporate water in air (undertree or overtree) and use the circulation (convection) of the cooled air to reduce fruit temperatures (convective cooling);
2.) apply water to the leaves and fruit, using the "cool" water to extract the sensible heat from the plant organs and carry it away via liquid "runoff" (hydro-cooling);
3.) apply water to the leaves and fruit and directly extract heat by sensible to latent heat transfer (evaporative cooling).

All water-based orchard cooling techniques will use one or more of these mechanisms, and their relative contribution will depend on climatic conditions, water application rates, application uniformity, and system operation. It can be shown that the most effective of these cooling modes will be evaporation of water from the fruit surface followed by removal of the water vapor by mass air movement (Merva and van der Brink, 1979; Barfield et al., 1974; Barfield et al., 1990; Chesness, et al., 1979; Hamer, 1986). The most effective fruit temperature reductions occur when the water directly evaporates from the surface of the fruit. Evaporation of water requires large amounts of heat (2.43 MJ/kg of water @ 30°C), and the heat for evaporation will come directly from solar radiation and/or any other heat source that is in contact with the evaporating water including air and vegetation. The interrelationship of these mechanisms can be shown through both the mass and energy balance equations.

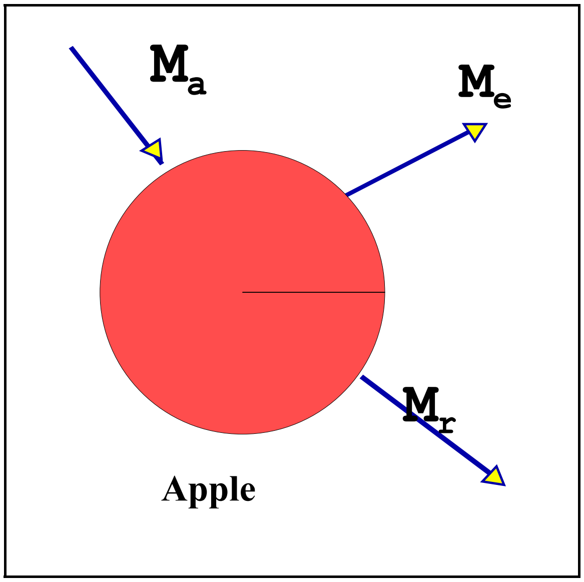

Figure 1. Diagram of the conservation of mass used for model development. M_a is the mass of water applied, M_r is the mass of water that runs off and M_e is the mass of evaporated water.

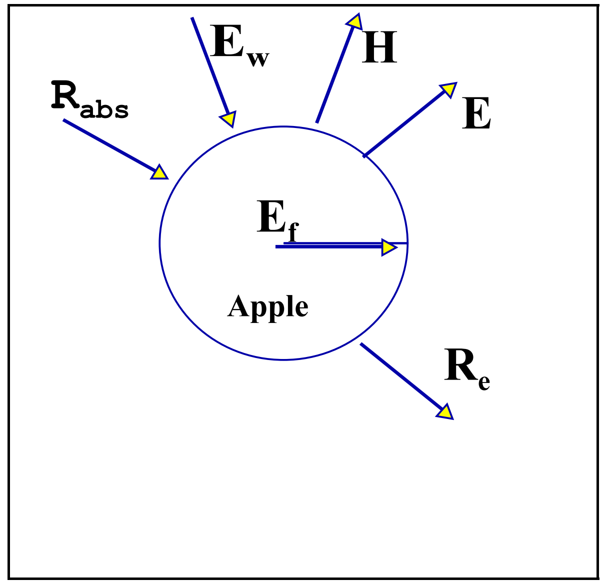

Figure 2. Heat energy balance diagram for the evaporative cooling model. R_{abs} is the total incoming radiation; R_e is the sensible emitted radiation of the fruit; E_w is the sensible heat supplied by the applied water; H is the sensible heat flux from the fruit; λE is the sensible to latent heat transfer by evaporation, and E_f is the sensible heat flux within the fruit.

Using a simple control volume approach where the fruit surface is the outer boundary and the fruit is assumed to be spherical, the mass balance equation from Figure 1 is:

$$I\frac{dM_a}{dt} - \frac{dM_e}{dt} - \frac{dM_r}{dt} = 0 \qquad \textbf{(1)}$$

where I is a dimensionless interception-efficiency factor ranging from about 0.6 at high application rates to about 0.2 at low water applications (Businger, 1965); M_a is the mass of water applied by the sprinkler; t is time (seconds); M_e is the total mass of evaporating water (taking latent heat) from the fruit surface; and, M_r is the mass of water that runs off (or drips off) the fruit. The mass of water retention/storage (not evaporated) on the fruit surface is considered negligible with respect to the other components

The heat energy balance equation from Figure 2 is:

$$E_f = (R_{abs} - R_e) + E_w - H - \lambda E = \rho_a C_p \frac{dT}{dt} \qquad \textbf{(2)}$$

where R_{abs} is the total incoming radiation (W/m^2); R_e is the emitted radiation (sensible) by the fruit (W/m^2); E_w is the sensible heat supplied by the applied water (W/m^2); H is the sensible heat flux from the fruit (W/m^2); λE is the sensible to latent heat transfer by evaporation (W/m^2); E_f is the sensible heat flux within the fruit (W/m^2); ρ_a is the density of air; C_p is the specific heat of air; and dT/dt is the change in temperature over time (seconds) in the control (fruit) volume. In an assumed steady state situation where the core temperatures are relatively constant during cooling, E_f is constant or ρ_a C_p*dT/dt can be set equal to zero. It should be noted that the climatic variables needed for the model are essentially the same needed for scientific irrigation scheduling using a Penman-based evapotranspiration model (Camp, Sadler and Yoder, 1996).

The quantity R_{abs}-R_e is the net absorbed radiation (W/m^2) flux. R_{abs} can be written as:

$$R_{abs} = S_T(1-\alpha) + \epsilon_a \sigma (T_a + 273)^4 \tag{3}$$

where S_T is the total short wave radiation; α is the reflectance of the apple surface (about 0.6); σ is the Stephan-Boltzmann constant (5.67E-8 W/[m^2*T^4] with T in Kelvin); T_a is the ambient air temperature(°C)); and ϵ_a is the emissivity of the atmosphere given by the equation (Brutsaert, 1974):

$$\epsilon_a = 0.58 * \rho_{va}^{1/7} \tag{4}$$

where ρ_{va} is the vapor density measured at the 1 to 2 m height. The first term in Equation 3 is the short wave radiation and the second term accounts for the long wave contribution (L_a). Since only one hemisphere of the fruit receives incoming radiation (and most of that is in the top half of the hemisphere), the other half of the fruit receives variable reflected radiation by the canopy and ground, the net absorbed radiation can be re-written as:

$$R_{abs} = a_S[(\frac{A_p}{A})S_p + (\frac{A_d}{A})S_d + (\frac{A_r}{A})S_r] + a_L[(\frac{A_d}{A})L_a + (\frac{A_r}{A})L_g] \tag{5}$$

where A_p, A_d, A_r, and A are the projected surface areas perpendicular to the sun, the projected area exposed to sky diffuse radiation, the projected area exposed to reflected radiation from the ground and canopy, and the total surface area of the fruit (e.g., $4\pi r^2$ for a sphere), respectively. The short wave absorptivity, a_s, is equal to 1 minus the reflectance, α, as defined in Table 1. Typical values for these area ratios for a fully exposed whole fruit are 1/4, 1/2 and 1/2, respectively, but they may be altered under less exposed conditions. However, if we only look at the "hottest" part of the fruit surface (relatively small areas where the sunburn occurs) perpendicular to the sun, the A_p/A, A_d/A, and A_r/A ratios would be 1, 1, and 0, respectively. S_p,

S_d, and S_r are the corresponding short wave radiation terms (W/m^2), respectively. L_a and L_g are the long wave radiation terms (W/m^2) for the air and ground, respectively. ϵ_f and ϵ_g are the respective emissivities (both about 0.97) from the fruit and the ground (Campbell, 1977). The above short wave components can be determined by the following equations (Campbell, 1977):

$$S_T = S_b + S_d \tag{6}$$

$$S_b = f_b * S_T \tag{7}$$

where S_b is the direct irradiance and f_b is the fraction of the total solar beam reaching the fruit given by (Campbell, 1993):

$$f_b = \frac{1.82}{1 + \dfrac{0.45}{S_T / S_{po} - 0.45}} \tag{8}$$

S_d is defined as:

$$S_d = 0.5 * S_{po} * (0.91 - a^m) * Sin\phi \tag{9}$$

where S_{po} is the solar constant (1360 W/m^2), Φ is the sun elevation angle, and "**a**" is the atmospheric transmission coefficient ($\approx$0.7 for a clear day) with an exponent **"m"** defined as:

$$m = \frac{(P/P_o)}{Sin\phi} \tag{10}$$

where P is the atmospheric pressure, and P_o is the atmospheric pressure at sea level. S_p can be calculated as:

$$S_p = a^m * S_{po} \tag{11}$$

S_r is determined by:

$$S_r = r_s (S_p \sin\phi + S_d) \tag{12}$$

where r_s is the reflectivity of the surface (about 0.4 for an apple, 0.6 for bare ground).

The incoming long wave radiation is:

$$L_a = \epsilon_a \sigma (T_a + 273)^4 \tag{13}$$

$$L_g = \epsilon_g \sigma (T_g + 273)^4 \tag{14}$$

The long wave reflected radiation from the ground is:

$$L_g = \epsilon_g \sigma T_g^4 \tag{15}$$

where T_g is the ground temperature. The emitted radiation is calculated as:

$$R_e = \epsilon_f \sigma (T_a + 273)^4 + \frac{\rho_a C_p (T_{fs} - T_a)}{r_r} \tag{16}$$

where T_{fs} is the temperature (°C) at the fruit surface; and, r_r is the radiative resistance.

Using the mass balance relationship, E_w (W/m^2) can be written as:

$$E_w = C' * [I \frac{dM_a}{dt} (T_w - T_{fs}) - \frac{dM_r}{dt} (T_{fs} - T_r)] \tag{17}$$

where C' is a units conversion of l/s to W/m^2 °C ([4.19 J/g°C * 1 g/ml * 1000 ml/L * W-s/J] / sprinkler spacing [S] in m^2); T_w is the temperature (°C) of the water at the fruit surface (assumed to be about wet-bulb temperature, T_{wb}, which generally applies to field sprinkler systems); and T_r is the temperature (°C) of water running off the fruit (usually assumed equal to T_{fs} so that the second term is 0).

H (W/m^2), heat flux can be written as:

$$H = \frac{\rho_a C_p (T_{fs} - T_a)}{r_{fa}} \tag{18}$$

where r_{fa} is the boundary layer resistance (s/m) of turbulent heat flow transfer from the fruit to the air. This resistance term can be estimated as (Campbell, 1977):

$$r_{fa} = 0.7 * 307 * \sqrt{\left(\frac{d}{u}\right)} \tag{19}$$

where d is a characteristic length approximately equal to 0.84 times the fruit diameter (m) (Campbell, 1993) and u is the wind speed (m/s).

λE (W/m^2) can be written as:

$$\lambda E = \frac{\lambda \Delta (T_{fs} - T_a)}{r_v} + \frac{\lambda (\rho'_{va} - \rho_{va})}{r_v} \tag{20}$$

where λ is the latent heat of vaporization (2.429 MJ/kg); Δ is the slope of the saturation vapor curve (kPa/°C); r_v is the vapor diffusion resistance; ρ'_{va} is the saturation vapor density (kg/m^3); and; ρ_{va} is the vapor density at ambient air temperature (kg/m^3). However, because of the waxy surface of the fruit, the water film is often discontinuous or in water "beads" on the fruit surface resulting in an effective resistance to vapor transfer (probably time variant depending on cooling intervals) referred to as r_{ve}. For purposes of this model, this is estimated as:

$$r_{ve} = \frac{1.0}{\frac{f_w}{r_{va}} + \frac{(1 - f_w)}{(r_{vs} + r_{va})}} = \frac{r_{va}}{f_w} \quad \textbf{(21)}$$

where f_w is the fraction of total surface that is wetted (estimated or measured) and has a large effect on the energy balance. The model is sensitive to this value (about 0.5 with uniform coverage on a spherical shape, but apples are not spherical and have wax on their skin so that water beads develop so that an f_w of about 0.60 or 0.75 may be more appropriate). r_{vs} is the surface resistance to vapor transport which is typically a large number due to the wax on the fruit surface so that r_{ve} can be approximated as r_{va}/f_w. The resistance to vapor transport in air, r_{va}, can be estimated by the equation (Campbell, 1977):

$$r_{va} = 0.7 * 283 * \sqrt{\frac{d}{u}} \quad \textbf{(22)}$$

where d and u are as previously defined. The latent heat term (Equation 17) can also be shown to be equal to:

$$\lambda E = \lambda C' \frac{dE_f}{dt} \quad \textbf{(23)}$$

where dE_f/dt is the heat flux in the fruit from the energy balance equation (generally unknown).

For a steady state condition with a constant gradient across the fruit, E_f can be shown to be:

$$E_f = \frac{\rho_a C_p (T_{fs} - T_{fc})}{r_t} \quad \textbf{(24)}$$

where T_{fc} is the fruit core temperature (°C) and r_t is a potentially time varying internal heat transfer resistance (s/m) that is small at small times and large at very long times. If $T_{fs} = T_{fc}$, the term is zero (simplest case).

Using the values in Table 1 and assuming that heat transfer by conduction from dry to wet areas is negligible, steady state conditions apply , water temperature (T_w) is assumed equal to the wet bulb temperature (T_{wb}), and low wind conditions exist, the above equations can be substituted, combined and reorganized to solve for skin temperature, T_s , and application rate, dM_a/dt, can be estimated. To solve for skin temperature it is necessary to set or calculate: S_T, T_a, $T_w = T_{wb}$, RH, u, I, and dM_a/dt, whereas dM_r/dt has to be estimated. Thus, T_{fs} is:

$$
\begin{aligned}
T_{fs} = {} & [R_{abs} - \epsilon_f \sigma (T_a + 273)^4 + \rho_a C_p \left(\frac{T_a}{r_r} + \frac{T_a}{r_{fa}} + \frac{T_{fc}}{r_t}\right) \\
& + C' I T_w \frac{dM_a}{dt} + C' T_r \frac{dM_r}{dt} + \frac{\lambda \Delta T_a}{r_{ve}} - \frac{\lambda (\rho'_{va} - \rho_{va})}{r_{ve}}] \; / \\
& [\rho_a C_p \left(\frac{1}{r_t} + \frac{1}{r_r} + \frac{1}{r_{fa}}\right) + C' I \frac{dMa}{dt} + C' \frac{dMr}{dt} + \frac{\lambda \Delta}{r_{ve}}]
\end{aligned}
\qquad \textbf{(25)}
$$

Likewise, to solve for the water application rate, dM_a/dt, it is necessary to set or calculate: S_T, T_a, $T_w = T_{wb}$, T_{fs}, RH, u, and I. As before, dM_r/dt must be estimated and necessary variables substituted, combined and reorganized to solve for dM/dt. Thus, the equation to solve for the application rate is:

$$
\begin{aligned}
\frac{dMa}{dt} = -\{ & R_{abs} - \epsilon_f \sigma (T_a + 273) + \rho_a C_p \left(\frac{T_a}{r_r} + \frac{T_a}{r_{fa}} + \frac{T_{fc}}{r_t} \right) \\
& - C' T_r \frac{dM_r}{dt} - T_{fs} \left[\rho_a C_p \left(\frac{1}{r_r} + \frac{1}{r_{fa}} + \frac{1}{r_t} \right) + \frac{\lambda \Delta}{r_{ve}} \right] \\
& + \frac{\lambda \Delta T_a}{r_{ve}} - \frac{\lambda (\rho'_{va} - \rho_{va})}{r_{ve}} \} / C' I (T_w - T_{fs})
\end{aligned}
\qquad (26)
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DISCUSSION AND RESULTS

The heat energy “load” on fruit that is exposed to the sun has two principal components: 1) direct radiative heating from the sun; and, 2) advective heating from hot air originating from outside the block moving through the orchard. Taking a simple physical approach, some calculations can be made to give the relative magnitude of the amount of water required for effective overtree evaporative cooling of exposed fruit. Assuming that a grower wanted to cool apples under conditions where the incoming solar radiation has an intensity of 800 W/m^2 with an air temperature of 35°C (reasonable numbers for the middle of a summer day), it would require the complete evaporation of about 3.13 L s^{-1} ha^{-1} applied above the tree canopy just to equal (neutralize) the energy from only the incoming solar radiation. However, there is also an advective (wind) component that is typically at least equal to the solar radiative heating during periods of high air temperatures, low relative humidity and low to moderate wind speeds. This means that at least 6.25 L s^{-1} ha^{-1} would have to be continuously applied over the tree during this “hot”period of the day to just equal both the incoming radiative and advective heat energy and maintain the exposed fruit surface at ambient air temperatures (in this example 35°C) under these assumed conditions. Cooling the exposed fruit to below ambient temperature would require the application of additional water. These basic calculations are supported by field data measuring actual exposed fruit temperatures on hot summer days in south central Washington of cooled and uncooled fruit (Evans et al., 1995). Higher wind speeds and/or higher air temperatures would increase the amount of water required for effective evaporative cooling. In fact, ambient air temperatures above 40°C are common during the growing season.

The energy balance model (Equation 24) was written in Visual Basic, and was run under the same environmental conditions as measured in the field (e.g., RH, solar radiation, air temperature, wind speed). As would be expected, the model results were sensitive to the estimated value of f_w (fraction of total surface that is wetted) used in the calculations) and the resistance to vapor transport (r_{ve}). Values of f_w of 0.75 and I of 0.6 were used for this analysis at this stage of fruit growth. The approximation of r_{ve} as r_{va}/f_w appears to overestimate the resistance term by about 25% and more work needs to be done to better define this value.

The model results were compared with data collected from the test stand when the fruit is being cooled (initiation of cooling is based on skin temperature thresholds). Data for August 14, 1998 are presented in Figures 3 and 4. Figure 3 shows the basic climatic data during the day for the model results in Figure 4. The model results are presented on Figure 4 compared to the measured average skin and core temperatures of both cooled and uncooled apples on the test stand. It can be seen that there is fairly close agreement with the measured and predicted cooled fruit skin temperatures until later in the afternoon when the model slightly overestimated. The effectiveness of evaporative cooling is seen by comparing the large differences between cooled and uncooled fruit temperatures. The slight overestimation later in the day was due to small increases in wind speeds and greater evaporation rates that cooled the wetted skin temperatures faster when water was not limiting. This same pattern of model to measured values represents conditions evident for several other days in 1998.

Actual water applications were pulsed based on measured core temperatures of on at 33°C and off at 32°C, which were probably too conservative because of the frequent water pulses used in this experiment. Cooled skin temperatures did not rise about abut 36°C during cooling but showed considerably more variability than core temperatures. This relatively high variability is due to the rapid influences of applied water temperatures as well as solar heating after surface layers of water have evaporated, indicating why skin temperatures are a poor measure for controlling cooling.

Many of the simplifying assumptions used in the model were based on quasi-steady state or moving average conditions, whereas the measured skin temperatures were instantaneous values. Thus, when comparing the difference of the model to the measured values during cooling, the range of the differences in total magnitude was small (about 5°C) and the variation in the model output was less than the magnitude of differences in the measured data (about 3°C). The average skin temperature over the cooling test period was 31.68°C and 32.22°C for the measured and model, respectively. Linear regression of the overall model results compared to measured cooled skin temperature of the data in Figure 4 had an R^2 of 0.7324 (Figure 5), and most of the variability occurs in the cooling interval.

This set of experiments showed that pulsing of water applications at the desired rates was sufficient to maintain the target fruit temperatures during cooling. Continuous water applications would have been excessive. There is a compromise between relative levels of sunburn protection and water application rates. Running the model over a season shows that average application rates below about 6 $L\ s^{-1}\ ha^{-1}$ may not minimize sunburn on extremely hot days. This is supported by observation and field data. Consequently, at lower rates, the decision must be made to either accept increased burn damage over the entire block on extreme days or to cool smaller blocks of more valuable fruit varieties at higher application rates. If the decision is to use evaporative cooling on a smaller area, the piping and pumping system must be designed to handle the increased local flows at required pressures.

The evaporative cooling process can be optimized in areas with low humidity and high daytime temperatures common to many fruit growing regions in the Pacific Northwest (USA) by the use of model or a fruit temperature-based initiation and duration control of pulsed water applications as long as sufficient water (e.g., 6.25 L s^{-1} ha^{-1}) is continuously available. Hydro-cooling should be minimized, not only because it is less efficient but also because orchard soils may become saturated over extended periods leading to disease, excessive deep percolation and other problems. Pulsing appears to use the least amount of water that is effective in maintaining exposed skin temperatures below critical levels. Rapid wetting followed by water evaporation directly from the fruit surface was shown to be effective in controlling fruit temperatures at the higher water application rates in both field tests and by the model.

Systems in windy areas need to be designed for higher application rates and shorter intervals between pulses. Droplet sizes need to be larger and sprinkler spacing must be closer to provide the necessary application uniformity and penetration of the canopy.

It must be noted that evaporative cooling is not a water conservation measure and will require extra water above required irrigation amounts. Based on the soil water measurements and irrigation scheduling results under evaporative cooling conditions, total seasonal water application amounts will be from 25% to 40% greater than historical irrigation requirements for an orchard (Evans et al., 1995). Even though transpiration is suppressed, additional water is required since, by design, much is lost to the atmosphere on a high frequency basis (e.g., daily).

The model agrees with observations that overtree sprinkle/microsprinkle systems that apply water at low application rates (e.g., 3.13 L s^{-1} ha^{-1}) tend to evaporate most if not all the applied water before it reaches the fruit. These losses are exacerbated due to the applications of very fine droplets (fogging or misting) which have a higher evaporation rate because of increased surface area. Thus, droplet sizes should be large enough to penetrate the canopy and wet all crop surfaces, and small sprinklers should be located as close to the canopy as practical. At appropriate flow rates, some type of control system will generally be required to pulse or "cycle" the water applications.

CONCLUSIONS

Evaporative cooling is the conversion of sensible to latent heat by a conduction controlled heat transfer from the fruit to the evaporating droplets/water film on a plant surface followed by removal of the water vapor by mass air movement. A process-based model was developed and partially verified using this concept during the evaporative cooling process.

The intent of developing the model was to predict skin temperatures during evaporative cooling based on climatic variables to prevent sunburn for controlling these systems. The alternative is to control EC based on sensors embedded in fully exposed fruit within the orchard which also works well but is more labor intensive. The model worked reasonably well for control purposes although it tended to slightly over-predict skin temperatures during times with higher advective heat energy. The model can also be used to initiate cooling in morning which is an important decision for growers to save water and to avoid sunburn.

In addition to improving the advective components, work is needed to better define the range of values for the wetted fraction of the fruit surface (f_w), estimates of fruit runoff losses (dM_r/dt) and resistance to vapor transfer (r_{ve}) terms. Results of this model indicate that it is appropriate for controlling cycled water applications based on sensor feedback (e.g., thermocouples measuring skin or core temperatures) to reduce water use even though it tends to slightly over estimate skin temperatures during cooling under relatively high advective conditions.

Experience gained with this model has shown that, in addition to the fact that evaporative cooling is not a true steady state problem, the following considerations are currently limitations.

1. Water applications may be pulsed so that fruit surface goes from wet to dry and back to wet (r_{ve} changes with time). Water applications are also not uniform in space or time.
2. α (reflectance) of the fruit changes over season as apple matures and changes colors. A fruit color algorithm based on temperature, ultraviolet light and other variables is needed to further refine the skin temperature predictions by variety and stage of growth.
3. Heat distribution within and around the fruit is transient and non-uniform which may require development of a finite element model to accurately solve (beyond the scope of this study).
4. RH and T_a are affected by sprinkling itself which changes λE rates.
5. The advective components of the model need additional refinement.
6. Estimations of the wetted fraction of the fruit and the surface resistance to vapor transport need to be improved.

This research has shown that use of a few easily measured climatic variables including solar radiation (S_T), ambient air temperature (T_a), wet bulb temperature (T_{wb}) or relative humidity (RH), and wind speed (u) along with estimates of the resistance to vapor transport (r_{ve}), fraction of the fruit that is wetted and fruit runoff losses (dM_r/dt) can be used to reasonably predict skin temperature and various selected water application rates (dM_a/dt) of apples when water supply is not limited and applications can be cycled.

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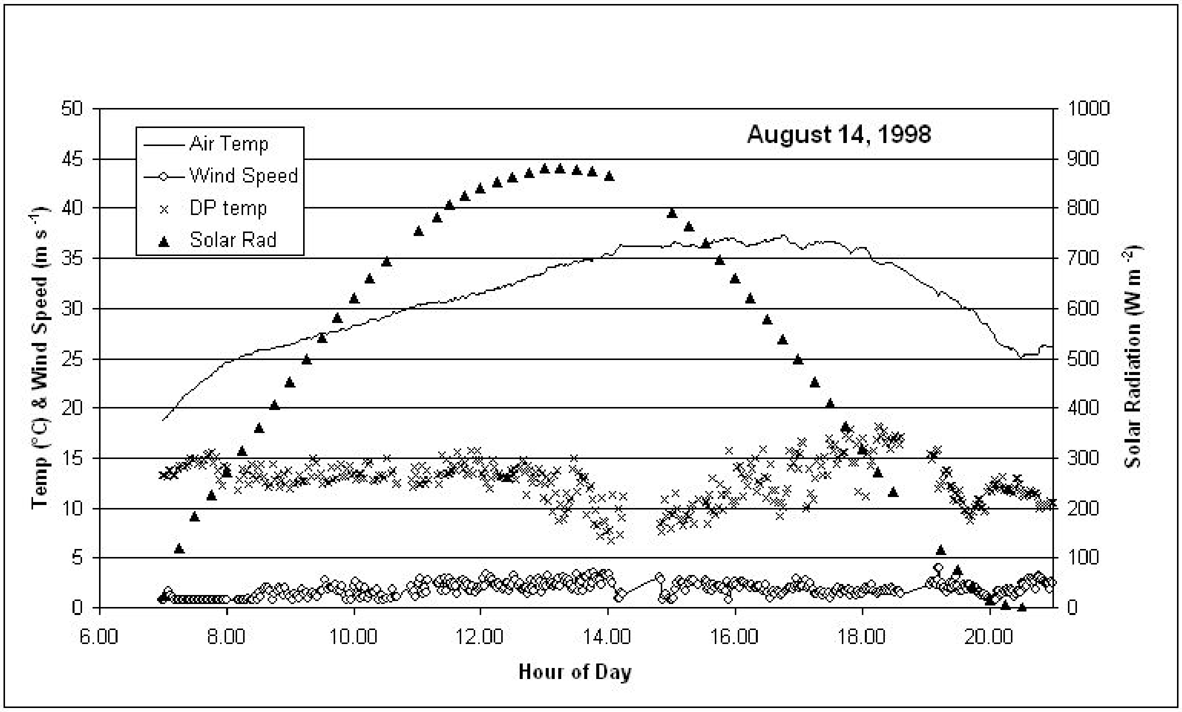

Figure 3. Climatic data on August 14, 1998 used to generate the model results.

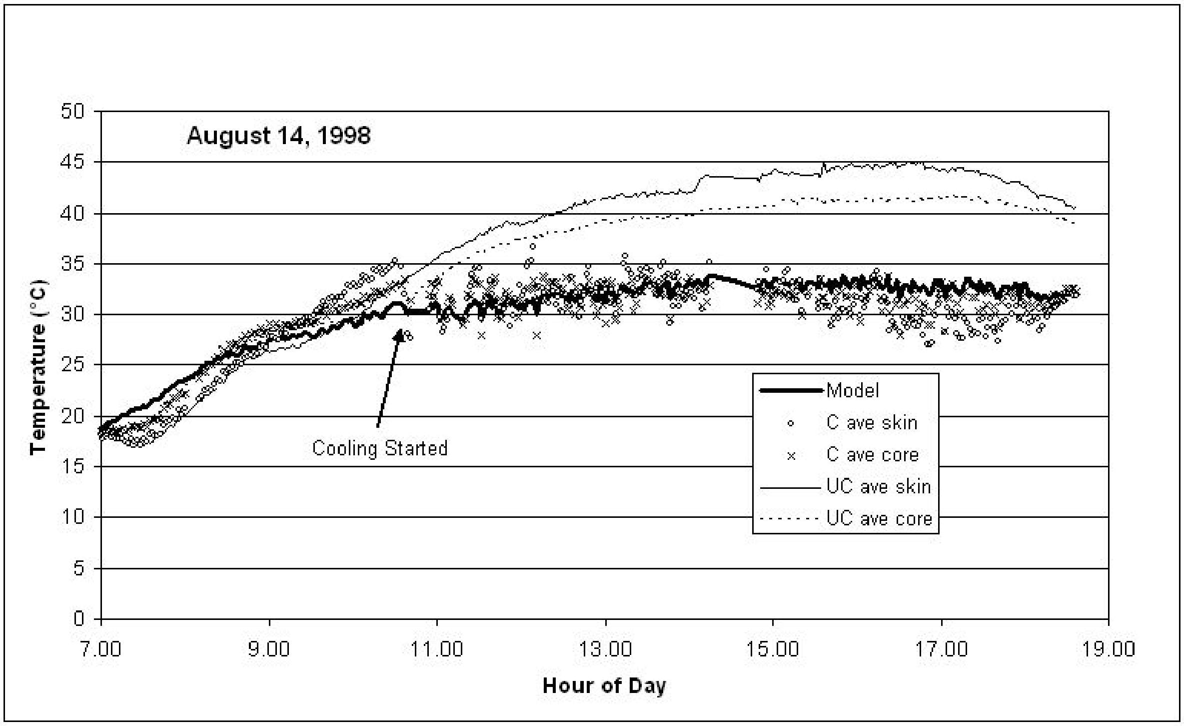

Figure 4. Comparison of model results to measured skin temperatures of exposed fruit in the field on August 14, 1998. "C ave" refers to cooled fruit temperatures where the core was maintained at about 31°C, "UC ave" refers to the temperatures of uncooled fruit (control).

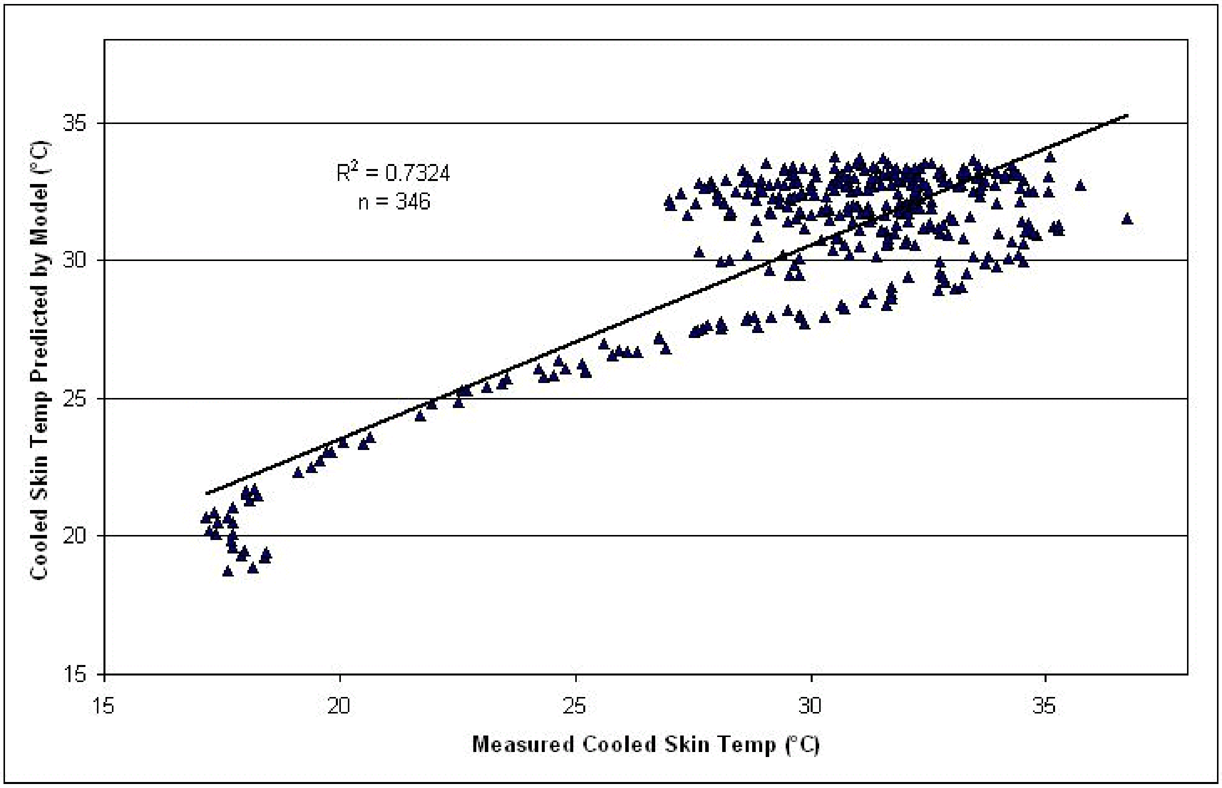

Figure 5. Results of the linear regression of model predictions of skin temperatures against the measured apple skin temperatures for August 14, 1998.

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