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Effects of High Humidity and Solar Radiation on Temperature and Color of Tomato Fruits[1]

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Abstract. Tomatoes were grown at Tucson in plastic covered greenhouses with normal or high relative humidity (RH). The fruits were exposed to the sun (Ex) or shaded by foliage (Sh), and some exposed fruits were painted either black (B) or white (W).

Temperatures of the surface (T_s), wall (T_w) and center (T_c) of the fruit were 2 to 3° C lower in high than in normal RH, even though the maximum air temperature ($T_{a\ max}$) in high RH exceeded that in normal RH by 1.5°. When T_s and air temperature (T_a) were measured simultaneously, T_s of Ex and B fruits was always higher than T_a, that of Sh fruits lower, and that of W fruits about the same as T_a. The exact gradient depended on RH and T_a.

T_w of Ex fruits almost invariably exceeded T_s or T_c, and thus the wall was a heat sink. Further, $T_{c\ max}$ exceeded $T_{a\ max}$ in small (diam 35 to 40 mm) or large (diam 60 mm) fruits.

The gradient T_c–T_a for large Ex fruits grown in normal RH ranged from −5° to 15° C during the day, while that for fruits grown in high RH ranged from 0° to 12°. The respective daily ranges for the gradient T_w–T_a were −5° to 20° and 0° to 13°. For small fruits all gradients were similar and ranged from 3° to 13°.

The incidence of defective coloration of the shoulders or sides of fruits was highest in Ex and seemed to be influenced by infrared and short-wave radiation. The possibility of protecting tomatoes from excess radiation is discussed.

The influence of fruit temperature on ripening of tomatoes has been previously investigated in respect to preharvest (9, 10, 12, 14), or postharvest temperatures (8, 15), or both (16). However, one report dealt only with air temperature, another included that of fruits, but air temperatures were measured distant from the fruits, and none reported on surface temperatures, or on the relation between fruit temperature and ambient relative humidity. Further, effects of size of fruit or of infrared and shorter wave length solar radiation on fruit temperature or color were not critically distinguished. Improved understanding of response of tomato fruits to high humidity and to solar radiation may suggest ways to reduce defective ripening and attendant economic losses.

Methods and Records

General. Cultural procedures, cultivars, and the environments in which tomatoes were grown have been described previously (11). In summary: normal relative humidity (RH) ranged from 50% to 90% and high RH from 70% to 100%, depending upon season and time of day. A spring (January to June) and a summer (July to November) crop were grown. Data in this report refer to the summer crop unless otherwise noted.

Treatment of fruits. Fruits with initial diameters of 15 to 30 mm, occasionally larger, were exposed to the sun either during part or all of each day, or they were shaded by leaves the entire day.

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The surface of some exposed fruits was painted black (B) or white (W), or left unpainted (Ex) as were fruits shaded by leaves (Sh). In the spring crop, some additional exposed fruits were shaded with black or white cloth. Further, some fruits had only half of their exposed side painted. Two coats of paint (Grumbacher "Hyplar" high copolymer, Mars black or titanium white) were applied undiluted. "Hyplar" was nontoxic, spread evenly, did not interfere noticeably with fruit growth, and peeled off readily for examination of the fruit surface. Most fruits were repainted once during growth. Albedos of the dry black and white paints were 6% and 56%, respectively, as determined with a Weston Sunlight Illumination Meter (Model 756). The light intensity outdoors was 8600 foot-candles at 10:00 MST September 27, 1968, as measured vertically and at ground level.

Diminution of short-wave radiation from sun and sky (18), by the clear plastic of the greenhouses and by the paint or cloth covers was determined with an Eppley pyranometer shaded with the appropriate material.

Measurement of temperatures. T_s and T_w, were measured on that side of the fruit directly exposed to the sun either in the morning or afternoon, depending on the location of the plant and fruit. T_s (± 1° C) was measured weekly with an infrared thermometer (Barnes Engineering, Model IT-2, 3° field of view) over a delineated area when it was judged to be near maximum.

Temperatures at the center of the fruits (T_c), in the wall (T_w) and of the air (T_a) were continuously measured with copper-constantan thermocouples and were printed out at 12-minute intervals. The junctions were protected from corrosion by a thin layer of plexiglass that had been dissolved in chloroform. T_a was measured in shelters that were continuously aspirated by a fan. Insertion of thermocouples into immature fruits had no adverse effect on growth or ripening.

Maximum daily temperatures ($T_{c\ max}$, $T_{w\ max}$, and $T_{a\ max}$) were determined by inspecting the print-outs. T_c, T_w, and T_a for comparison with weekly T_s measurements on the same fruits, were taken from the print-outs for the time periods during which T_s was measured.

All temperatures were recorded as °F, then converted to °C and rounded to the nearest half degree.

Evaluation of fruits. Incidence of defective ripening of the shoulders or sides (11) and of scald was recorded as the percentage of fruits showing any color defect.

Results and Discussion

Temperature Relationships

General. Tomatoes growing in normal RH were warmer than those in high RH, regardless of surface coating, even though $T_{a\ max}$ was 1.5° C lower in normal than in high RH (Table 1). Further, the high T_w and $T_{w\ max}$ indicate that the wall of the fruit is a heat sink.

Temperature records are adequate when only 1 environment is tested but gradients will be used henceforth because they permit comparison between environments, and because they more clearly reflect patterns of heat transfer.

Surface temperature. Table 2 indicates that high RH reduced the difference between T_s and T_a in exposed or shaded fruits, however, T_s of the former generally was higher than T_a and that of the latter was lower. The gradients of T_s–T_a also indicate that T_s of W and B fruits varied with T_a, unlike T_s of Ex and Sh fruits. Thus, Ex and Sh fruits compensated for changes in T_a, but W and B fruits did not, presumably because the paint interfered with transpiration.

The predictability of T_s from T_a would be useful in the absence of infrared radiometers. However, the only reliable relation existed for small Ex fruits grown in high RH ($r = .939$; $Y = -30.4 + 1.42\,x$; $n = 6$) where the error did not exceed ±1.5° C over a 10° range in T_a.

Heat accumulation by the walls of tomato fruits in

Table 2. Difference between the surface temperature of tomato fruits with various surface exposures and coatings and air temperature in normal or high relative humidity, for 3 air temperature ranges.

Treatment	Relative humidity	Air temperature range (°C): 23.0 to 24.5	26.5 to 28.5	29.5 to 31.0
		Surface minus air temperature (°C)		
Fruits exposed to sun				
Not painted (Ex)	Normal	9.0	7.0	4.5
	High	8.0	3.5	0.5
Painted white (W)	Normal	3.5	0.5	–1.5
	High	–0.5	–1.5	–1.0
Painted black (B)	Normal	18.5	18.5	19.5
	High	16.5	10.0	10.0
Fruits shaded				
Not painted (Sh)	Normal	–5.0	–6.0	–9.0
	High	–1.0	–3.5	–4.0

Table 1. Temperatures[z] of tomato fruits with various exposures and surface coatings growing in normal or high relative humidity. October 24, 1968.

Relative humidity	Exposure and surface coating	Fruit temperature: T_s	T_w	T_c	$T_{w\ max}$	$T_{c\ max}$
		°C	*°C*	*°C*	*°C*	*°C*
Normal	Exposed to sun					
	None	40.0	42.5	38.0	42.5	38.5
	Black	45.0	46.0	—	46.5	—
	White	28.5	33.0	—	33.0	—
	Shaded					
	None	21.5	—	—	28.0	—
	(Maximum air temp. = 27.0° C)					
High	Exposed to sun					
	None	28.5	—	—	40.5	38.0
	Black	41.0	43.5	—	44.5	—
	White	24.5	30.5	—	30.5	—
	Shaded					
	None	27.0	—	—	28.5	—
	(Maximum air temp. = 28.5° C)					

[z]Dashes indicate no data available from same fruit within a temperature class.

both environments was confirmed by the consistently positive values for T_w–T_s (Table 3).

Pulp temperatures. $T_{w\ max}$ of Ex fruits consistently exceeded T_a (Table 4), and unlike T_s was not influenced by RH.

The measured values for $T_{w\ max}$ parallel those found by others under similar T_a (9, 10, 12), and approached injurious levels (12). Further, the highest $T_{w\ max}$ in normal RH exceeded that in high RH, thus paralleling the results for T_s.

The net heat gain of tomatoes, as shown by $T_{w\ max}$, was higher in normal RH (44 to 45° C) than in high RH (41 to 42°) even though T_a was 1° to 2° lower in normal RH. Clearly, fruit grown in high RH exchanged energy with its environment at least as readily as fruit grown in normal RH.

$T_{w\ max}$ for Ex fruits exceeded T_a, and $T_{a\ max}$, even on cloudy days, and the mean gradient $T_{w\ max}$–T_a was greater in normal (8.5° C) than in high RH (6.0° C). The fruits cooled little under clouds, because the 60% reduction in incoming short-wave radiation was partly offset by a 50% reduction in outgoing infrared radiation (18).

RH and fruit size had little influence on the gradient $T_{c\ max}-T_{a\ max}$, which always was positive (Table 5). However, the center of fruits, as the walls, were cooler in high than in normal RH.

The mean gradient $T_{w\ max}$–$T_{c\ max}$ was small regardless of RH over a 13° C range in $T_{w\ max}$ and was influenced by size of fruit in normal RH (Table 6).

Fruit temperatures during color change. Attempts to determine temperature differences due to fruit color were inconclusive. The variance was too great to permit resolution of the contradiction in the literature (9, 15) in respect to red and green fruits. However, T_s–T_a decreased by 4° C as yellow-fleshed fruits ripened.

Diurnal temperature changes. Diurnal changes in T_w–T_a or T_c–T_a (Fig. 1) indicate that high RH reduces the rate and magnitude of temperature change of large fruits and that fruit color did not influence this pattern. In contrast, RH had little effect on the diurnal pattern of small fruits, and their gradients ranged over only about 10° C, unlike those for the large fruits, which ranged over 20° or more.

Color Quality

Relatively cool Sh and W fruits had only 22% and 18% unevenly colored fruits, whereas Ex and B fruits had 64% and 62%, with the 2 groups differing at *P* 1%. The relatively low incidence in the cooler fruits was expected (3, 4), but the nearly equal incidence in Ex and B fruits was not, because B fruits were substantially hotter than Ex fruits. The incidence of specific defects as a function

Table 3. Difference between temperatures of wall (T_w) and surface (T_s) of tomato fruits[z] growing in normal or high relative humidity for 3 ranges in air temperature.

Relative humidity	Air temperature range (°C) 23.0 to 24.5	26.5 to 28.5	29.5 to 31.0
	Wall minus surface temperature (means)		
	°C	°C	°C
Normal	5.0	4.5	4.0
High	5.5	4.5	3.5

[z]Includes Ex and W fruits; insufficient data available for B or Sh fruits.

Table 4. Difference between maximum temperature of walls ($T_{w\ max}$) of tomato fruits growing in normal or high relative humidity and air temperature (T_a) at time of $T_{w\ max}$.

Relative humidity	Size of fruit[x]	Period covered[y]	$T_{w\ max}$–T_a Range	Mean	$T_{w\ max}$ Range
			°C	°C	°C
Normal	Large	Early	10.5 to 16.0	13.5	38.5 to 45.0
		Late	11.5 to 18.0	15.0	34.0 to 44.5
	Small[z]	Late	8.5 to 15.0	11.5	34.0 to 41.0
High	Large	Early	5.0 to 15.0	8.5	35.5 to 42.0
		Late	11.0 to 15.0	14.0	37.0 to 41.5
	Small	Early	5.0 to 14.0	11.0	33.0 to 41.5
		Late	9.5 to 16.5	11.5	39.0 to 42.0

[x]See Table 6 for actual sizes.
[y]Early: mid-September to mid-October; late: mid-October to early November. Periods overlap about 1 week.
[z]No early fruit available.

Table 5. Difference between maximum temperatures of centers ($T_{c\ max}$) of tomato fruits growing with normal or high relative humidity and of air ($T_{a\ max}$).

Relative humidity	Size of fruit[x]	Period covered[y]	$T_{c\ max}$–$T_{a\ max}$ Range	Mean	$T_{c\ max}$ Range
			°C	°C	°C
Normal	Large	Early	2.0 to 8.0	6.0	33.5 to 40.5
		Late	6.5 to 14.5	10.5	33.0 to 41.5
	Small[z]	Late	8.0 to 14.5	10.0	34.0 to 42.0
High	Large	Early	4.0 to 9.0	5.5	34.0 to 41.0
		Late	8.0 to 10.5	9.0	34.5 to 39.5
	Small	Early	1.5 to 6.5	4.0	31.5 to 39.0
		Late	6.0 to 10.5	8.0	35.0 to 39.5

[x]See Table 6 for actual sizes
[y]Early: mid-September to mid-October; late: mid-October to early November. Periods overlap about 1 week.
[z]No early fruit available.

Table 6. Difference between maximum temperatures of wall ($T_{w\ max}$) and center ($T_{c\ max}$) of large or small tomato fruits growing in normal or high relative humidity and being exposed to the sun either mornings or afternoons.[y]

Relative humidity	Size of fruit: Class	Diameter: Initial	Final	$T_{w\ max}$–$T_{c\ max}$ Range	Mean	$T_{w\ max}$ Range
		mm	mm	°C	°C	°C
Normal[z]	Large	40±10	62± 8	0.5 to 5.0	3.0	34.0 to 45.0
	Small	17	40	−0.5 to 0.5	0	34.0 to 42.0
High	Large	33± 3	62±10	−0.5 to 3.5	1.5	33.5 to 42.0
	Small	19± 3	23± 6	0.5 to 3.5	2.0	32.0 to 42.0

[y]Period covered is from mid-September to early November.
[z]For a large fruit exposed to the sun all day the relevant values were −0.5° to −2.0°, −1.5, and 33.0 to 40.5.

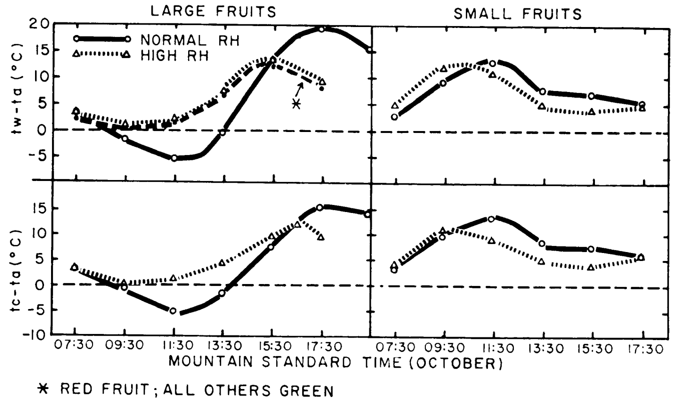

Fig. 1. Diurnal pattern of the gradients T_w–T_a and T_c–T_a for large and small tomato fruits growing in a greenhouse with high or low RH. The mean diameters of the fruits are given in Table 6. (T_w, T_c, and T_a are temperatures of the walls and centers of tomato fruits and of the air, respectively; red fruit grown in high RH).

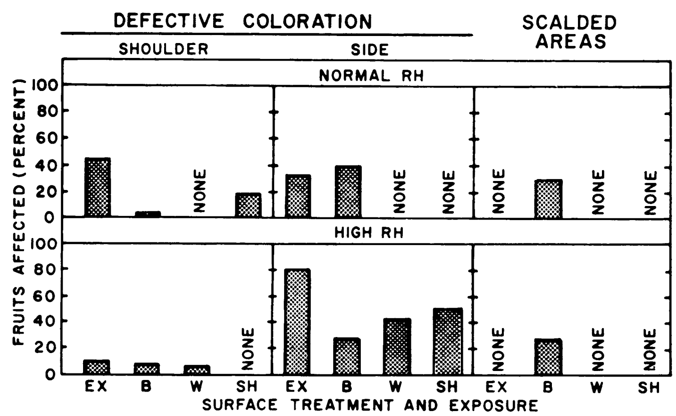

Fig. 2. Incidence of color defects in ripe tomato fruits grown in a greenhouse with normal or high RH and when exposed in various degrees to direct solar radiation. (Ex–exposed, not painted; B–exposed, painted black; W–exposed, painted white; SH–shaded by leaves, not painted.)

of treatments is shown in Fig. 2, and in relation to solar radiation in Fig. 3.

The illustrations show that the black and white paints effectively altered the quality of radiation striking the fruits, presumably in respect to short- and long-wave radiation. Differential effects on ripening due to wave-length had been implied but not directly evaluated in earlier work (2, 4).

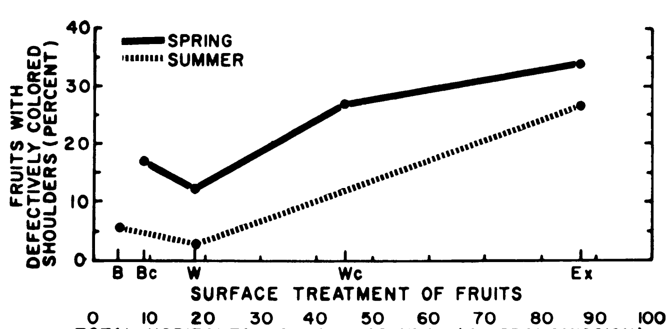

Fig. 3. Incidence of defectively colored shoulders of tomato fruits in relation to exposure to total horizontal solar radiation during their growth. (All fruits in path of direct sun; B–painted black; Bc–covered with black cloth; W–painted white; Wc–covered with white cloth; Ex–not painted).

Had defective coloration of shoulders been primarily a heat effect, its incidence should have been highest in B rather than in Ex fruit. Consequently, short-wave radiation, probably between 0.3 and 0.7μ (7), seems largely responsible for this defect in Ex fruits. The approximate contributions of long- and short-wave radiation to the defective coloration of Ex fruits can be calculated from Fig. 3. If the incidence of defective coloration in B or B_c fruits is due to heating alone, then the ratio of affected B or B_c fruits to that of affected Ex fruits gives the fraction of the incidence caused by heating, while the remainder, is due to short-wave radiation, which was about 1/2 in spring and about 4/5 in summer. However, the contribution of short-wave radiation may be even higher than calculated, because Ex fruits were cooler than B fruits, and consequently less injured by heat.

The pattern of defective coloration of a partly Ex and partly W fruit (Fig. 4) further implicates short-wave radiation in this defect, because it was confined to the unpainted side. If temperature alone had been responsible, there should have been a gradual transition between the sides, because a difference in T_s of 7° to 10° C would produce a diffuse gradient, not a sharp line.

Defective coloration of the sides was induced in high RH when $T_{w\ max}$ was 38.0° C or higher on 6 of the last 14 days before harvest, and in normal RH when 9 of those days reached 38°. High rates of transpiration (17) could not have contributed greatly to this disorder because the average incidence was lower in normal than in high RH. Short-wave radiation as a cause of yellow sides is suggested because the incidence in the cooler Ex fruits was almost 3 times that in B fruits.

Since solar long- and short-wave radiation seem responsible for yellow sides of Ex fruits, likely via reduction

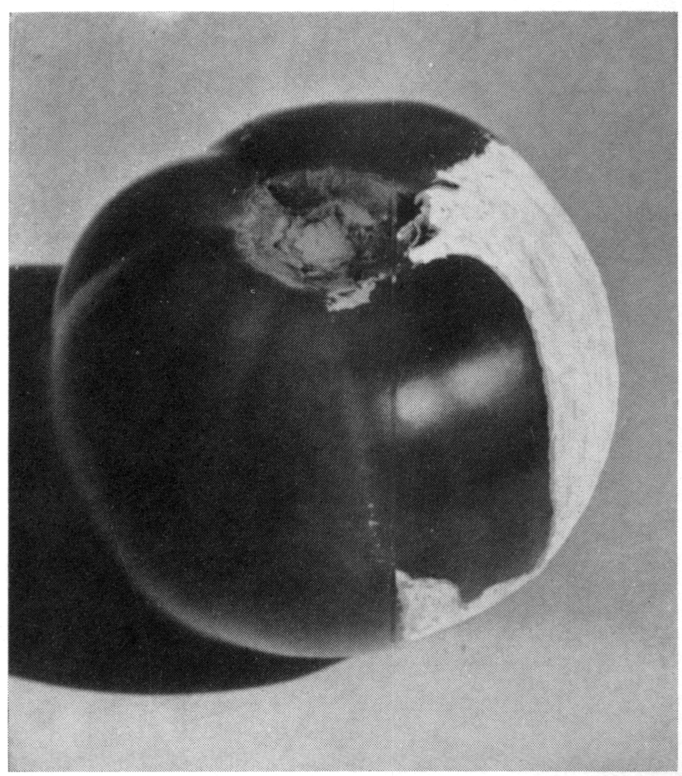

Fig. 4. Tomato fruit with red (shiny, right) and orange (dull, left) shoulders. Red part was protected by white paint during fruit development, orange part was exposed. Border of white paint, now partly removed, approximately followed a line indicated by the white specks in lower half of fruit. (Color transparency loaned upon request).

in carotenoid synthesis (13), the term "solar yellowing" seems preferable to "blotchy ripening", which is overly broad and not related to any specific cause.

Solar yellowing may have been more common in high than in normal RH (Fig. 2, center) because the large amount of water vapor in high RH may have repeatedly reflected short-wave radiation and thus increased the effective radiation load.

Since scald was confined to B fruits (Fig. 2, right) it can be entirely attributed to excessively high T_w, which reached 50° C in some fruits.

Discussion and Conclusions

A previous report (11) suggested that tomatoes could be grown successfully in greenhouses in which RH and T_a frequently were higher than desirable, if certain precautions were taken. However, not only should high T_a be avoided (6), but the fruit also must be protected from short-wave radiation if defects in coloration are to be minimized, particularly in areas of high light intensity. Shading of the fruits by foliage, combined with a spray of a non-phytotoxic white-wash (19), may be desirable even when light intensities are rather low (2).

Successful coloration of most tomatoes under black cloths or paint implies that B fruits were sufficient hours below 30° C (1, 5) to negate the inhibition of ethylene production at 40° or higher (5). Consequently, since Ex fruits were cooler than B fruits, more Ex fruits should have ripened properly. Possibly, Ex fruits did not ripen normally because short-wave radiation inhibited ethylene production.

Finally, results of this, and of an earlier report (11) suggest that a detailed knowledge of the response of tomatoes to their micro-environment may improve their production in generally favorable environments and lead to methods that will permit their production under marginal conditions.

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