COOLING CHARACTERISTICS OF CABBAGE

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The effects of thermocouple location, product mass and gas composition on the cooling characteristics of cabbage were assessed and compared. The results were expressed in terms of cooling rate (CR) derived from Newton's Law of Cooling, and in terms of cooling coefficient (CC) defined as "product degree cooled per hour per degree temperature difference between the product and the cooling medium." The best thermocouple location for optimum approximation of CR was at the mass-average temperature location. Both CR and CC were found to be related exponentially to the product mass. The averaged CC value obtained for cabbage cooled under controlled atmosphere of 3% CO_2, 5% O_2 and 92% N_2 was 1.5% greater than under normal air (0.03% CO_2, 21% O_2 and 79% N_2). The magnitude of the CC values was affected by the characteristics of the cooling medium, the response of the product metabolism to the cooling medium, the variations in setup performance and the time interval over which CC was computed.

INTRODUCTION

In conjunction with low temperature and high relative humidity (RH) controlled atmosphere (CA) storage implies the addition or removal of gases involved in the respiration process of the stored commodity (Raghavan and Gariepy 1985). One of the main advantages of CA storage is to reduce considerably the heat of respiration of the stored product. In a calorimetric assessment of the heat of respiration of different fruits and vegetables, Toledo et al. (1969) estimated heat generation of a fresh produce exposed to CA to be 30% of its value in regular atmosphere (RA). This aspect of reduction in heat generated can be viewed as a beneficial factor at the precooling stage. However, there are no studies in the literature on its application. Other factors relevant to cooling studies are: (i) the physical characteristics of the product; (ii) the nature of the cooling medium; and (iii) the metabolism responses of the product to the cooling environment.

Newton's Law of Cooling and Mass-average Temperature

Newton's Law of Cooling can be applied when the heat transfer is exclusively due to the temperature difference between the surface of the object and its surroundings (Mohsenin 1980). This implies nonexistence of temperature gradient within the object and equality of its surface temperature with its internal temperature. The equation representing Newton's law of cooling is:

$$dQ/d\Theta = -hA(t-t_a) \qquad (1)$$

where $dQ/d\Theta$ is the energy lost by the object per unit of time, h is the convective heat transfer coefficient, A is the surface area of the object, t is the object temperature, and t_a is the surrounding temperature. This is basically an exponential type of cooling and when plotted on a semi-log paper, the cooling curve can be described by the following equation:

$$(t-t_a)/(t_i-t_a) = j\exp(-CR\cdot\Theta) \qquad (2)$$

where the cooling rate (CR) is the slope of the line, and the lag factor, j, is an indication of the error in assuming a Newtonian cooling.

In cooling fruits and vegetables, most of the conditions required for the application of Newton's law do not hold. There is a temperature gradient in the product during cooling, and the heat transfer is not only through surface conduction but also by convection and radiation. Schneider (1955), Guillou (1960) and Smith and Bennett (1965) have reported that cooling of agricultural products could follow Newton's law when the average product temperature is used. Smith and Bennett (1965) have defined the mass-average temperature (M-AT) as a single value obtained from the overall temperature distribution that can be used to represent the heat content of an object at any time during transient cooling. Linearity of the internal temperature distribution and homogeneity of the material are the two assumptions required to estimate the M-AT location of a spherical object. The approximate location of the M-AT is obtained by determining the inner sphere radius, r_i, that will divide the mass of the sphere, R, into two equal masses:

$$r_i = 0.79R \qquad (3)$$

Additional information on how to determine the exact M-AT location and on the advantages of using this concept are discussed in Smith and Bennett (1965) and Mohsenin (1980).

Cooling Coefficient

Lentz and van den Berg (1977) assessed the effects of factors related to the cooling rate of cabbage under conditions similar to those in commercial refrigerated storage rooms. Their results have been expressed in terms of a cooling coefficient (CC) defined as degrees cooled per hour per degree temperature difference between product and ambient air. It can be computed with the following equation:

$$CC = \sum_{i=0}^{i=n} \times \left[\frac{\dfrac{t_c|_{\Theta_i}^{\Theta_{i+1}}}{\Delta\Theta}}{\left(\dfrac{(t_c-t_a)|_{\Theta_{i+1}} + (t_c-t_a)|_{\Theta_i}}{2}\right)} \right] \Bigg/ n \qquad (4)$$

where CC is in C/C-h, n is the number of time interval used to calculate CC, t_c is the object temperature and t_a is the cooling medium temperature. They reported that CC was less sensitive to the variation of the experimental setup than the cooling time.

The objectives of the study are:

(i) To determine the thermocouple

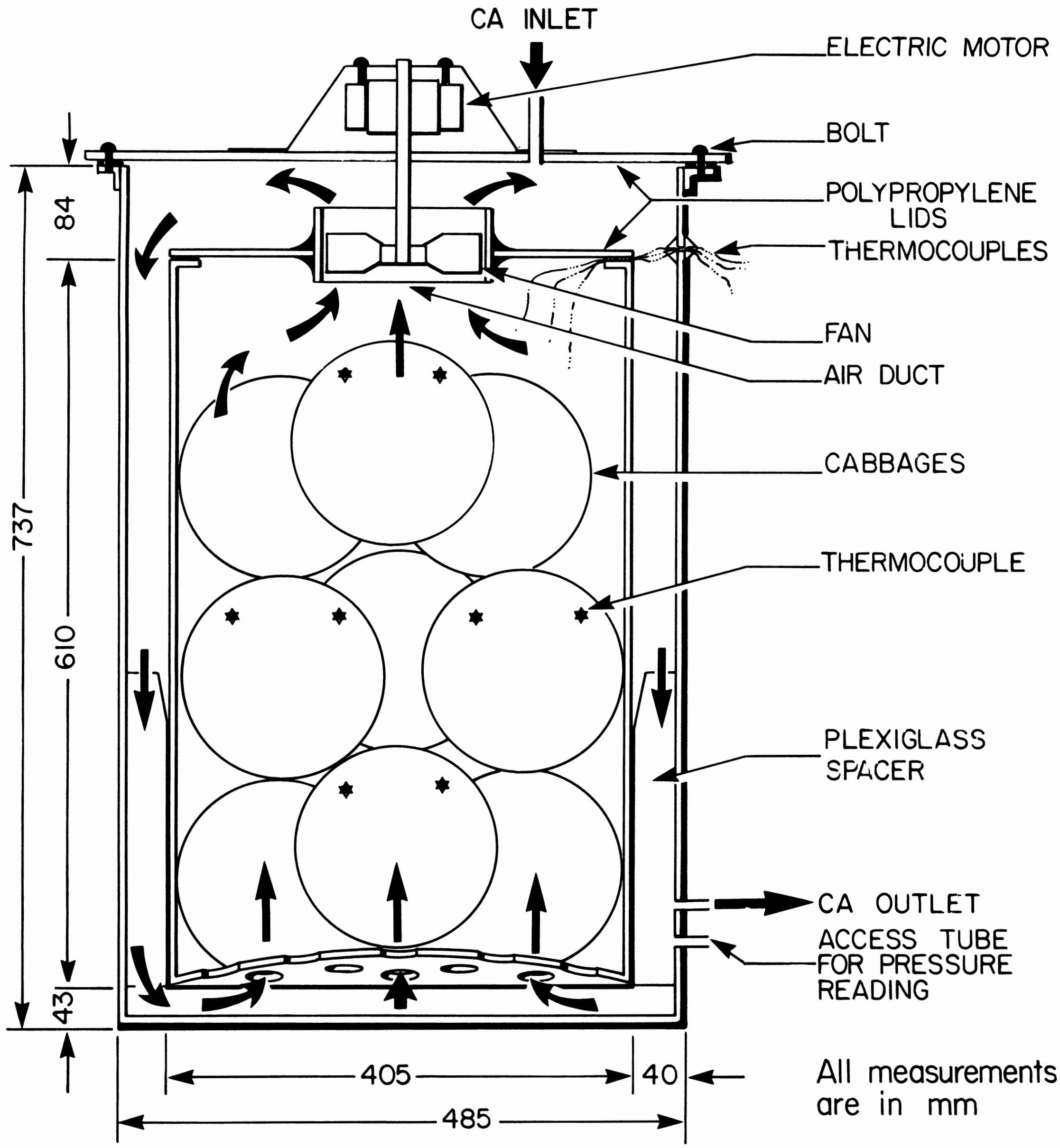

Figure 1. Cross-section view of the double-walled container.

location that will yield the best approximation of the cabbage cooling rate using Newton's Law of Cooling.

(ii) To assess the effect of cabbage mass on its cooling characteristics determined at a given thermocouple location.

(iii) To determine and compare the cooling characteristics of cabbage maintained under RA and under CA of 5% CO_2, 3% O_2 and 92% N_2.

MATERIALS AND METHODS

Effects of Thermocouple Location and Cabbage Mass on the Cooling Characteristics

The first cooling experiment was performed to determine the best thermocouple location for calculating CR and CC. Six cabbage heads of mass varying between 1.6 and 6.0 kg were used in this study. Cabbage temperatures were measured with type-T thermocouples at the following locations: under the first outer cabbage leaf, L-1; 25 and 75 mm into the leafy portion, L-25 and L-75; and 25 and 75 mm into the stem, S-25 and S-75.

To assess the reproducibility of the cooling conditions, the cabbages were subjected to two consecutive cooling cycles. Each cycle consisted of a 24-h warm-up phase at 15°C followed by a 15-h cooling phase at 0°C. During the cooling cycle, the air and cabbage temperatures were measured at 2-h intervals and recorded with a data logger having a resolution of 0.1 C. CR and CC were then estimated using Eqs. 2 and 4, respectively.

Cooling Characteristics of Cabbage under RA and CA of 5% CO_2, 3% O_2 and 92% N_2

The second experiment was performed to determine CC of cabbage stored under RA and CA conditions. Figure 1 shows a cross section of one of the four double-walled containers used in this experiment. The container made of polyethylene plastic was designed to hold 25 kg of cabbage. The desired gas mixtures were generated by mixing pure gases from high-pressure cylinders equipped with double-stage regulator and rotometer. The gas compositions were obtained by adjusting the flowrate of each constituent to the calculated values. As shown in Fig. 2, two sets of gas cylinders were used for the experiment. Set-A was kept in an adjacent cold room maintained at 0°C and it was used during the cooling phase. Set-B was held outside the cold room at 20°C and used for the warm-up phase. The gas flushing rate was 1 L/min per container and maintained constant throughout the experiment.

Each gas composition was applied twice to the containers in the sequence shown in Fig. 3. The overall duration of the experiment was 160-h with warm-up (20°C) and cooling (0°C) phases lasting 24 and 16 h, respectively. The cabbage temperature was measured 25 mm deep into the leafy portion with two type-T thermocouples per head. The temperature data were collected in four cabbage heads per container. Air and cabbage temperatures were recorded every 2 h with a data logger having a resolution of 0.1°C. The average cabbage mass was 2.8 kg with a standard deviation of 0.2 kg. Nonparametric statistics were used to analyze the data, since CC obtained under the conditions tested were compared on an individual cabbage basis.

TABLE I. CR, *J*-VALUES AND CC VALUES OBTAINED AT DIFFERENT THERMOCOUPLE LOCATIONS IN THE 3.43-kg CABBAGE

Cooling cycle	Thermocouple location†	*j*-value	CR (2–12 h)	R^2	CC (0–12 h)	CC (2–12 h)
1	L-1	0.65	0.24	0.948	0.40	0.21
	L-25	0.96	0.20	0.999	0.24	0.20
	L-75	1.18	0.16	0.982	0.16	0.18
	S-25	0.95	0.22	0.997	0.26	0.22
	S-75	1.12	0.19	0.994	0.19	0.20
2	L-1	0.64	0.25	0.950	0.58	0.22
	L-25	0.95	0.20	0.999	0.26	0.19
	L-75	1.15	0.16	0.986	0.16	0.17
	S-25	0.91	0.21	0.994	0.29	0.20
	S-75	1.07	0.18	0.998	0.21	0.19

†L = depth of thermocouple in cabbage leaves; S = depth of thermocouple in cabbage stem.

RESULTS AND DISCUSSION

Effects of Thermocouple Location and Cabbage Mass on the Cooling Characteristics

In this experiment, two consecutive cooling cycles were performed on cabbage exposed to normal air composition. The thermocouple location that yields best approximation of cabbage CR was obtained by plotting the temperature difference ratio versus time on a semi-log paper over the first 12 h of cooling. The trends observed were similar for all six cabbage heads studied and will be described using the temperature data collected for a 3.43-kg cabbage during the first cooling cycle (Fig. 4). Closest agreements with the theoretical Newtonian cooling curve were observed with thermocouples L-25 and S-25 with *j* values of 0.96 and 0.95 respectively (Table I). From these results, it appeared that the MA-T location (*j* value of 1.0) resided just below 25 mm into the cabbage. Although the

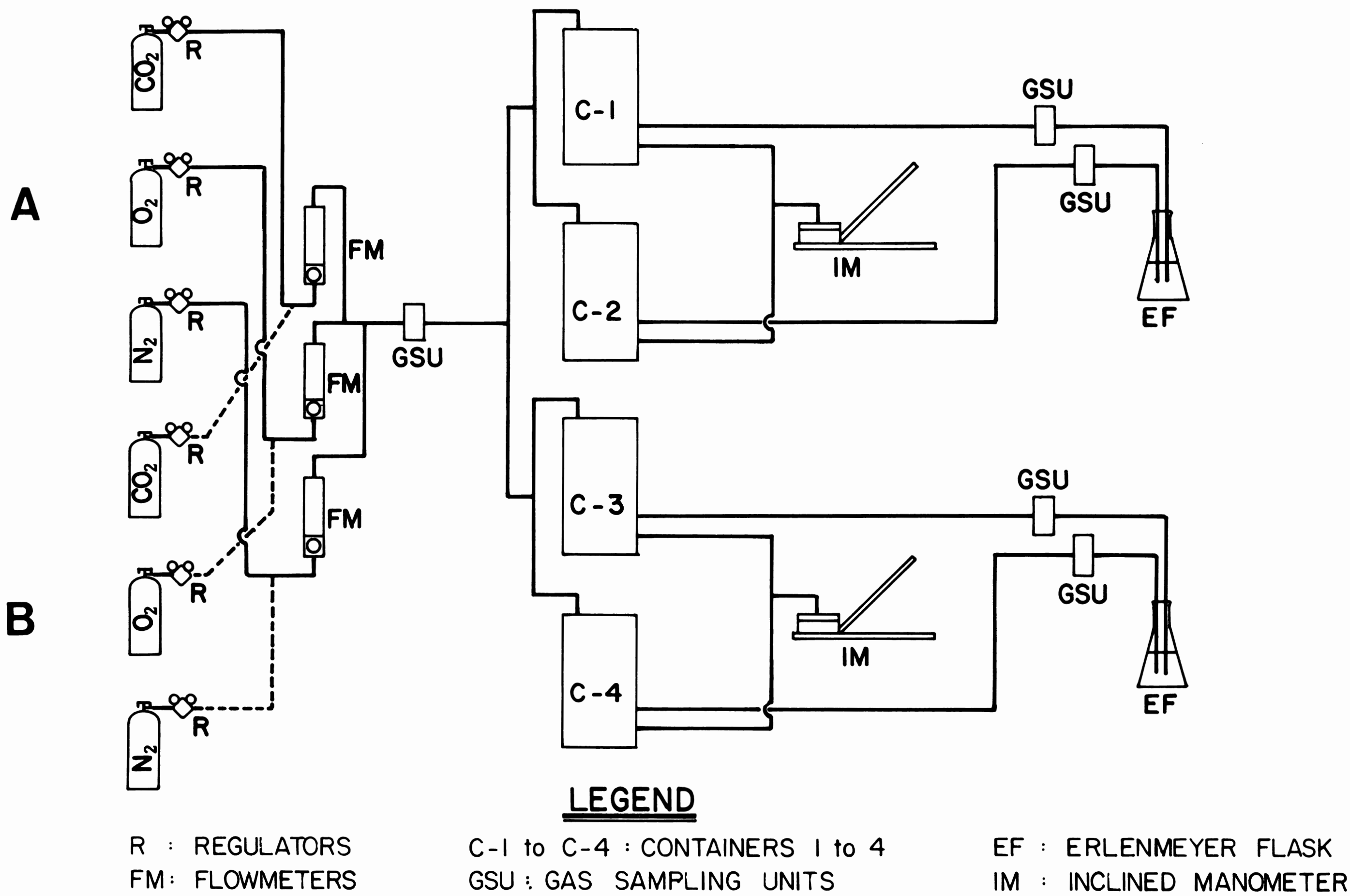

Figure 2. Schematic of the gas flow system used to provide the desired gas composition.

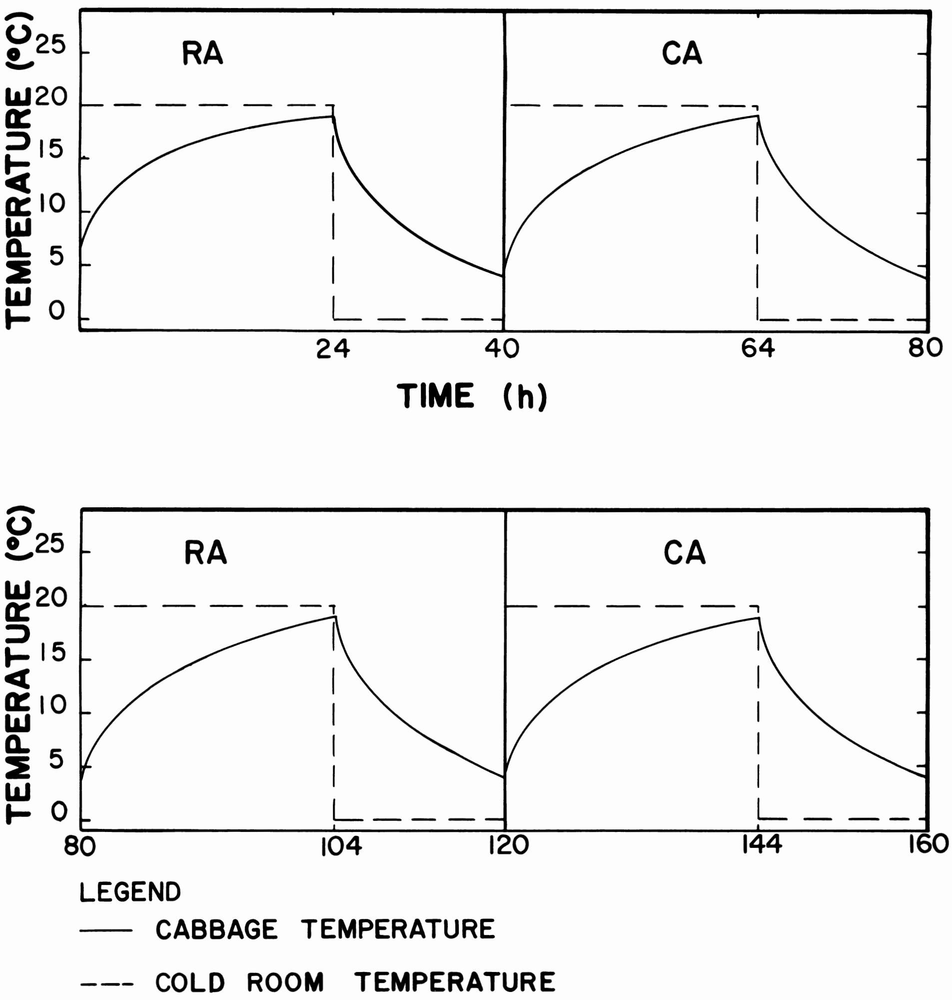

Figure 3. Cyclical sequence followed for studying the cooling characteristics of cabbage under RA and CA of 5% CO_2, 3% O_2 and 92% N_2.

TABLE II. LOWEST, AVERAGE AND HIGHEST GAS CONCENTRATIONS MAINTAINED IN THE EXPERIMENTAL CONTAINERS DURING THE EXPERIMENT ON COOLING CHARACTERISTICS OF CABBAGE STORED UNDER RA AND CA OF 5% CO_2, 3% O_2 AND 92% N_2

Gas composition tested	% CO_2			% O_2			% N_2		
	Low	Avg.	High	Low	Avg.	High	Low	Avg.	High
RA-1	0.1	0.4	0.7	19.7	20.8	21.4	78.6	78.8	80.2
CA-1	4.6	4.9	5.5	3.1	3.4	3.7	91.5	91.7	92.0
RA-2	0.1	0.3	0.5	21.1	21.3	21.5	78.3	78.4	78.4
CA-2	4.7	4.8	4.9	2.5	2.9	3.3	91.9	92.3	92.7

TABLE III. AVERAGE CC VALUES OBTAINED UNDER EACH GAS COMPOSITION TESTED AND COMPUTED OVER DIFFERENT TIME INTERVALS

Gas composition	CC (2–14 h)	CC (2–12 h)	CC (4–10 h)
RA-1	0.351	0.364	0.293
CA-1	0.360	0.370	0.298
RA-2	0.346	0.360	0.292
CA-2	0.350	0.364	0.294

cabbage head was not a perfect sphere made of homogeneous material, Eq. 3 yielded a good estimate of the actual MA-T location with 21 mm.

At each thermocouple location, CC was determined with Eq. 4 over the same time interval (Table I). The values obtained were much higher than those for CR. However, when based on the time interval of 2–12 h, CC values were closer to their corresponding CR values. This demonstrates the importance of computing CC over the straight portion of the cooling curve.

To assess the reproducibility of the cooling system, a Wilcoxon matched-pairs signed-rank test was performed on CR and CC data obtained for cycles 1 and 2. Under the conditions tested, the reproducibility was acceptable since the differences between cycle-1 and cycle-2 were not significant at the 0.05 level.

To assess the effect of mass on the cooling characteristics of cabbage, CR and CC values computed at L-25, were plotted against the cabbage mass (Fig. 5). They were exponentially related to the cabbage mass. The CR regression equation was:

$$CR = -0.127 \ln(m) + 0.372 \quad (5)$$

with an R^2 of 0.812 (0.0001 level of significance). The regression equation for CC was:

$$CC = -0.117 \ln(m) + 0.358 \quad (6)$$

with an R^2 of 0.804 (0.0001 level of significance). When established for a given set of cooling conditions, these equations are very useful to predict the CR and CC of the product just by knowing its mass.

Cooling Characteristics of Cabbage under RA and CA of 5% CO_2, 3% O_2 and 92% N_2

This experiment was conducted to determine and compare the cooling characteristics of cabbage stored under RA and CA of 5% CO_2, 3% O_2 and 92% N_2. Chromatographic analyses of the gas composition maintained in the containers are presented in Table II. The CO_2 concentrations maintained under both RA treatments were higher than the level of 0.03% found in regular air due to CO_2 accumulation resulting for the product respiration.

Three different time intervals were used to compute the CC values (Table III). Characteristics of the cooling medium, variations in the setup performance, response of the product metabolism to the cooling medium and the time interval over which CC was computed were factors responsible for the differences in the

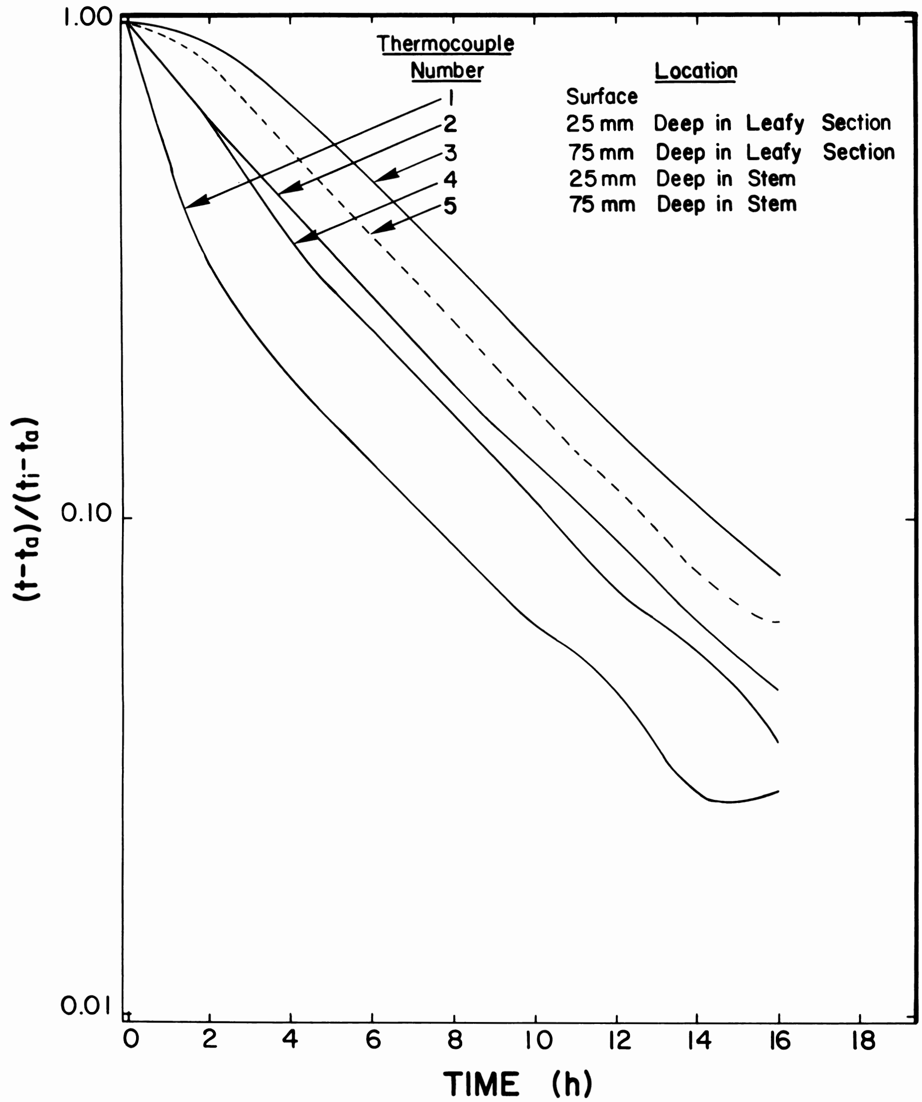

Figure 4. Temperature ratio versus time curves obtained from the temperature data collected at different thermocouple location in the cabbage of 3.43 kg.

magnitude of CC values. A Wilcoxon matched-pairs signed-rank test was used to determine whether the differences in CC between two consecutive treatments were significant (Table IV). Since the cabbage temperature was measured at 32 different locations, it was possible to use the normal distribution to estimate the test probability (Daniel 1978). As shown in Table IV, most matched-pairs tested were significantly different at the 0.05 level. Although the time interval over which CC was computed yield different values for the same treatment, it did not drastically affect the results of the statistical analysis. However, the analysis performed for the time interval 4–10 h yielded less significant results.

Even if the statistical analysis seemed to indicate that the cabbage stored under 5% CO_2, 3% O_2 and 92% N_2 cooled faster than under normal air composition, the differences observed were too small (less than 1.5% on the average) to be economically practiced.

RECOMMENDATIONS

(1) The best thermocouple location for optimum approximation of the cooling characteristics of cabbage with Newton's Law of Cooling is at the mass-average temperature location.

(2) Equations that expressed the CR and CC as a function of the product mass under a given set of cooling conditions are very useful in predicting the cooling characteristics of product of different masses.

TABLE IV. RESULTS OBTAINED FROM THE WILCOXON MATCHED-PAIRS SIGNED-RANK TEST PERFORMED ON THE CC DATA COMPUTED OVER DIFFERENT TIME INTERVALS

Matched pairs	Corrected number of observations	T+	T−	Z	Pr Z
CC (2–14 h)					
RA-1 and CA-1	29	134.0	301.0	−1.806	0.0351*
CA-1 and RA-2	32	456.5	71.5	−3.600	0.0002**
RA-2 and CA-2	28	61.0	345.0	−3.236	0.0006**
CC (2–12 h)					
RA-1 and CA-1	32	95.5	432.5	−3.152	0.0008**
CA-1 and RA-2	32	427.0	101.0	−3.049	0.0011**
RA-2 and CA-2	32	101.0	427.0	−3.049	0.0011**
CC (4–10 h)					
RA-1 and CA-1	32	168.5	359.5	−1.786	0.0367*
CA-1 and RA-2	31	350.5	145.5	−2.009	0.0222*
RA-2 and CA-2	29	155.0	280.0	−1.353	0.0885

**Test between matched pairs is significant at the 0.01 level.
*Test between matched pairs is significant at the 0.05 level.

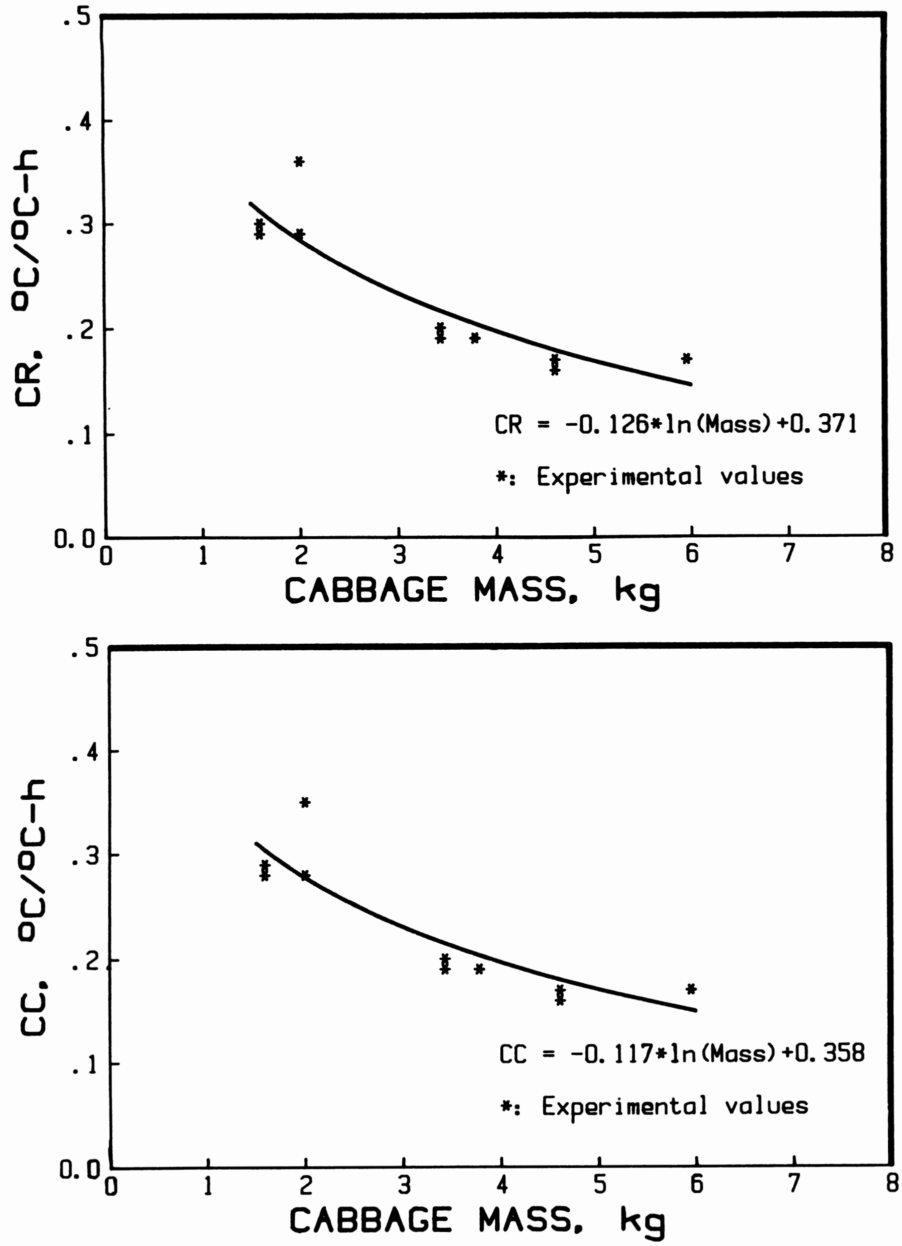

Figure 5. CR (top) and CC (bottom) obtained from the temperature data collected at L-25 plotted against the cabbage mass.

(3) The time interval over which CC and CR are computed affects the magnitude of theses parameters and therefore should be carefully selected by the user in order to represent the cooling procedures studied.

(4) The averaged CC value obtained for cabbage cooled under CA of 5% CO_2, 3% O_2 and 92% N_2 was 1.5% greater than under RA and therefore does not have any economical potential from the cooling point of view.

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