EFFECTS OF VACUUM RATE ON THE VACUUM COOLING OF LETTUCE

by

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ABSTRACT

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The deterioration of freshly harvested horticultural crops can be minimised by precooling prior to storage. This technique of quickly cooling the produce does not only increases the shelf life, but it also reduces the size of the refrigeration system needed for storage facility. Vacuum cooling is an effective method of precooling leafy vegetables, but has a major drawback of requiring substantial initial capital investment. Thus, vacuum coolers are generally limited to large-scale or co-op operations where the initial investment can be spread across a large quantity of produce.

The conventional philosophy behind precooling design is to establish systems to cool produce as quickly as possible; this concept is more so with vacuum coolers. By changing certain design criteria of a vacuum cooler, it may be possible to reduce the capital cost of vacuum coolers by reducing the rate of vacuum. Though the time to cool the produce may be increased, the reduction in the size of the vacuum pump and the refrigeration system, and hence the capital cost of the cooler, may be beneficial to small-scale producers who can not justify the large expenses incurred when purchasing a conventional system.

Experiments were performed on a modified vacuum cooler in which the rate of vacuum could be controlled. The cooling characteristics, including the temperature distribution and mass loss, and the lettuce quality were determined for different rates of vacuum. A relationship between the speed of the vacuum and the peak product refrigeration load was developed and tested with experimental data. The results suggest that slower vacuum coolers can be successfully designed and built for small-scale operations.

RÉSUMÉ

TIMOTHY JOHN RENNIE

M. Sc. Génie Agricole et des Biosystèmes

EFFETS DE LA VITESSE DE MISE SOUS VIDE SUR LE REFROIDISSEMENT DE LA LAITUE

La détérioration des fruits et des légumes fraîchement récoltés peut être réduite en utilisant un refroidissement rapide immédiatement après la récolte. De plus, en retirant la chaleur de champs accumulée dans le produit avant de le placer en entrepôt, cela permet de réduire considérablement la capacité des unités frigorifiques installées. Le refroidissement sous vide est une méthode rapide et efficace qui est bien adaptée au refroidissement des légumes feuillus. Son principal inconvénient est le coût relié à l'achat des équipements. Pour cette raison, son utilisation commerciale est limitée aux entreprises agricoles d'envergure ou aux coopératives agricoles qui refroidissent de grandes quantités de produits.

La philosophie conventionnelle derrière la conception des systèmes de pré-refroidissement vise habituellement la performance technique, et cela, particulièrement pour les refroidisseurs sous vide. Les systèmes doivent se libérer le plus rapidement possible de leur tâche afin de maximiser les vitesses de refroidissement, et la qualité du produit traité. Cependant, il serait possible de réduire considérablement la dimension et le coût des composantes du système de pré-refroidissement sous vide en acceptant une baisse de performance du système sans pour autant affecter de façon marquée la qualité des produits refroidis. La diminution du coût d'achat de l'équipement pourrait permettre aux petits producteurs d'utiliser de cette technique de refroidissement rapide.

Des essais ont été effectués en laboratoire pour étudier les effets de la vitesse de mise en régime sous vide sur le taux de refroidissement et la qualité de la laitue pommée. Les caractéristiques de refroidissement, incluant la distribution de la température, les pertes de poids et la qualité de la laitue ont été mesurées et comparées pour différentes

vitesses de mise en régime sous vide. Une relation mathématique reliant la vitesse de mise sous vide et la demande maximale en réfrigération a été développée et validée. Les résultats obtenus suggèrent que des refroidisseurs sous vide plus lents peuvent être conçus sans pour autant affecter la qualité des produits refroidis. Cette idée devrait permettre la conception et la construction de refroidisseurs sous vide de moins grande capacité répondant ainsi aux besoins des entreprises agricoles de plus petites tailles.

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FORMAT OF THESIS

This thesis is submitted in the form of original papers suitable for journal publication. The thesis format has been approved by the **Faculty of Graduate Studies and Research, McGill University,** and follows the conditions outlined in the **"Guidelines Concerning Thesis Preparation,** section 7, **Manuscripts and Authorship"** which are as follows:

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The work reported here was performed by the candidate and supervised by **Dr. G.S.V. Raghavan** of the Department of Agricultural and Biosystems Engineering, Macdonald Campus of McGill University, Montreal, and **Dr. C. Vigneault** of the Postharvest Quality Laboratory, Horticultural Research and Development Centre, Agriculture and Agri-Food Canada, Saint Jean-sur-Richelieu. The entire research project was conducted at the Horticultural Research and Development Centre. The authorship for the papers are 1) T.J. Rennie, G. S. V. Raghavan, C. Vigneault, and Y. Gariépy, 2) T.J. Rennie, G. S. V. Raghavan, C. Vigneault, and J. DeEll, 3) T.J. Rennie, G. S. V. Raghavan, and C. Vigneault for the papers in Chapters IV, V, and VI, respectively.

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NOMENCLATURE

a	Constant in equation
A	Surface area (m^2)
A	Pressure at which control begins (mm Hg)
b	Constant in equation
B	Vacuum pump speed parameter (s^{-1})
B_i	Biot number
c	Constant in equation
C_1, C_2, C_3, C_4, C_5, C_6, C_7	Constants used in equations
c_p	Specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)
c_{pc}	Specific heat of vacuum chamber ($J \cdot kg^{-1} \cdot K^{-1}$)
C_T	Transpiration coefficient ($g \cdot kg^{-1} \cdot s^{-1} \cdot Pa^{-1}$)
CC	Cooling coefficient (s^{-1})
C_2H_4	Ethylene molecule
$C_6H_{12}O_6$	Glucose molecule
CO_2	Carbon dioxide molecule
CR	Cooling rate (s^{-1})
d	Constant in equation
E	Total energy used (kJ)
EC	Energy coefficient
Fo	Fourier number
F_M	Maximum total fluorescence (dark adapted)
F_M'	Maximum total fluorescence (light adapted)
F_V	Maximum variable fluorescence (dark adapted)
F_V'	Maximum variable fluorescence (light adapted)
ΦF	Fluorescence yield
ΦF_M	Maximum fluorescence yield
ΦF_O	Minimum fluorescence yield
h	Convection heat transfer coefficient ($J \cdot s^{-1} \cdot m^2 \cdot K^{-1}$)

h_{fg}	Latent heat of vaporisation ($kJ \cdot kg^{-1}$)
h_{fgt}	Triple point latent heat of vaporisation ($kJ \cdot kg^{-1}$)
H_2O	Water molecule
j	Lag factor
k	Thermal conductivity ($J \cdot s^{-1} \cdot m^{-1} \cdot K^{-1}$)
k_D	Thermal deactivation rate constant
k_F	Fluorescence rate constant
k_P	Photochemical reaction rate constant
k_T	Excitation energy transfer rate constant
m	Mass (kg)
m_L	Mass loss (kg)
m_p	Mass of product (kg)
M_T	Transpiration rate ($g \cdot s^{-1}$)
NaCl	Sodium chloride molecule
O_2	Oxygen molecule
p	Absolute pressure (kPa)
P	Pressure (mm Hg)
$P_i - P_o$	Water vapour pressure difference (Pa)
p_{ws}	Saturation pressure of water (Pa)
ΦP	Photochemical reaction potential yield
Q	Heat removed per unit mass ($kJ \cdot kg^{-1}$)
Q_f	Heat removed (kJ)
Q_{10}	Temperature coefficient
q	Heat transfer rate ($J \cdot s^{-1}$)
q_g	Heat generation rate ($J \cdot s^{-1} \cdot m^{-3}$)
q_p	Product cooling rate ($J \cdot s^{-1}$)
RQ	Respiratory quotient
S	Pumping rate ($m^3 \cdot s^{-1}$)
S_O	Characteristic dimension
t	Temperature ratio
T	Absolute temperature (K)

T_a	Cooling medium temperature (K)
T_c	Critical temperature (K)
T_i	Initial product temperature (K)
T_{ma}	Mass-average temperature (°C)
T_p	Product temperature (K)
TRPML	Temperature reduction per percent mass loss (°C)
$T_{½}$	Fluorescence half-life (ms)
v	Specific volume ($m^3 \cdot kg^{-1}$)
V	Volume (m^3)
V_t	Total volume of retort (m^3)
W	Sensible heat removed (kJ)
W_v	Water vaporised ($kg \cdot kg^{-1}$ produce)
W_P	Produce mass (kg)
x	Spatial co-ordinate (m)
y	Spatial co-ordinate (m)
z	Spatial co-ordinate (m)
Z	Half-cooling time (s)
ΔT	Produce temperature change (°C)
λ	Ratio of latent heats
ρ	Density ($kg \cdot m^{-3}$)
ρ_p	Product density ($kg \cdot m^{-3}$)
θ	Time (s)

I. GENERAL INTRODUCTION

Postharvest losses of fresh fruits and vegetables are of great concern to the food industry. It is estimated that the losses are 5 to 25 percent of the total harvest in developed countries and 20 to 50 percent in developing nations, depending on the commodity (Kader, 1992). Though fruit and vegetable production is much lower than grain production, they hold an important part in the diet as they are, in general, high in nutrients and minerals. Thus, preventing postharvest losses are important in order to supply produce with high nutritional value. Advances in postharvest technologies are important to reducing these losses.

The difficulty with the postharvest handling and storage of fresh fruits and vegetables is that they are living organisms and must remain alive until they are either processed or consumed (Fraser, 1991). After harvest, the commodity continues to respire using the food reserves that were stored in the produce prior to harvest (Mitchell *et al.*, 1972). Respiration is responsible for providing energy to the produce to perform life-sustaining process. The process of respiration involves the breakdown of organic material and the liberation of carbon dioxide and heat. As decreasing the product temperature slows the respiration process, low temperature storage above the freezing point enhances the storage life of the produce.

Upon harvest, it is important to immediately place the produce in a cold environment to prolong its shelf life, with exception to a few specific crops that benefit from holding them at warmer temperatures for suberization or wound healing before their subsequent storage period. The immediate placing of warm produce into regular cold storage rooms has two major drawbacks. The first is that the immediate cooling load imposed on the refrigeration system will be quite large, as the system must remove the sensible heat and the respiratory heat of the produce as quickly as possible. Once achieved, the refrigeration load is much smaller as all that is required is to provide the necessary cooling to maintain the storage temperature, which includes air infiltration, heat conduction and convection, and removal of the heat of respiration, which is at a minimum due to the low temperature of the produce. Thus, the total refrigeration system

is using very little of its refrigeration capacity for the majority of the storage period. The second problem is that the cooling of the produce is very slow in normal storage rooms as the produce is cooled by convection and generally the airflow is not adequately distributed nor in enough quantity to quickly cool the produce. Therefore, the produce undergoes more deterioration than if it had been cooled quickly. For some produce this quick cooling is essential, as they may deteriorate as much in one hour at 26°C as they would in a week at 1°C (Boa *et al.*, 1976).

For these two problems, precooling can provide a solution. Precooling is the quick cooling of produce immediately upon harvest and before being placed in cold storage or into long distance transport. There are a number of precooling methods, such as forced-air, hydrocooling, liquid-ice, and vacuum cooling. Each method has its advantages and disadvantages. The answer to which method to use depends on the type or types of produce to be cooled and the size of the operation. The characteristics of the produce have a profound influence as some produce are readily damaged due to water exposure or may experience high moisture loss when subjected to airflow. Some methods have low capital cost but high operating costs while other methods may be the opposite with high capital costs and low operating costs.

The latter is the case for vacuum cooling. Vacuum coolers are very effective at quickly cooling produce that have high surface area to mass ratios, but the number of such produce is limited and the capital cost of a vacuum cooler is large. Vacuum coolers are, in general, limited to large scale operations, or co-ops, where the capital costs can be spread over a large quantity of produce or amongst many producers. In areas where vegetable production is important but done at a relatively small scale, such as in Québec and Ontario, many of the operations cannot justify the purchase of a vacuum cooler that has been designed in the traditional sense. For some produce, such as lettuce, a slight delay in reaching its storage temperature may not greatly affect its storage duration or quality. Thus, if a vacuum cooler were to be designed with a slower vacuum rate, the size of the vacuum pump, and possibly the refrigeration system, could be reduced, resulting in the reduction of the capital cost of the cooler. The lettuce could still be vacuum cooled with little or no effect on the long-term quality of the lettuce, while maintaining the benefits of vacuum cooling lettuce. The other alternative would be to use

hydrocooling or forced-air cooling to cool the lettuce, but both these approaches are not suited for lettuce as the water left on the lettuce increases the susceptibility to micro-organism growth and forced-air cooling tends to cause too much moisture losses from lettuce. Unfortunately, very little is known about the effects of reducing the vacuum rate on the quality of the lettuce, the cooling characteristics, and the size of the required refrigeration system.

II. GENERAL OBJECTIVES

The overall objective of this study is to determine the effects of the vacuum rate on the vacuum cooling of lettuce. The study can be broken down into three main categories as follows:

1. Evaluation of the temperature distribution and the mass loss under different vacuum rates (cooling characteristics).
2. Evaluation of the lettuce quality during the subsequent storage as affected by the rate of vacuum application.
3. The relationship between the product refrigeration load and the vacuum rate for lettuce.

III. LITERATURE REVIEW

3.1 Postharvest Physiology

Freshly harvested fruits and vegetables, though appearing as inanimate objects, continue to live in a dynamic state. Upon harvest, they lose the supply of nutrients, minerals, and water that the parent plant was delivering for necessary life functions. The fruit or vegetable continues to live by relying on the nutrients, minerals, and water that it has stored. Harvest time coincides with the maximum "potential quality" of the commodity. The nutrient and mineral contents are at the maximum, as these can only decrease as they are being used to keep the commodity alive. On the other hand, the "consumer quality" may not be at its highest when harvested. The commodity may be harvested while still immature, and the subsequent storage will allow it to ripen and become more flavourful. In both cases, postharvest physiology plays an important role in the quality of the commodity. It is desirable to maintain high nutritive quality as well as providing a high consumer quality when delivered to the market. The physiological processes that occur within the commodity after harvest are directly linked to its quality. Therefore, understanding of the major postharvest physiological processes is necessary in the implementation of proper postharvest systems. Four aspects of physiology of major concern in postharvest systems are: (1) product respiration, (2) product transpiration, (3) ethylene synthesis, (4) chilling injury.

3.1.1 Respiration

Respiration occurs continuously in all active cells of a fruit or a vegetable after harvest. It is an oxidation-reduction process in which photosynthetic compounds are oxidised to carbon dioxide (CO_2), and oxygen (O_2) is reduced to form water. The chemical reaction under aerobic conditions is often represented as the following (Hopkins, 1995):

$$C_6H_{12}O_6 + 6O_2 \Rightarrow 6CO_2 + 6H_2O + 2872 \text{ kJ/mol} \qquad (3.1)$$

The reaction shown above is based on one mole of glucose ($C_6H_{12}O_6$). The above reaction is simplified for easy understanding. The entire reaction is actually made up of more than 50 component reactions, with each reaction occurring due to a different enzyme. The process of respiration can use many substrates other than $C_6H_{12}O_6$, such as starches, sucrose, fats, organic acids, and proteins (Salisbury and Ross, 1992). The formation of adenosine triphosphate (ATP) is the most important function of respiration. ATP is formed by the addition of an inorganic phosphate to adenosine diphosphate (ADP). The formation of ATP is a method of storing energy for later use in the cells, for essential functions such as growth and ion accumulation. By-products are produced as the reaction proceeds. Some of the by-products include carbon-skeleton intermediates, which are used as the basic building blocks of cell structure, such as amino acids.

When the process of respiration completely oxidises carbohydrates, such as glucose, sucrose, or starch, the amount of CO_2 evolved will equal the amount of O_2 absorbed. If other substrates are used, or if there is incomplete oxidation, then the amount of O_2 used and the amount of CO_2 evolved will not always be equal. The ratio of CO_2 to O_2 is referred to as the respiratory quotient (RQ) and may be expressed as follows:

$$RQ = \frac{CO_2 \text{ evolved } (\text{ml } CO_2 \cdot kg^{-1} \cdot h^{-1})}{O_2 \text{ absorbed } (\text{ml } O_2 \cdot kg^{-1} \cdot h^{-1})} \qquad (3.2)$$

The value of RQ can be useful in determining what type of substrates the cells are using. The difficulty in this is that many substrates can be oxidised at the same time and the RQ value gives an average of the CO_2 and O_2 relations.

The respiration rate depends on enzymatic activity, which is a function of temperature. Thus, temperature plays a significant role on the overall respiration rate since respiration requires the action of over 50 enzymes and the level of enzyme activity is affected by temperature. The effect of temperature on the respiration rate is often quantified by determining the Temperature Coefficient (Q_{10}) (Hopkins, 1995):

$$Q_{10} = \frac{\text{Respiration rate at } (T°C + 10°C)}{\text{Respiration rate at } T°C} \quad (3.3)$$

The Q_{10} may be calculated based on the number of $ml \cdot kg^{-1} \cdot h^{-1}$ of CO_2 evolved or O_2 absorbed. Generally, the respiration rate (Q_{10}) is increased by a factor of 2 to 4 for each temperature increase of 10°C (Kader, 1992). The rates of respiration of some common produce at different temperatures are shown in Table 3.1.

Table 3.1: Heat of respiration of produces at different temperatures (Singh and Heldman, 1984)

	Respiratory heat generated per unit mass ($mW \cdot kg^{-1}$)			
Commodity	0°C	5°C	10°C	15°C
Apples	10-12	15-21	41-61	41-92
Asparagus	81-237	161-403	269-902	471-970
Blackberries	46-68	85-135	154-280	208-431
Blueberries	7-31	27-36	69-104	101-183
Cabbage	12-40	28-63	36-86	66-169
Cauliflower	53-71	61-81	100-144	136-242
Celery	21	32	58-81	110
Corn, Sweet	125	230	331	482
Leeks	28-48	58-86	158-201	245-346
Lettuce, head	27-50	39-59	64-118	114-121
Mushrooms	83-129	210	297	---
Onions	7-9	10-20	21	33
Oranges	9	14-19	35-40	38-67
Peaches	11-19	19-27	46	98-125
Pears	8-20	15-46	23-63	45-159
Raspberries	52-74	92-114	82-164	243-300
Strawberries	36-52	48-98	145-280	210-273

Modification of the gas composition surrounding the produce after harvest may be used to control the respiration rate. It has been observed that increasing the CO_2 level and decreasing the O_2 level tends to decrease the rate of respiration of some produce (Kays, 1997). It is important not to allow the O_2 level to go too low or anaerobic respiration will occur, resulting in the occurrence of fermentation and unwanted by-products such as aldehydes and alcohol. Exposure of some produces to short periods of anaerobic conditions may be enough to produce off-flavours and these flavours may

persist even if the produce are returned to aerobic conditions (Kays, 1997). High CO_2 levels have been known to cause damage to some produces (Kays, 1997), resulting in irregular ripening in some fruits or an increase in the susceptibility of decay (Kader, 1992).

3.1.2 Transpiration

Transpiration is the movement of water from the fruit or vegetable to the surrounding atmosphere. This process reduces the overall weight of the produce. If a significant water loss occurs, the produce may experience shrivelling or become limp, resulting in lower customer satisfaction. Transpiration is a mass transfer process with the driving force being a water vapour pressure gradient. The relationship between the rate of water loss and the pressure difference is generally given as (Sastry et al., 1978):

$$M_T = C_T \cdot W_p \cdot (P_i - P_o) \tag{3.4}$$

where

M_T = Transpiration rate ($g \cdot s^{-1}$)

C_T = Transpiration coefficient ($g \cdot kg^{-1} \cdot s^{-1} \cdot Pa^{-1}$)

W_p = Produce mass (kg)

$P_i - P_o$ = Water vapour pressure difference (Pa)

Sastry et al. (1978) gives an extensive list of transpiration coefficients that have been cited in literature. The water vapour pressure deficit is the difference between the water vapour pressure inside the produce and the water vapour pressure of the surrounding air. The water vapour pressure inside the produce is considered to be the saturated water vapour pressure evaluated at the product's surface temperature since most fruits and vegetables contain 80 to 95 % water (Sastry et al., 1978). The ambient temperature and relative humidity determine the ambient water vapour pressure.

Other factors have been noted to have an effect on transpiration. The air velocity around the produce can have a slight effect on the rate of moisture loss when the product and the ambient air are in thermal equilibrium (Sastry et al., 1978). A difference between

the temperature of the product and its surrounding environment, such as during cooling, would increase the effect of air movement as the air film thickness surrounding the product would be reduced (Sastry et al., 1978).

The respiration rate affects the transpiration rate due to the liberation of heat. This tends to increase the temperature of the produce and hence increases the water vapour pressure deficit (Sastry et al., 1978). On the other hand, the process of respiration uses up substrates and produces water, the end result is a dilution of the substrates. This gives rise to a positive change in the water vapour pressure and therefore increases the transpiration rate.

The process of transpiration itself can affect the rate of moisture loss. This happens in two ways: first, the loss of water will concentrate the water and substrate mixture. This concentration will lower the saturation vapour pressure and hence increase the transpiration rate. Secondly, the cooling effect due to the evaporation of water from the product's surface causes localised cooling. This localised cooling which will tend to reduce the water vapour pressure deficit and decrease the transpiration rate. Many other factors can affect the transpiration rate, such as size, shape, surface area, surface structure, and maturity.

The attempt to reduce transpiration losses in storage is usually done by keeping a high relative humidity. For most produce, the relative humidity is kept in the range of 85 to 95 %. High relative humidity can result in condensation on the produce, and cause surface cracking on some produces (Kader, 1992). A relative humidity close to 100 % may be ideal for microorganism growth. Increasing the relative humidity in a storage room is usually done through the use of mechanical humidifiers, spray nozzles, or steam injection systems (Kader, 1992).

3.1.3 Ethylene

The third major physiological process that must be dealt with in postharvest storage of fruits and vegetables is that of ethylene (C_2H_4) synthesis. In fruits, C_2H_4 is the hormone that triggers ripening and senescence. As cells deteriorate, they produce C_2H_4, which spreads through the fruit causing senescence to begin in other cells. This can be a substantial problem in the storage of fruits. One fruit that begins to ripen can produce

high amounts of C_2H_4 that starts a chain reaction causing more fruits to begin to ripen. Respiration rates increase for many produces in the presence of C_2H_4.

Ripening, and the production of C_2H_4, may be delayed if the temperature of the produce is low, in the same way as respiration is slowed due to low temperature. Both low O_2 concentrations and low temperatures can slow the rate of C_2H_4 synthesis (Kays, 1997).

3.1.4 Chilling injury

Careful attention should be directed to produce which is susceptible to chilling injury. Chilling injury can occur when the produce is stored at low temperatures and results in internal and external browning, surface pitting, failure to ripen, increased susceptibility to micro-organisms, textural changes, and loss of quality (Kader, 1992). It is permanent or irreversible physiological damage caused to plant tissues, cells, or organs due to low temperature stress (Lyons and Breidenbach, 1987). The chilling temperature is a critical threshold temperature that will cause injury to the produce if it is stored below that temperature (Lyon and Breidenbach, 1987). For many warm season vegetables, this threshold temperature is between 10 and 12°C (Lyon and Breidenbach, 1987). In general, tropical and sub-tropical fruits are more likely to experience chilling injury than fruits from temperate zones (Ryall and Pentzer, 1974).

Chilling injury plays a crucial part in the postharvest storage of fruits and vegetables. The main method of prolonging storage life of produce is by maintaining low temperature conditions, which is not possible with chilling sensitive produce. Symptoms of chilling injury are often not displayed at the low temperature conditions, but usually developing rapidly after being removed from low temperature storage (Lyon and Breidenbach, 1987).

3.2 Precooling Methods

The effect of the respiration rate on the quality of fruits and vegetables has been extensively studied and documented. Some fresh fruits and vegetables may deteriorate as much in one hour at 26°C as in one week at 1°C (Boa and Lindsay, 1976). The major

reason for the deterioration is a high respiration rate, which results in quick reduction of the finite amounts of substrates available. A decrease in the temperature of the produce reduces the respiration rate, and hence prolongs the quality of the fruit or vegetable. For most produces, a storage temperature of 0 to 2°C is ideal. Quickly cooling the produce after harvest can lower the deterioration rate of the produce.

Precooling can be defined as the quick removal of field heat before the product is shipped to a distant market, processed, or stored (ASHRAE, 1998b). Generally, precooling takes a few minutes to a few hours, anything beyond this range can not be considered a precooling process. Temperature management plays the largest role in controlling the physiological processes that determine product quality.

As some produces are highly perishable, immediate precooling after harvest is necessary to maintain their quality. Fruits that fall into that category include apricots, avocados, all berries except cranberries, peaches and nectarines, plumes and prunes, mangoes, papayas, and pineapples (ASHRAE, 1998b). Vegetables that require immediate precooling include asparagus, snap beans, broccoli, cauliflower, sweet corn, cantaloupes, summer squash, vine ripened tomatoes, leafy vegetables, brussels sprouts, cabbage, celery, carrots, snow peas, and radishes (ASHRAE, 1998b).

Some produce should not be immediately cooled down after harvest. This is true for potatoes, yams, and sweet potatoes, which benefit from maintaining them at a temperature of 15 to 25°C for up to two weeks to allow for wound healing and suberization (Dennis, 1984). The temperature to which produce is cooled depends on their susceptibility to chilling injury.

The net effect of precooling operations is the increased storage life of the produce. This has economic benefits by extending the market season and increasing the potential distribution range. If it is expected that the produce is to be sold on the market within a reasonable amount of time, then precooling becomes unnecessary and its expenses can be avoided.

The choice of a precooling method is largely based on the physiognomy of the produce. The size, shape, and texture of the product need to be considered. The effect on the produce by exposure to high airflow, cold, or wet environments is important in choosing a precooling method. Some produce may be cooled by more than one method,

but with varying degrees of success. This, coupled with the economics of the precooling method, should be considered.

3.2.1 Room cooling

Room cooling is not considered as a true precooling method. The reason is that it does not quickly remove field heat. It deserves mentioning because it is one of the most widely used forms of cooling. Room cooling involves placing produce in a refrigerated room and allowing cold air to flow around the produce containers or pallets (Figure 3.1). For sufficient heat removal, the air velocity should be at least 1 to 2 m/s (Kader, 1992). Pallets should be placed so that the cold air from the evaporators travels across the top and around all sides of the pallet. For good air distribution, several small evaporators evenly spaced along one wall of the room are better than one large evaporator (Bartsch and Blanpied, 1984). Poor contact between the airflow and the pallets may not cool produce in the centre of the bin or pallet rapidly enough (Somogyi et al., 1996). Space should be left between all pallets and they should be orientated so that the forklift openings run in the same direction as the airflow.

This method of cooling has several advantages. It has low capital and energy costs and is very flexible. The produce can be cooled in the same room as they will be stored in, resulting in less handling of the produce compared to other precooling methods. The type of packaging used for the produce has an effect on the rate of cooling. Non-packaged produce cool faster than packaged produce. The amount of venting of fibreboard boxes can have a significant effect on the cooling time. Venting of 5% results in a reduction of the cooling time by 25% compared to boxes with no venting (Mitchell et al., 1972). The 5 % venting will cause a 2 to 3 % reduction in container strength as long as the vents are not situated in the corners of the container (Mitchell et al., 1972). It is preferable to have a few large vents rather than many small ones. Also, the vents should not be of a size and shape that would easily get blocked by the produce.

To maximise the cooling rate of room cooling, proper room management is necessary. Gradually filling the room with produce will allow the cooling to be quicker than if the room was filled to the maximum at one time. When the room is filled to the

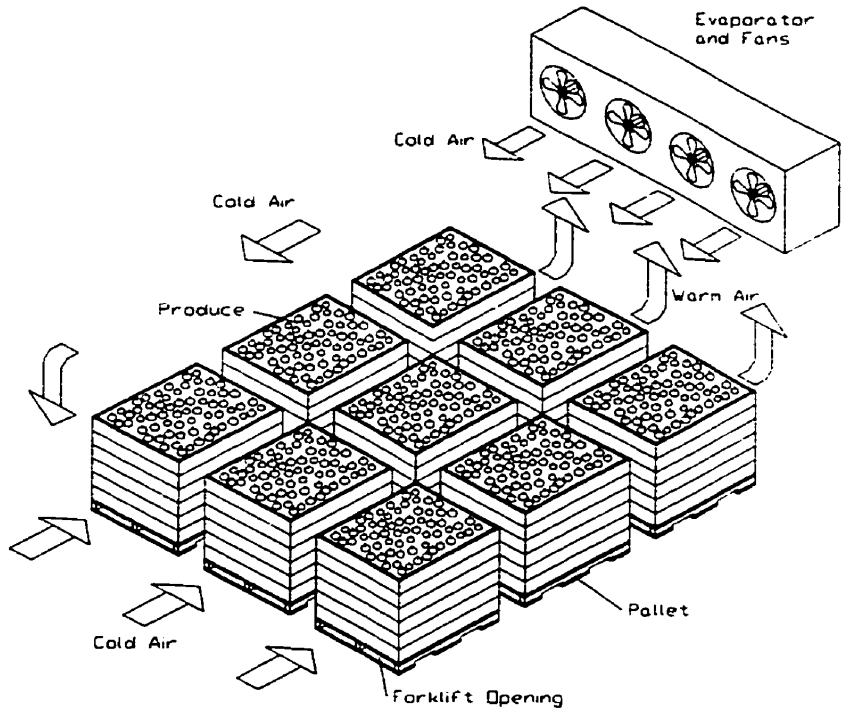

Figure 3.1: Schematic of air circulation during room cooling

maximum at one time, the refrigeration capacity is at its maximum since all the produce is at field temperature and the respiration rate is at its highest. By slowly adding produce, say at 10 % capacity per day, the greatest cooling load occurs when the final produce is placed in the room. At this time, 90 % of the produce will have fairly low temperatures and producing little respiratory heat. Only 10 % of the produce would require high cooling requirements.

Care must be taken when warm produce is added to a room containing cold produce. Warm produce may increase the air temperature and its humidity, when this air subsequently comes into contact with cold produce, the air will cool down and may cause moisture condensation on the cold produce (Mitchell et al., 1972). This problem may be avoided if the storage room is designed with cooling bays. A cooling bay is an area of the storage room that is sectioned off from the rest of the room. Thus, after the air is sent through the produce, it goes directly to the refrigeration system to be cooled. Warm and humid air is not allowed to reach cool produce. The airflow rate for each cooling bay may be controlled independently. This type of arrangement allows warm produce to be

cooled with large airflow rates without subjecting already cooled produce to moisture condensation or airflow rates that may cause excessive moisture loss.

3.2.2 Forced-air cooling

Forced-air cooling is one of the most widely used methods of precooling. It is an improvement over room cooling in that air is pulled through the produce mass rather than just being circulated around the produce containers. This close interaction between the airflow and the commodity results in forced convection cooling, which is much faster than conduction through the container walls and natural convection. Due to the change in the heat transfer method, forced-air cooling can cool produce four to ten times faster than room cooling (Mitchell et al., 1972). The movement of air through the containers allows for a more uniform temperature distribution inside the pallet (Boyette, 1996).

Forced-air cooling offers a number of advantages over other precooling techniques. The equipment costs are generally low and makes it an affordable method for small-scale operations (Fraser, 1991). The cooling rate is relatively high and many different produces are suitable to be cooled by this method. There are a number of different configurations used in forced-air cooling, but they all work on the same basic principle. Fans are used to create a static pressure difference between opposite sides of a pallet. This difference results in a movement of air from the high-pressure side to the low-pressure side. The pallets are arranged in such a manner that the air has only one path, through the mass of produce. This will replace the warm air between the commodities by cold ambient air. The static pressure difference that is created is usually in the range of 3 to 25 mm of water gauge, with 12 mm of water being a typical value (Fraser, 1991). For adequate heat removal, the airflow rate should be between 0.5 to 3 $L \cdot s^{-1}$ per kilogram of produce (Fraser, 1991). Fans should be selected that match the required airflow rate at the given static pressure difference. Most fan manufacturers produce performance charts for their fans. These charts generally indicate the size of the fans, the power requirements, rotational speed, and the flow rate at a given static pressure difference. Some manufacturers have fan performance charts prepared by independent organisations that test the fans under standard testing procedures. The Air Movement and Control Association (ACMA, Arlington Heights, Illinois) in co-operation with the

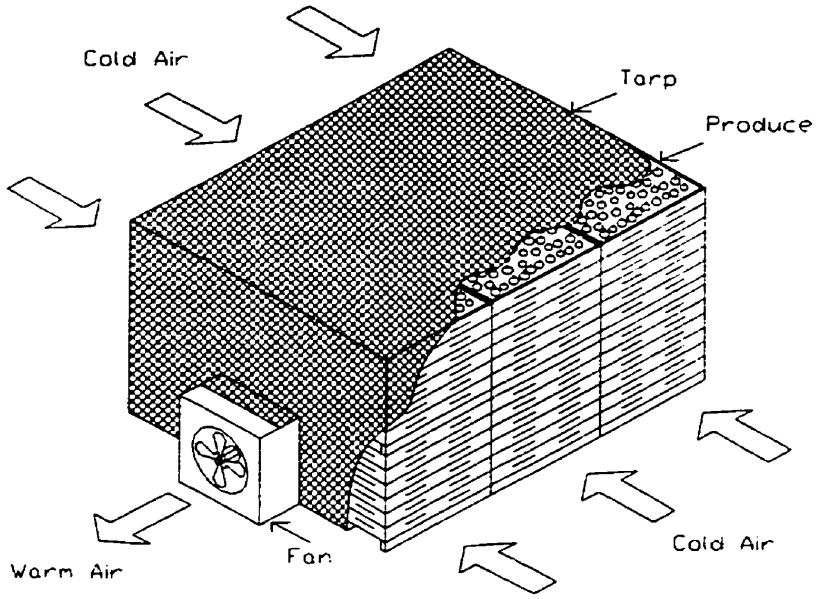

Figure 3.2: Schematic of a forced-air cooling tunnel

American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE, Atlanta, Georgia), have published Standard 210 which describes lab procedures for the testing of fans. The Prairie Agricultural Machinery Institute (PAMI, Humboldt, Saskatchewan) is a major organisation that tests fans for agricultural applications in Canada.

One of the most common types of forced-air cooling is the forced-air tunnel system as shown in Figure 3.2. Two rows of palletised containers are placed so that a tunnel (plenum) exists between them. A fan is placed at one end of the tunnel and the remaining open area of the tunnel is covered with a tarp. The tarp must be well attached to the pallets to reduce the amount of air that can enter the plenum without going through the produce. The fan should be set up to create a negative static pressure in the plenum. Pulling the air through the containers is more effective than pushing the air through (Somogyi et al., 1996).

Care must be taken when using a forced-air tunnel system in a room where cooled produce is present because the exhaust air from the tunnel is warmer than the ambient. As this warm air passes over the cold produce, the water vapour may condense on the produce. Placing the end of the tunnel directly at the air intake of the cooling system can

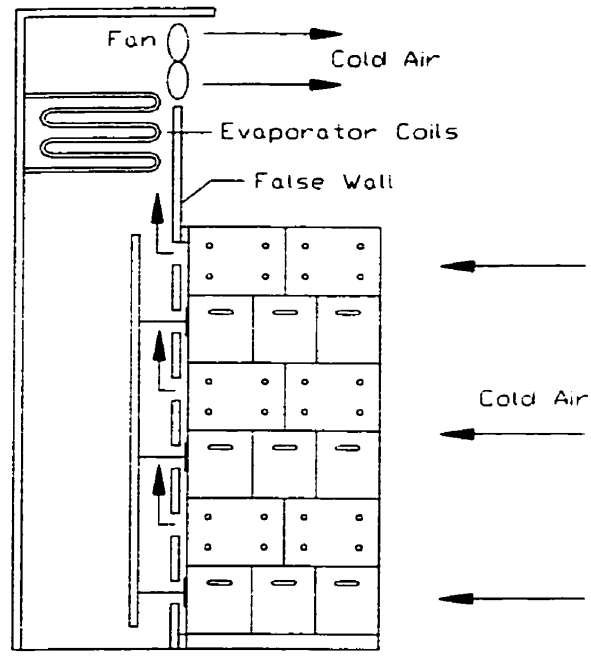

Figure 3.3: Schematic of the cross sectional view of a cold wall cooling system

eliminate this problem. In some situations, this may also allow for the elimination of the air fan, as the cooling system will also be equipped with its own fans. This configuration of the fans may be used if the fans are situated such that the required static pressure difference can be achieved. If this system is used, then the produce should be moved promptly after it has been cooled to avoid excessive dehydration. Forced-air tunnels require little capital investment, as the only equipment that is needed is an adequate sized fan and tarp.

Some forced-air cooling systems involve more capital cost, but they also provide more flexibility. One such system is the cold wall cooling system (Figure 3.3). In this system, one of the walls of the cold room is false, which creates a plenum between the false wall and the true wall. The plenum is equipped with exhaust fans that allow the required static pressure to be applied. The false wall has a number of vents where pallets may be placed against it to subject them to the static pressure difference. A number of different damper systems may be constructed so when the pallet is placed against the false wall the vents will be opened. Thus, when the pallet is removed, the vents close and

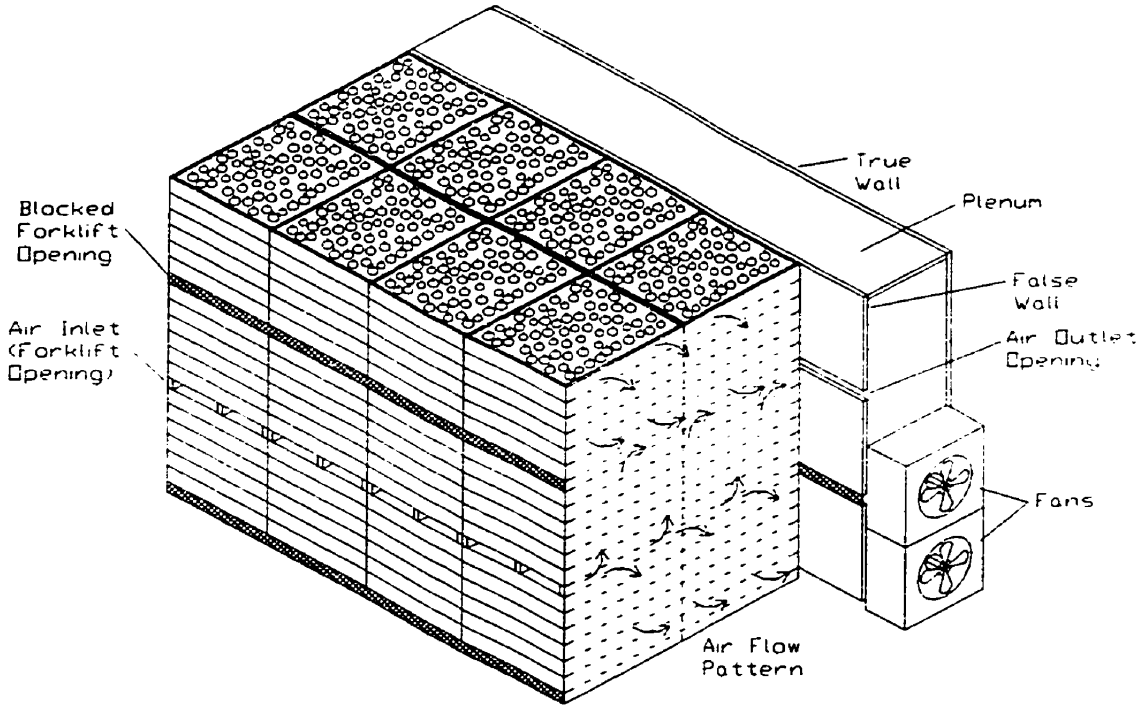

Figure 3.4: Schematic of a serpentine cooling system

short-circuiting is eliminated. A good damper design will allow different types of packages or partially filled pallets to be used.

A cold wall system allows for better management of forced-air cooling than the tunnel system. Each pallet may begin cooling immediately as it is placed in the cold room since it is not required to wait until a sufficient number of pallets is available, as in the case of tunnel cooling (Kader, 1992). Cooled pallets should be immediately removed from the false wall as excessive moisture loss may occur.

Serpentine cooling is a modification of the standard cold wall cooling method. It is a type of cooling that is applied to pallet bins. The pallet bins used in serpentine cooling must have bottom ventilation, though side ventilation is not necessary (Kader, 1992). Rows of pallet bins that are several bins high and deep are set up against the cold wall (Figure 3.4). The openings in the cold wall must coincide with the forklift openings on the pallet bins. The forklift openings are used as plenums for air supply and return. Every second row of vent openings in the false wall is covered so that they do not act as air return plenums and their respective forklift openings act as air supply plenums. The forklift openings staggered to the ones mentioned above are covered on the cold air side.

Therefore, any air entering the forklift openings must travel either up or down through the mass of produce before returning to the false wall via the air return plenums.

This method allows very quick cooling of produce since the air travels through a shallow layer of produce (Kader, 1992). Rows are not limited in height and large volumes of produce may be cooled at one time, if the size of the refrigeration system and fans are adequate.

In most forced-air applications, the airflow direction is usually vertical in pallet bulk bins (Figure 3.4) and horizontal for produce packed in containers (Figure 3.3). Research has been conducted on the cooling rate of some produces when exposed to vertical forced-air versus horizontal forced-air cooling. Lettuce, carrots, and strawberries were tested under both treatments and it was found that strawberries cooled quicker under vertical forced-air cooling while there was no significant difference for carrots or lettuce. The lettuce and carrots were of better quality under the vertical forced-air cooling (Edeogu et al., 1997). The scope of the study was not large enough to conclude that vertical cooling is better overall than horizontal cooling,

3.2.3 Hydrocooling

As the name implies, hydrocooling is the cooling of produce with water. Water provides a better heat transfer medium than air, due to its high specific heat and the ability to have good contact with all produce. When water comes into contact with the produce, the produce's surface becomes essentially the same temperature as the water (ASHRAE, 1998b). With sufficient water flow, the heat transfer resistance at the surface of the produce becomes negligible. The rate of cooling is then dependant on the internal heat transfer. The internal heat transfer is a function of the produce size, shape, and thermal conductivity. Hydrocooling plays an important role in the precooling of fruits and vegetables. It is effective on many produces and some facilities can handle up to 30,000 crates per day during the peak season (ASHRAE, 1986a). These systems are more costly then room cooling or forced-air cooling systems, though they can generally cool produce faster, in the range of 10 minutes to 1 hour, depending on the product and water temperature (Thompson, 1995). The other main advantage is that hydrocooling

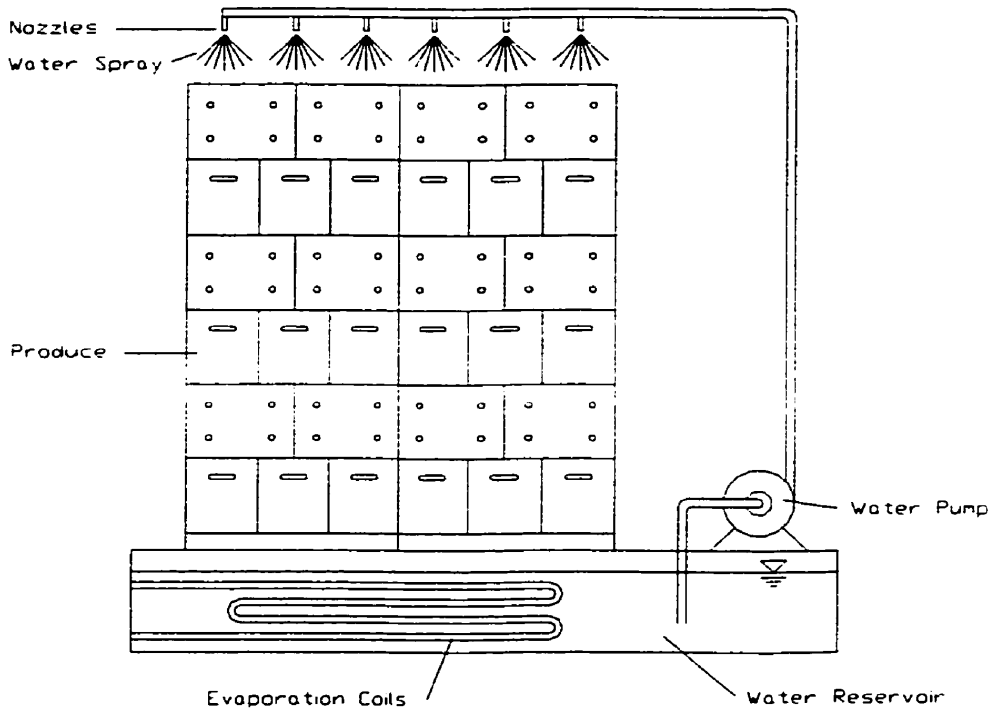

Figure 3.5: Schematic of a shower type hydrocooler

does not remove water from the commodity (Sargent et al., 1991). Immersion and shower systems are the two methods generally used for hydrocooling (Kader, 1992).

In immersion systems, the produce is often moved through a tank of cold water by a conveyor and lifted up out of the water at the end by an inclined conveyor. Continuous flow systems are best suited for produces that have a higher density than water. Therefore the produce remains immersed in the water rather than floating to the top (Thompson, 1995). The produce may be in bulk or packed in containers. Generally, the speed of the produce through the water is not great enough to provide adequate water movement around the produce. A solution to this problem is to have pumps or propellers installed which circulate the water (Mitchell et al., 1972). For sufficient heat removal, a minimum water velocity of 0.1 m/s around the produce should be used (Ryall and Pentzer, 1974).

Shower systems can be continuous flow or batch operations (Figure 3.5). Water is sprayed onto the produce from above or also from the sides. The produce may be in boxes, bins, or loose on a conveyor belt. The water is recollected in a bottom reservoir and reused. The rate of water application should be 280 to 490 $L \cdot min^{-1} \cdot m^{-2}$ for shallow

produce layers (Thompson, 1995). Hydrocoolers built for double stacked pallets use water application rates between 800 and 1000 $L \cdot min^{-1} \cdot m^{-2}$ (Thompson, 1995). There are two main methods of adding water from overhead. One method is with the use of spray nozzles. The water is pumped from the bottom reservoir and distributed over the produce through the spray nozzles. The other method involves a reservoir with a perforated floor. Water is pumped into the reservoir and the perforations allow water to be dispersed on the produce below. In both methods, the drop height of the water should be limited to 15 to 20 cm as some produce may be damaged with greater drop heights (Thompson, 1995). Produces in pallet or field bins can be further protected by covering them with a perforated cover (Thompson, 1995). Spray nozzles have a higher pumping requirement then the perforated floor reservoir (Thompson, 1995).

The water is usually cooled with a mechanical refrigeration system. The evaporator of the refrigeration system may be placed in the lower water reservoir or in the perforated floor reservoir above the produce. The advantage of placing the evaporator coils in the upper reservoir is that it leaves the lower reservoir free for easy cleaning of accumulated dirt. The problem with placing the coils in the upper reservoir is that the water may be only cooled while the hydrocooler is operating since that is the only time that water is present in this reservoir. If the coils are placed in the lower reservoir then the refrigeration system may be used even when the hydrocooler is not running and ice can accumulate in the reservoir. It would be possible to use a smaller refrigeration unit to get the same amount of cooling. The ice may be accumulated in the reservoir during off-peak hours when energy costs are low. Sometimes adding ice from an external source may be needed since hydrocoolers need a large amount of refrigeration in a very short time. This would also decrease the necessary size of the refrigeration unit. It has been reported that in some hydrocoolers up to half of the refrigeration may be lost due to insufficient insulation of the hydrocooler (Mitchell et al., 1972).

Hydraircooling is a modification to regular hydrocooling where refrigerated air and water in a fine mist are sprayed on the product. This reduces the water requirements and may improve sanitation (ASHRAE, 1998b).

Hydrocooling methods are very efficient on produce that are in bulk or that are packaged. It is commonly used for melons, root vegetables, stem vegetables, and many

types of tree fruits (Thompson, 1995). The drawbacks are that the produce and the containers must be tolerant to water contact and the chlorine levels used to sanitise the water. Water left on the surface of some produce, such as grapes and most berries, can encourage decay (Thompson, 1995).

Water used for hydrocooling should be treated, especially if it is to be reused. It should come from a clean source, either a well or domestic source (Thompson, 1995). Chlorine in the concentration range of 100 to 150 ppm should be used as disinfectant (Sargent et al., 1991). It is recommended that the hydrocooler be drained and sanitised at least daily. Washing dirty produce beforehand helps to reduce the amount of dirt in the water. Screens and filters can be used to remove debris and dirt before the water gets reused.

It is recommended to keep the cooling water between a temperature of 0 to 0.5°C for most produce (Thompson, 1995). It is possible to cool produce that are chilling sensitive with water at 0°C as long as the cooling time is limited (Thompson, 1995).

3.2.4 Package-icing

Package-icing is one of the oldest and simplest methods of cooling. Ice is placed in the containers with the produce or placed on top of the pallets. The contact between the ice and the produce results in a very rapid initial cooling of the produce. The rate of cooling quickly drops off as the ice melts and a layer of air develops between the ice and the produce. This layer of air will act as insulation and decrease the rate of heat transfer. The amount of ice needed depends on the produce and its initial temperature. Generally, the amount of ice added is 1 kg of ice for every 4 kg of produce (Belzile, 1982).

The arrangement of ice in the containers has an effect on the cooling rate and cooling uniformity (Vigneault *et al.*, 1995). The simplest method of adding ice is after all the produce has already been placed in the container. Ice may then be added to the top manually or automatically. In small operations, the ice may be added by shovel or blown on which requires a lot of work since each container must be opened by hand before icing and then closed afterwards. In larger operations, the whole process may be automated, including the opening and closing of the containers (Kader, 1992). This method of adding ice provides slow cooling since only the top layer of the produce is in good

contact with the ice (Sargent et al., 1991). The coating of ice may also block vent spaces causing a reduction in air movement and the centre of the load may warm (Sargent et al., 1991). Such use of ice is not an effective precooling method. Package-icing is recommended to be used after another type of precooling and prior to shipping, to act as a heat sink and to maintain a high relative humidity (Sargent et al., 1991).

The effectiveness of package-icing may be increased if the ice and produce are packed in alternating layers. This can be done on large pallet bins. This method is more labour intensive than top icing, but results in faster and more uniform cooling (Sargent et al., 1991). It is recommended that all points in a bulk load should be within a 150 mm radius from the closest ice (Prussia and Shewfelt, 1984).

The product and containers must be tolerant to long exposure to wet and cold conditions. Therefore, the required containers are more expensive. Handling of the containers after icing is also more costly due to their weight. The containers should have enough holes to drain away the melted water (Kader, 1992). Waxed fibreboard cartons are well suited for package-icing since they have minimal openings, providing some insulation from the surrounding environment, and they retain their strength when wet (Boyette and Estes, 1992).

3.2.5 Liquid-icing

Liquid-icing is a hybrid of hydrocooling and package-icing. A slurry of water and ice is pumped into the produce containers. The water has two functions: to supply some initial cooling of the produce and to provide a means of transportation for the ice. It has been shown in studies that the cold water can contribute up to 40 % of the cooling effect on broccoli (Boyette and Estes, 1992). As the water drains from the container it leaves the ice well distributed within the container.

The slurry is either drenched over the produce or pumped into individual containers through the handholds. Liquid-icing requires more equipment than package-icing, but results in more uniform cooling and faster procedure. Given the proper equipment, two workers can liquid-ice a 30-container pallet in 5 minutes (Boyette and Estes, 1992). Large systems that liquid-ice full pallets can do a pallet of 40 containers in 30 seconds.

The use of an ice crusher in the system may be necessary to crush the ice into suitable sized particles if the ice comes in blocks or in flakes that are too large. The ice should be no larger than 9.5 mm so that the ice particles easily enter voids between produce (Boyette and Estes, 1992). Vigneault *et al.* (1995) demonstrated that the optimal sixe of ice particles is 4.5 mm. As well, small particles of ice are less likely to damage produce compared to relatively larger ice particles.

A mixture of ice and water will have an equilibrium temperature of 0°C (Boyette and Estes, 1992). The melting of 1 kg of ice requires 335 kJ of heat. The addition of 1.0 kg of sodium chloride (NaCl) to 20.8 L of slurry can reduce the equilibrium temperature to - 2.8°C, though this lower temperature does not decrease the cooling time significantly (Boyette and Estes, 1992). Additional, brine solutions may cause produce to lose more water than is desired (Boyette and Estes, 1992).

Conventionally, liquid-ice systems have been batch systems (Vigneault et al., 1995). Batch systems require high power inputs. Between batches the reservoir for the ice-water mixture must be refilled very quickly in order to keep the system operating efficiently in terms of the number of containers iced per unit time. Quick ice crushing, filling and mixing of the ice-water reservoir requires high power inputs (Vigneault et al., 1995). Continuous systems do not require as high power because the operations of ice crushing and mixing are spread out evenly over time. Some experimental work has been done on developing a continuous flow liquid-ice system with lower power requirements than current systems (Vigneault et al., 1995).

Generally, a very large volume of produce needs to be cooled by liquid-icing to justify the purchase of a liquid-icing machine due to its high initial and operating costs (Vigneault et al., 1995). Continuous flow systems reduce the high operating power requirements by continually crushing and mixing of ice and water just prior to injecting it into containers. The mixing rate and the power requirements for mixing are much lower in this type of system (Vigneault et al., 1995).

3.2.6 Vacuum cooling

This method of precooling began on a commercial scale in Salinas, California in 1948. The first produce used was iceberg lettuce (Friedman and Radspinner, 1956).

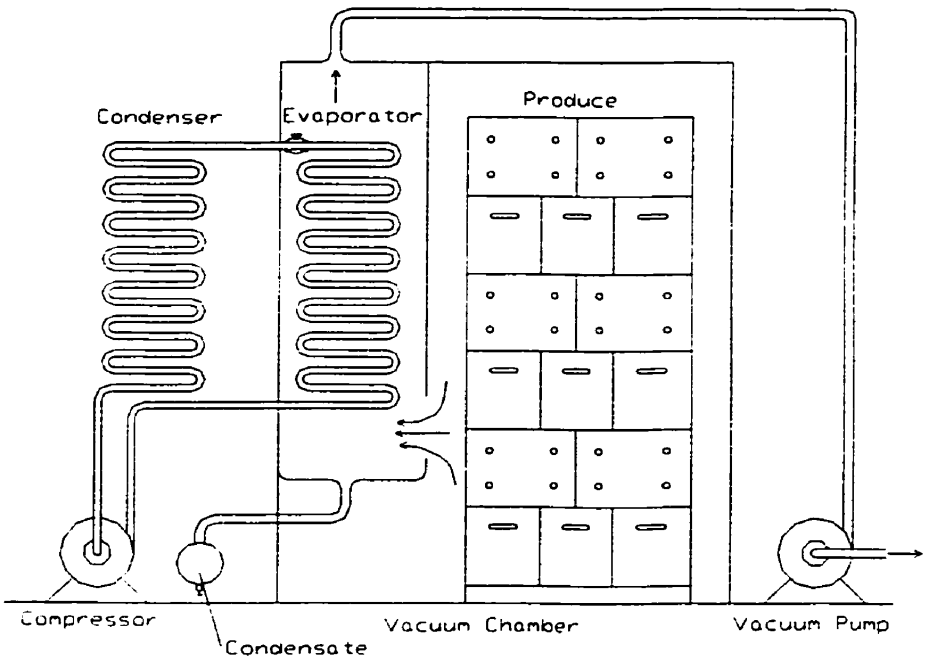

Figure 3.6: Schematic of a vacuum cooler

Vacuum cooling is a precooling method best suited for produce with high surface area to mass ratios. The rate of cooling is generally 2 to 3 times faster than forced-air cooling (Mitchell et al., 1972). Some produce, such as lettuce, can be cooled in 20 to 30 minutes.

Vacuum coolers are equipped with three main components: a vacuum chamber, a vacuum pump, and a refrigeration system with evaporator coils inside the vacuum chamber (Figure 3.6). The vacuum chamber must be constructed to withstand low pressures (high vacuum). The vacuum pump must evacuate the air from the chamber in a reasonable amount of time. To avoid water vapour entering the vacuum pump and because the volume of the vapour is large, the refrigeration system is used to condense all the vapour.

Pressure, volume, and temperature relationships play an important role in vacuum cooling. The basic principle behind vacuum cooling is the relationship between atmospheric pressure and the boiling point of water. Water boiling point temperature is a function of water purity and ambient pressure. In any discussion about vacuum cooling, atmospheric pressure is considered to have predominant effect on the boiling point of

water. It is well known that the boiling point of water at the standard atmospheric pressure of 101.325 kPa is 100°C (ASHRAE, 1998b). If the ambient pressure is lowered, the water boiling point temperature is also lowered. The relationship between the saturated vapour pressure over liquid water for the temperature range of 0°C to 200°C can be empirically expressed as (ASHRAE, 1997):

$$\ln(p_{ws}) = \frac{C_1}{T} + C_2 + C_3 T + C_4 T^2 + C_5 T^3 + C_6 \ln(T) \qquad (3.5)$$

where,

p_{ws} = Saturation Pressure (Pa)

T = Absolute Temperature (K)

C_1 = -5.800 220 6 E+03

C_2 = 1.391 499 3

C_3 = -4.864 023 9 E-02

C_4 = 4.176 476 8 E-05

C_5 = -1.445 209 3 E-08

C_6 = 6.545 967 3

Most vacuum coolers operate at a lower pressure limit of 0.610 kPa, which corresponds to a saturation temperature of 0°C (ASHRAE, 1998b). For some produce, such as lettuce, the cooling rate can be increased by reducing the pressure to 0.507 kPa, corresponding to a saturation temperature of –2.8°C, without causing any freezing damage to the produce (ASHRAE, 1986b). Generally, pressures are not reduced to this level due to the freezing potential of some produce and the amount of extra work by the vacuum pump.

The process of pumping the air out of the chamber can be divided into two phases. The first phase begins as soon as the pump is started. During this phase, the water vapour saturation pressure is lower than the atmospheric pressure. It continues until the flash point is reached. The flash point is where the atmospheric pressure has been reduced to the water vapour saturation pressure (based on the produce temperature)

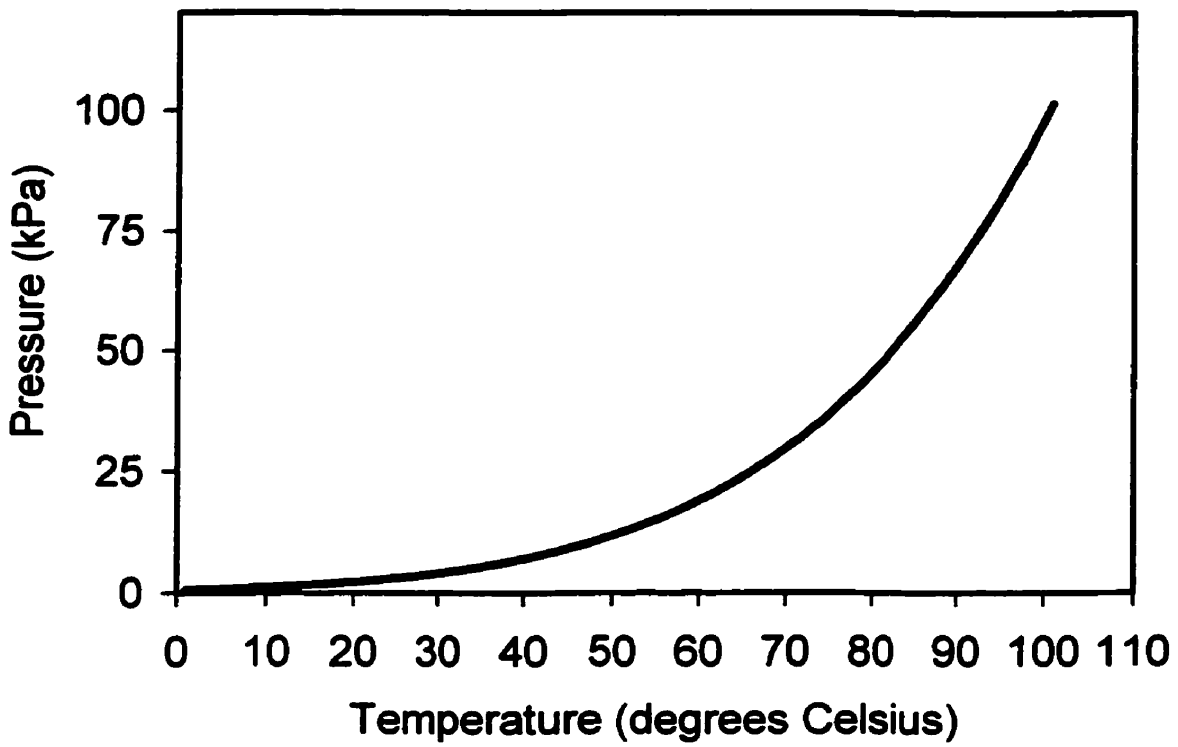

Figure 3.7: Theoretical saturation water vapour pressure as a function of temperature

and boiling begins. The approximate solution to the thermodynamic process of the first phase may be represented as follows, according to the ideal gas law (ASHRAE, 1998b):

$$pv = 8.697\ \mathrm{kN \cdot m \cdot kg^{-1}} \tag{3.6}$$

where,

p = Absolute Pressure (kPa)

v = Specific Volume ($m^3 \cdot kg^{-1}$)

As the first phase ends, boiling occurs and water vapour is suddenly released in the vacuum chamber. The second phase occurs at saturation until the desired product temperature is reached. The approximate solution of the thermodynamic process, based on the ideal gas law, for the second phase is (ASHRAE, 1998b):

$$pv^{1.056} = 16.985\ \text{kN}\cdot\text{m}\cdot\text{kg}^{-1} \qquad (3.7)$$

Theoretically, during the first phase the temperature should remain constant, assuming the initial temperature of the product and the chamber air are equal and therefore convection is not occurring. Once the pressure is reduced to the saturation temperature and phase two begins, the temperature in the chamber should theoretically follow the saturation line (Figure 3.7). The measured produce temperature should behave in a similar fashion. This varies somewhat depending on the location of temperature probes in the produce, the physical characteristics of the produce, and the amount of available surface water on the produce (ASHRAE, 1986a). Most of the vaporisation of water occurs off the product surface, though it is possible for some to occur in the intercellular spaces (ASHRAE, 1986a). The rate of cooling of the produce is dependent on; the surface area to volume ratio, the rate at which the vacuum is created in the chamber, and the rate of heat conduction through the produce. The phase change of water from liquid to vapour requires large energy inputs. Torquato and Smith (1984) described the latent heat of vaporisation using the following empirical equation, which yields good results:

$$\lambda = 0.722t^{0.333} + 5.334t^{0.790} + 8.973t^{1.208} - 11.931t + 3.312t^{2} + 1.633t^{3} \qquad (3.8)$$

where,

$\lambda = h_{fg}/h_{fgt}$

h_{fg} = Latent heat of vaporisation ($kJ\cdot kg^{-1}$)

h_{fgt} = Latent heat of vaporisation at the triple point (2501.00 $kJ\cdot kg^{-1}$)

$t = (T_c - T)/T_c$

T_c = Critical temperature of water (K)

T = Absolute temperature of water (K)

In practice, the cooling of the produce is due to the evaporation of water from the surface of the produce, heat convection from the surface, and conduction of heat from the centre to the surface. The convection portion of heat removal is very small. Thus, it is

assumed that the convection is negligible and that all the heat removal is due to the evaporation of water from the surface. The amount of water removed from the produce during cooling will be a function of its specific heat and the change in temperature (ASHRAE, 1986a). A list of specific heats for produces often vacuum cooled is given in Table 3.2. Heat removed from the produce may be expressed as the product between the water vaporised and the latent heat of vaporisation (ASHRAE, 1986a):

$$Q = W_v \cdot h_{fg} \tag{3.9}$$

where,

Q = Heat removed ($kJ \cdot kg^{-1}$ produce)

W_v = Water vaporised, (kg water$\cdot kg^{-1}$ produce)

h_{fg} = Latent heat of vaporisation of water, ($kJ \cdot kg^{-1}$ water)

Assuming a constant latent heat of vaporisation and a constant specific heat of the product throughout the vacuum cycle, the following theoretical temperature change would occur for every 1% moisture loss from the product:

$$\Delta T = \frac{0.01 h_{fg}}{c_p} \tag{3.10}$$

where,

ΔT = Temperature reduction (K)

c_p = Specific heat of produce ($kJ \cdot kg^{-1} \cdot K^{-1}$)

Common values for the specific heat range from 3.3 to 4.1 $kJ \cdot kg^{-1} \cdot K^{-1}$ and the latent heat of vaporisation is generally in the range of 2442 to 2501 $kJ \cdot kg^{-1}$. Using the typical values of 3.8 $kJ \cdot kg^{-1} \cdot K^{-1}$ and 2472 $kJ \cdot kg^{-1}$ from these ranges a typical theoretical ΔT is 6.5°C for each 1% moisture loss.

Experimental results have shown that the amount of moisture evaporated from the produce is proportional to the cooling effect (Barger, 1963). Every 1 % moisture loss results in a 5 to 5.6°C temperature reduction (Barger, 1963). Produce being cooled could lose up to 5 % of its moisture during the vacuum cooling cycle. High moisture losses are undesirable for most produce. Produce is generally sold on a mass basis and

Table 3.2: Specific heats of some commonly vacuum cooled produce (ASHRAE, 1986b)

Commodity	Specific Heat, $kJ \cdot kg^{-1} \cdot K^{-1}$
Artichokes	3.650
Asparagus	3.952
Broccoli	3.852
Brussels sprouts	3.684
Cabbage	3.919
Cauliflower	3.919
Celery	3.986
Endive	3.952
Leeks	3.684
Lettuce	4.019
Mushrooms	3.885
Parsley	3.684
Peppers, sweet	3.919
Snap Beans	3.818
Spinach	3.952
Sweet Corn	3.316

the loss of excess moisture reduces the market value. The moisture loss may also cause detrimental effects, such as wilting or shrivelling, to the quality of some commodities. It is possible to reduce these moisture losses by wetting the produce before or during the vacuum process. Modifications to the conventional vacuum cooler, under the commercial name of Hydro-Vac™, re-circulate water in the chamber throughout the vacuum cycle. The water is sprayed on the produce from above and is collected in a sump from where it is pumped back over the produce. This modification has two main effects, the first is that it decreases the moisture loss from the produce by supplying the water that is to be evaporated. In some cases, pre-wetting has been shown to increase the product's weight (Barger, 1963), though some water was left on the surface. The second function of adding water is the direct heat exchange due to the contact between the produce and the cold water. If the water remains in the vacuum cooler after a vacuum

cycle then it will be cold and affects the new batch of produce once the water system begins (ASHRAE, 1986a).

An advantage of vacuum cooling over most other methods of precooling is its flexibility with different types of containers and packaging systems. The type of container has a negligible effect on the process of vacuum cooling (Longmore, 1973). The major restriction is if the product requires wrapping in plastic film, the film must be perforated to obtain efficient cooling (Cheyney *et al.*, 1979). If produce is pre-wetted or subjected to Hydro-Vac™, then the containers and packaging should be water-resistant and designed to distribute the water uniformly and drain of the excess water.

As mentioned above, produce that has large surface area to mass ratios tend to be best suited for vacuum cooling. The produce can also be difficult to cool by other methods. Leafy vegetables can be difficult to cool due to the pockets of air created by the overlapping of leaves. The pockets act as insulation and reduce air and water movement. The produce that are common to vacuum cooling include lettuce, sweet corn, celery, green beans, and mushrooms.

Produce does not necessarily cool uniformly during vacuum cooling. Lettuce is one produce that can experience differential cooling effects. The leaves release moisture quicker than the core and can therefore be several degrees cooler (ASHRAE, 1986a). It has been found that temperature differences between the leaves and the core of lettuce can reach up to 6.7°C during the vacuum cycle and 2.2°C when the vacuum cycle is broken (Harvey, 1963). Therefore, determining produce temperature during commercial cooling is often problematic. In industry, temperature probes are seldom used as a means of temperature measurement since the operators can not be depended on to remove the probes after each run and therefore the probes could easily be broken when the produce is removed (Thompson and Rumsey, 1984). The most common way of determining the produce temperature is either based on a combination of pressure and time or by using a wet bulb temperature sensor in the chamber. The problem with the wet bulb temperature sensor in a vacuum is that the reading will not be of the true wet bulb temperature since there is no air to pass over the wet bulb.

Studies performed on the energy use of vacuum coolers found that for cooling lettuce the energy use was on average 0.22 kWh per carton of lettuce, with 23 to 27 kg of

lettuce per carton (Thompson et al, 1986). The same study used an energy coefficient to better estimate the energy efficiency since the mass of produce in a carton varied from carton to carton. The energy coefficient used can be described as follows (Thompson et al., 1986):

$$EC = \frac{W}{E} \tag{3.11}$$

where,

EC = Energy coefficient (unitless)

W = Sensible heat removed (kJ)

E = Total energy used (kJ)

Energy use in vacuum coolers comes mainly from the operation of the compressors for the condensing of the water vapour. In the study of Thompson *et al.* (1986) two vacuum coolers were examined under normal operating conditions and it was found that the coolers had energy coeffiecients of 2.8 and 2.1 with the compressors contributing 72 and 61 % of the total energy consumption, respectively. The energy use in vacuum coolers can be reduced by operating the compressors only when necessary. It takes a few minutes for the vacuum pump to reduce the pressure low enough to start the evaporation of water, during this time it is not necessary to operate the compressor (Thompson et al., 1986).

3.3 Heat Transfer and Associated Parameters

The process of precooling fruits and vegetables is within the domain of heat and sometimes, mass transfer. A good understanding of the basis of heat transfer is necessary to evaluate the performance of precooling operations. The heat transfer involved in the precooling of fruits and vegetables is not trivial, usually more than one mode of heat transfer occurs at the same time and the modes are dependent on each other.

3.3.1 Heat transfer principles

Heat transfer from an object to its surroundings can be divided into 3 conditions based on the dimensionless Biot number, Bi (Mohsenin, 1980):

$$\mathrm{Bi} = \frac{hS_O}{k} \tag{3.12}$$

where,

h = convection heat transfer coefficient ($J \cdot m^{-2} \cdot K^{-1} \cdot s^{-1}$)

S_O = characteristic dimension (m)

k = thermal conductivity ($J \cdot m^{-1} \cdot K^{-1} \cdot s^{-1}$)

For the case when Bi < 0.2, the *lumped heat capacitance system* may be used (Mohsenin, 1980). In such a case, the internal resistance to heat transfer is considered to be negligible compared to the external resistance. Therefore, the temperature is considered to be uniform throughout the produce and during the cooling process (Dinçer, 1997). With these assumptions, Newton's Law of Cooling may be applied to obtain cooling parameters. Newton's Law of Cooling may be expressed as a temperature ratio, t:

$$t = \frac{T_p - T_a}{T_i - T_a} = e^{-\left[\frac{hA}{\rho c_p V}\right]\theta} \tag{3.13}$$

where

T_p = object temperature (K)

T_a = cooling medium temperature (K)

T_i = initial object temperature (K)

A = object surface area (m^2)

ρ = object density ($kg \cdot m^{-3}$)

c_P = object specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)

V = object volume (m^3)

θ = Time (s)

For Bi > 10, the convection heat transfer coefficient is large enough to make the thermal conductivity of the product the limiting factor (Mohsenin, 1980). Therefore the temperature difference between the object's surface and the cooling medium becomes negligible (Mohsenin, 1980). For this case, Fourier's Law of Cooling may be applied. For three dimensional heat flow through an object with homogenous thermal conductivity and with heat generation, q_g, Fourier's Law of Cooling may be expressed as (Mohsenin, 1980):

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}+\frac{q_g}{k}=\frac{\rho c_p}{k}\frac{\partial T}{\partial \theta} \tag{3.14}$$

where

x, y, z = Cartesian co-ordinates

For 0.2 < Bi < 10, there is an finite internal and external resistance to heat transfer from an object being cooled (Mohsenin, 1980). For this situation, the temperature ratio, Y, is a function of the Biot number and the Fourier number, *Fo* (Singh and Heldman, 1984):

$$Fo=\frac{k\theta}{\rho c_p S_O} \tag{3.15}$$

Temperature-time charts, based on the temperature ratio, Fourier's number, and the Biot number, may be used to find solutions to heat transfer problems involving well-defined shapes such as sphere, infinite cylinder, and infinite slab (Singh and Heldman, 1984). Combinations of an infinite slab and an infinite cylinder can be used to evaluate a finite cylinder (Singh and Heldman, 1984). Conduction equations have been developed and presented for this type of cooling situations by Carslaw and Jaegar (1959).

3.3.2 Cooling coefficient and half-cooling time

When Newton's Law of Cooling is valid, certain parameters can be calculated that allow the prediction of cooling times for produce. One such parameter often used in commercial precooling is the cooling coefficient. Graphically it is the slope of the line from a plot of the natural log of the temperature ratio against time (Guillou, 1958). It can also be expressed as (Mohsenin, 1980):

$$CC = \frac{hA}{\rho c_p V} \tag{3.16}$$

Other variations of calculating the *CC* may be found in literature (Gariépy et al., 1987, Goyette et al., 1996).

The half-cooling time, Z, can be derived from the cooling coefficient by the relationship (Guillou, 1958):

$$Z = \frac{1}{CC} \ln 2 \tag{3.17}$$

The half-cooling time represents the time required for the temperature difference between the object and the cooling medium to be halved. For each time span of Z, the difference is halved (Figure 3.8). Thus, after 3Z, the temperature ratio is $1/8^{th}$ of its original value. This is often termed the $7/8^{ths}$ cooling time and is often used as the cooling time in commercial precooling (Mitchell et al., 1972).

The thermal resistance within fruits and vegetables usually results in a large temperature gradient inside the commodity during cooling (Smith and Bennett, 1965, Guillou, 1958). Thus, Newton's Law of Cooling does not hold for cooling of fruits and vegetables. Despite this, Newton's Law of Cooling is still used extensively for determining the parameters in precooling operations. Guillou (1958) stated that Newton's law could still be applied with good results if the temperature taken is the average temperature of the product. It has been suggested that a modified equation, using

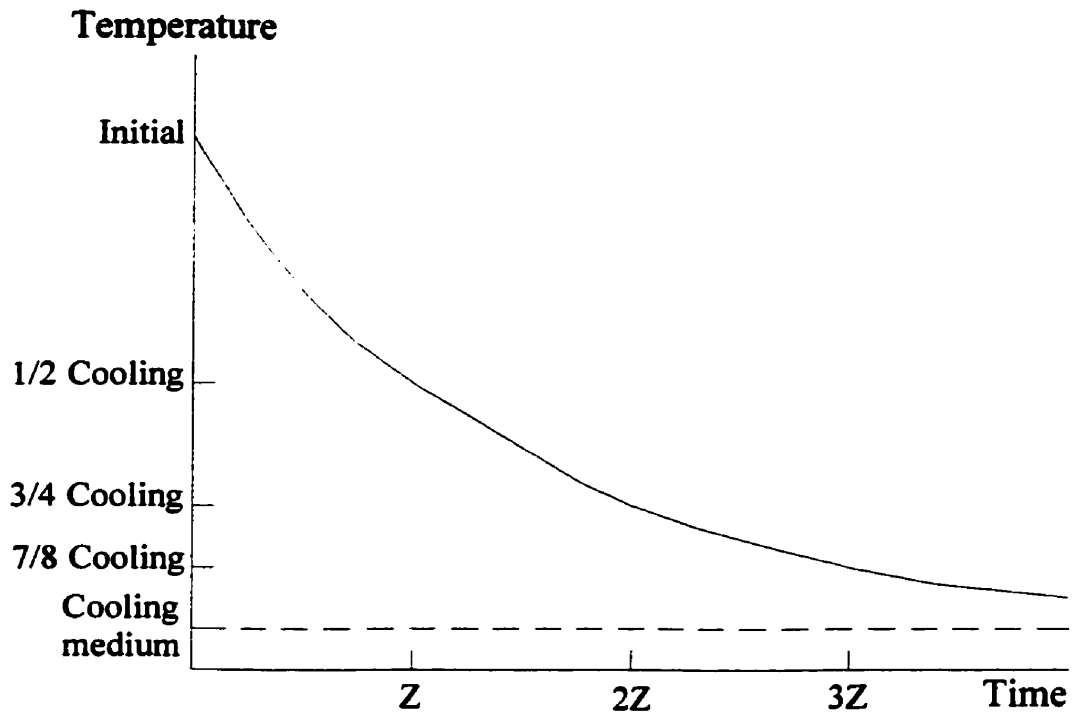

Figure 3.8: Cooling rate following Newton's law of cooling

a lag factor *j*, for Newton's law can be used to better predict the heat transfer (Mohsenin, 1980):

$$\frac{T_p - T_a}{T_i - T_a} = je^{-CR(\theta)} \tag{3.18}$$

It has also been noted that the surface resistance to heat transfer is often too large to be neglected in cooling operations (Ramaswamy et al., 1982). Therefore, in cooling operations, the heat transfer is for the case with the Bi number representing a finite internal and external resistance to heat flow. Ramaswamy et al. (1982) stated that temperature-time charts are only useful for obtaining approximate solutions. Ramaswamy et al. (1982) developed simplified equations to solve the conduction equations of Carslaw and Jaeger (1959).

3.3.3 Mass-average temperature

Most equations and techniques for developing cooling coefficients and half-cooling times require one temperature value that represents the whole object. This is problematic with transient heat flow since the temperature profile is non-linear and changing. The temperature at the centre of the product is often used but is not representative of the actual product temperature. The centre of the product cools the slowest so any heat removal calculations based on the central temperature will yield results much lower than the actual value. For spherical or cylindrical objects, which are common for most fruits and vegetables, the majority of the mass that is edible is often located on the outside portion of the commodity. The central temperature may indicate that the commodity has gone under little cooling, though a substantial amount of heat has been removed from the outer mass (ASHRAE, 1998b).

To standardise temperature measurements and to use a temperature that is more representative of the product temperature, Smith and Bennett (1965) proposed that the mass-average temperature be used for transient cooling of fruits and vegetables. The mass-average temperature is a single value from the temperature distribution that would become the uniform product temperature under adiabatic conditions (Smith and Bennett, 1965). The mass-average temperature is useful as it is most likely to always occur in the tissue mass that makes up the majority of the edible portion of the produce (Smith and Bennett, 1965). In comparison, the usefulness of the central temperature is diminished due to the presence of pits, cobs, seed cores, voids, or piths (Smith and Bennett, 1965).

3.3.4 Heat load

Refrigeration capacity for precooling is much larger than the refrigeration capacity needed for storage. The precooling load is more dynamic since it involves decreasing the product temperature rather than just holding it at a constant temperature. For economical reasons, the refrigeration capacity for precooling should be determined as accurately as possible (ASHRAE, 1998b). The refrigeration system must remove heat from the following sources: product field heat, respiratory heat, containers, air infiltration, ambient air, and heat produced by accessories such as motors, fans, and lights. The field heat represents the largest load for precooling (ASHRAE, 1998b). The

field heat load, Q_f, is a function of the mass of product to be cooled, m, the specific heat, c_p, and the temperature reduction ($T_i - T_{ma}$). The calculation of the heat removed should be based on the mass-average temperature (Smith and Bennett, 1965) and takes the form of:

$$Q_f = mc_P(T_i - T_{ma}) \tag{3.19}$$

In ordinary storage situations, the refrigeration capacity required for product cooling in the cold room is based by dividing equation 3.19 with an estimated time for the cooling to take place, thus giving a rate of heat removal (ASHRAE, 1998a). Little information on the method of estimating this time is given in literature. The time would be based on the temperature difference between the produce and the air, the airflow pattern and air interaction with the product, as well as the physical and thermal characteristics of the product itself.

Nomographs have been published that are used to determine the refrigeration load for different produces (ASHRAE, 1998b). The nomographs are based on the cooling medium temperature, initial produce temperature, the cooling time, and the size of the produce. The disadvantage to using the nomographs is that they are not sensitive to changes in some of the parameters of the cooling method, such as cooling fluid flow rates.

For vacuum cooling, there is no cooling medium, which makes the use of nomographs more difficult. As well, the definition of a cooling coefficient and half cooling time becomes problematic as these are based on a constant temperature cooling medium. In vacuum cooling, the driving force for heat transfer is based on the evaporation of water from the surface, which is a function of the vapour pressure difference for water at the surface of the product. The pressure in the chamber is continually changing and cannot be considered as constant. As well, the cooling does not begin until the flash point is obtained. Despite these considerations, Wang and Gitlin (1969) developed the following equation to determine the product refrigeration load:

$$q = \frac{\frac{2}{3} c_p (T_1 - T_2) m}{1/2 \text{ actual cooling time}} \tag{3.20}$$

where the refrigeration load, q, is measured in Watts, T_1-T_2 is the temperature change of the product (K), and m is the total mass (kg) of the product. This equation assumes that the cooling only occurs after the flash point and that two thirds of the cooling occurs in the first ten minutes, considering a total of 20 minutes of cooling. For design purposes, this equation does not consider the interaction between the rate of vacuum application and the refrigeration load, as it would be expected that changing the vacuum rate would affect the rate of evaporation from the product.

IV. TEMPERATURE DISTRIBUTION IN VACUUM COOLED LETTUCE UNDER VARYING PROCESS PARAMETERS

4.1 Introduction

Rapid cooling, or precooling, immediately after harvest can significantly reduce postharvest deterioration of fruits and vegetables, thus prolonging their storage life (Mitchell *et al.*, 1972). The deterioration may be caused by numerous sources, including physiological breakdown, moisture loss, and pathogens (Raghavan *et al*, 1996). Because physiological activities are temperature related; decreasing the produce temperature results in less photosynthate and mineral resource depletion in the commodity, less deterioration, and hence a longer storage life (Kader, 1992).

Vacuum cooling has been proven to be an effective method of precooling certain types of fresh vegetables (Thompson *et al.*, 1986). It is most effective on commodities with high surface area to mass ratios, such as lettuce, spinach, and other leafy vegetables (ASHRAE, 1998). It is a specific application of evaporative cooling (Griener and Kleis, 1962). During the process, the produce is placed in an airtight retort equipped with a refrigeration system. The pressure in the retort is reduced by a vacuum pump, and as the pressure decreases, the boiling point of water is reduced. When the boiling point of the water is reduced to the produce temperature, the water in the produce begins to evaporate. The evaporating water requires energy to undergo this phase change, which comes from the sensible heat of the produce, thus effectively cooling it. At a reduced absolute pressure of 610 Pa, the boiling point of water is 0°C (ASHRAE, 1998). The rate of cooling depends on the produce's surface to volume ratio, its resistance to moisture loss, and the rate at which the vacuum is applied. A refrigeration system is needed to condense the vast amounts of water vapour that is released. Vacuum coolers are generally designed for 30 minute turn around cycles which include product loading and unloading times (Longmore, 1973).

The evaporation of water from the produce results in a mass loss of the product. For every 5 to 5.6°C temperature reduction, the product will lose 1% of its mass (Barger,

1963, Boa and Lindsay, 1976, Guillou, 1958). The moisture loss can have detrimental effects on the quality of some produces.

The temperature distribution in produce, as they are cooled, is generally not uniform (Thompson and Rumsey, 1984). Temperature differences between the leaves and the core of lettuce can reach up to 6.7°C during the vacuum cycle and 2.2°C when the vacuum cycle is broken (Harvey, 1963). Thompson and Rumsey (1984) suggest that the best method of determining the temperature of lettuce in a vacuum cooler is with the use of a simulated lettuce head.

Vacuum pumps are generally selected to evacuate the retort to the desired pressure in 5 to 10 minutes (Wang and Gitlin, 1964). The same authors suggest that the pump capacity in terms of volume per minute should be equal to the volume of the retort. Theoretically, the effect on the retort pressure due to the operation of the pump can be modelled as an exponential decay function. However, this assumption will yield a slight error since pump efficiency decreases with reduction in retort air pressure (Wang and Gitlin, 1964).

The main disadvantages of vacuum coolers are high investment costs, mass loss of vacuum cooled produce, and limited range of produce that may be cooled by this method. The large investment costs are due to the size of the vacuum pump and the refrigeration system. Use of a smaller vacuum pump would decrease the rate of vacuum application and the size of refrigeration unit that would be needed, thus effectively decreasing the cost of the vacuum cooler. Unfortunately, it would increase the turn-around time of the system, reducing the amount of produce that could be cooled in a given amount of time.

4.2 Objective

The objective of this study was to determine the effect of different rates of vacuum application on the following parameters for head lettuce:

1. Mass loss
2. Temperature reduction per percent mass loss
3. Temperature differences between different locations of the produce
4. Final temperature

4.3 Materials and Methods

4.3.1 Experimental setup

The tests were performed using a laboratory scale vacuum cooler. A Model Y1 series 77-003 "Lyo-Tech" freeze-dryer (Lyo-San Inc., Lachute, Qc, Canada) was used as a vacuum cooler. It was equipped with a belt driven Welch duo-seal vacuum pump (Sargent-Welch Scientific Inc., Skokie, Illinois) operated with a 0.75 kW (1 hp), 120V electric motor. The vacuum pump dropped the pressure from normal atmospheric to 25 mm Hg in an average time of 5 minutes and 53 seconds.

The vacuum cooler was instrumented with temperature sensors and a pressure sensor. Seven type-T thermocouples (+/- 0.5°C) and three type-K OS36 IRt/c™ Series infrared thermocouples (Omega Engineering, Stamford, CT) were used for temperature measurements. The infrared temperature sensors had a 2% accuracy range between temperatures of –18 to 27°C with a type-K thermocouple signal output.

The data collection and control of the pressure was conducted by the use of a 12 bit resolution DATAshuttle Express (Strawberry Tree, Inc, Sunnyvale, CA) data acquisition system. The sampling rate was one hertz and the data was saved in ASCII format so that it could be analyzed later using a standard spreadsheet program. The DATAshuttle express was connected to a portable computer and was controlled using WorkBench PC for Windows™ (Strawberry Tree, Inc., Sunnyvale, CA) software.

4.3.2 Temperature measurements

Each lettuce was instrumented with three type-T thermocouples and one infrared temperature sensor. The infrared temperature sensor measured the surface temperature of the lettuce and one flexible thermocouple was located under the first leaf of the lettuce. Another temperature probe was inserted to measure the mass-average temperature of the lettuce. The mass-average temperature is a single temperature measurement from the temperature distribution that would represent the uniform temperature of the product if left to adiabatic conditions (Smith and Bennett, 1965). The determination of the depth at which the mass-average temperature was taken was based on the approximation used by Smith and Bennett (1965). This depth was determined to be ¼ the radius of the lettuce,

assuming the lettuce to be a sphere with homogenous density and specific heat. The final temperature probe was inserted into the centre of the lettuce head. The temperature data was then averaged for every ten seconds to reduce variation and noise effects before the analysis on the temperature distributions.

4.3.3 Pressure control

The pressure of the cooler was allowed to drop to 25.0 mm Hg as fast as possible. Upon reaching 25.0 mm Hg, the pressure was controlled to simulate different rates of vacuum by using a controlled air leak through a tube. The air leak was controlled by the use of solenoid valves placed in parallel. A pressure sensor supplied the operating pressure to the data acquisition system that determined whether or not the leak should be opened and to what extent. The rate of vacuum was modelled based on an exponential decay function in the form of:

$$P = Ae^{-B\theta} \tag{4.1}$$

Where P is the pressure (mm Hg), θ is the time (s) starting when the control began, and A and B are process variables. The A value was set to 25.0 mm Hg, which was the initial pressure for control and the B value was changed as the dependent variable in the system. The B value controlled the rate at which the vacuum was decreased. Three B values were used, each one corresponding to a different time for the vacuum to drop from 25.0 mm Hg to 6 mm Hg. The values are shown in Table 4.1.

Table 4.1: A and B values used for the controller

Time (25 mm Hg to 6 mm Hg)	A Value (mm Hg)	B Value (s^{-1})
15 min	25.0	0.00159
30 min	25.0	0.000793
60 min	25.0	0.000396

When the controlled pressure reached 6.0 mm Hg, the pressure in the chamber was regulated to 6.0 ± 0.4 mm Hg until the average mass-average temperature of the

lettuce reached 2.5°C. Once attained, the vacuum was broken and the lettuce removed. The choice to regulate at 6.0 mm Hg was based on preliminary trials. At 5.0 ± 0.4 mm Hg, the produce showed signs of freezing, thus the lower limit was increased to avoid freezing.

4.3.4 Experimental design

Information about the effects of the vacuum rate on the mass loss, efficiency of cooling, and temperature distribution in produce is limited. The experiment was designed to measure these quantities as affected by the vacuum rate. Three different rates of vacuum were applied as given in Table 4.1. Three replicates were used for each treatment, and two lettuces were used for each replicate. The order in which the trials were performed was randomised beforehand. Each lettuce was instrumented with four temperature sensors. The masses of the lettuces were measured before and after the cooling process. The mass loss, the temperature reduction per percent mass loss (TRPML), and the temperature differences due to location were analysed with the *B* values as the treatment factors and no block factors. The final temperatures were analysed with the position of the temperature sensors as the treatment and the *B* values as the block factor.

4.4 Results and Discussions

4.4.1 Mass loss and temperature decrease per percent mass loss

The results of the mass loss and the TRPML are reported in Table 4.2. The mass loss is based on the percent loss of the initial mass. The TRPML is the total temperature reduction divided by the percent mass loss. The total temperature reduction was based on the mass-average temperature of the lettuce. No significant differences were found in the mass loss or the TRPML. It was shown that a temperature reduction of 5.0 to 5.8°C per percent mass loss and thus conformed to literature values.

Table 4.2: Mass loss and temperature reduction per percent mass loss (TRPML)

B Value (s^{-1})	Mass Loss (%)	TRPML (°C / % mass loss)
0.00159	3.52	5.60
0.000793	3.69	5.29
0.000396	3.69	5.28

Theoretically, the mass loss (m_L, kg) during vacuum cooling can be predicted by the following equation by knowing the mass of the product (m, kg), its specific heat (c_p, $kJ \cdot kg^{-1} \cdot K^{-1}$), the temperature change (ΔT, K), and the latent heat of vaporisation of water (h_{fg}, $kJ \cdot kg^{-1}$):

$$m_L = \frac{m * c_p * \Delta T}{h_{fg}} \tag{4.2}$$

The values for the latent heat of vaporization were determined using an equation developed by Torquato and Smith (1984) and were evaluated at the average mass-average temperature during the vacuum cycle. Results of the predicted mass loss and the actual mass loss are given in Figure 4.1. The actual mass losses are consistently higher than the predicted mass losses.

4.4.2 Temperature differences

The temperature differences between various locations in the product were analysed for the average temperature differences, final temperature differences, maximum temperature difference and the temperature differences when the pressure reached 6.0 mm Hg. The temperature differences were measured for all possible combinations of the surface, leaf, mass-average, and the centre locations. All temperature differences were analysed for significance separately with the *B* values as the treatment factor. Due to malfunction of one of the infrared temperature sensors, the results could only be analysed on one of the lettuces per trial.

No significance due to different *B* values was found for any of the different locations. The results of the final temperature difference and the maximum temperature

difference for the cases of centre versus mass-average and mass-average versus leaf are shown in Table 4.3.

Table 4.3: Final and maximum temperature differences for centre/mass-average and mass-average/leaf

B Values	Centre/Mass-Average Difference		Mass-Average/Leaf Difference	
	Maximum (°C)	Final (°C)	Maximum (°C)	Final (°C)
0.00159	2.8	2.7	2.6	1.1
0.000793	3.6	2.7	2.2	0.8
0.000396	3.2	1.6	1.5	0.6

During the processes, for *B* values of 0.00159, 0.000793, and 0.000396, the largest temperature differences between the centre and leaf were 5.2, 7.1, and 3.1°C, respectively. For the same *B* values, the resulting maximum-recorded centre final temperatures were 2.8, 6.5, and 2.6°C, respectively. These results are comparable to the results of Harvey (1963).

4.4.3 Final temperatures

The final temperatures reached were analysed with the location of the temperature sensor as the treatment and the rate of vacuum as the block factor. The results showed that there was no significant difference in the temperatures of the surface, leaf, and mass-average locations. However, all three of these locations had significantly lower temperatures compared to the centre mass of the lettuce, which was, on average, 1.5°C above the mass-average temperature. The vacuum was broken when the average mass-average temperature reached 2.5°C. Table 4.4 lists the average final position temperatures.

Table 4.4: Final temperature by position

Position of Temperature Sensor	Temperature (°C)
Surface	2.6
Leaf	1.9
Mass-average	2.6
Centre	4.0

These results suggest that using infrared temperature sensors to measure the surface temperature could approximate the mass-average temperature of lettuce. The only concern with this is the reliability of the infrared sensor measurements. In this experiment, considerably more variation was detected using the surface temperature compared to type-T thermocouples. The standard deviation associated with the infrared temperature sensor was 2.3°C compared to 0.8, 0.3, and 1.4°C, for leaf, mass-average, and centre temperatures, respectively. Thus, some problems may be associated with using infrared temperature sensors as a means of determining product temperature. More research on using different types of infrared sensors and the quality of the sensors themselves needs to be carried out. The use of the infrared temperature sensor has the benefit of recording the area of the lettuce that freezes first.

4.4.4 Temperature profiles

Sample temperature profiles for each of the different B values are shown in Figure 4.2, 4.3, and 4.4. The profiles show the temperatures measured at the surface, under the first leaf, at the mass-average location, and at the centre. Figure 4.2 shows the profile for a B value of 0.00159, which corresponds to the most rapid cooling of the three situations. Of the three profiles, it represents the profile that is closest to the shape of regular profiles of vacuum cooled produce; it is also the situation that is closest to the real situation. The temperatures remain fairly constant until the flash point occurs, then the cooling begins to be significant. The flash point represents the time when the pressure is reduced close to the saturation vapour pressure of water. Rapid evaporation begins and the temperature drops. It was observed that in many situations some of the temperature readings actually

increased close to the flash point. Similar trends are found in the data presented by Shaw and Kuo (1987), suggesting that this is not just an isolated case. The temperature increases were consistently associated with the surface and the leaf temperatures, whereas the mass-average and the centre temperatures did not seem to be affected. The flash point, and the temperature increase, occurred when considerable lower pressures were obtained. In all cases, this occurred at a pressure below 25 mmHg. At this pressure, there is a considerable decrease in the density of the air in the retort, resulting in a definite decrease in the thermal conductivity of the air. This would greatly reduce heat transfer by conduction or convection through the air. The produce in the retort was shielded from radiation effects from the evaporator coils by 51 mm thick polystyrene insulation. Thus, it is expected that the increase in the temperature was due to condensation of water vapour on the surface of the lettuce. Further support of this idea is that the temperature increases only occurred from parts of the lettuce that were cooler. Thus as the water started evaporating quickly from the warmer areas of the lettuce, the whole lettuce would become surrounded by water vapour. The areas that were cooler and below the water vapour saturation temperature for the corresponding retort pressure would cause the water to condense on that area, effectively increasing the local temperature. The temperature increases were not great, being in the order of only 1 to 2°C.

4.5 Conclusions

Changing the rate of applied vacuum had no significant effect on the mass loss, temperature reduction per percent mass loss, or temperature differences between the various locations. The significance of these findings is that vacuum coolers with smaller vacuum pumps could be designed without any changes to the cooling characteristics of lettuce, though the implications of lettuce quality regarding such changes is still unknown. The non-significance with regard to the TRPML indicates that the same total amount of cooling is required, despite the speed at which the vacuum is applied, but the time period of the required refrigeration is increased for slower vacuum rates. This

would suggest that the peak refrigeration capacity could be decreased for slower vacuum rates, though more studies need to be done to confirm and quantify this relationship.

The location of the temperature sensor is important as significant temperature differences exist between the centre and other locations at the end of the cooling process. Infrared temperature sensors may prove to be an effective method of evaluating the lettuce temperature, as they closely resemble the mass-average temperature. The variation in the results form the infrared sensors was greater than that of thermocouples.

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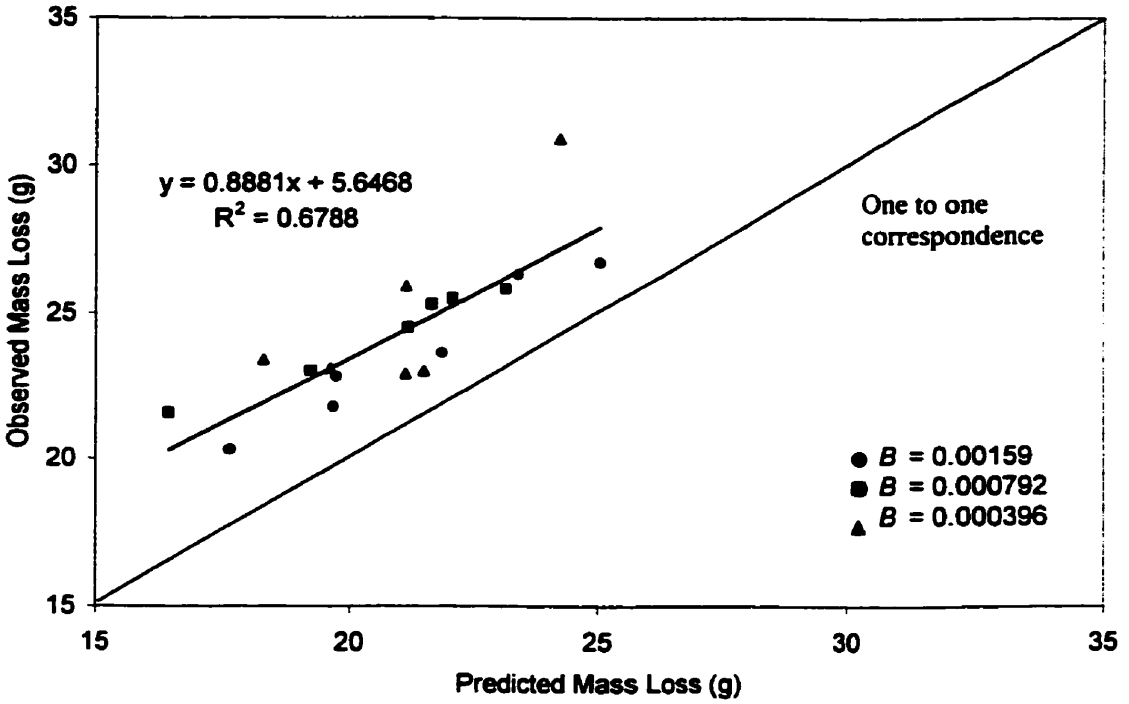

Figure 4.1: Observed versus predicted mass losses for vacuum cooled lettuce for different B values.

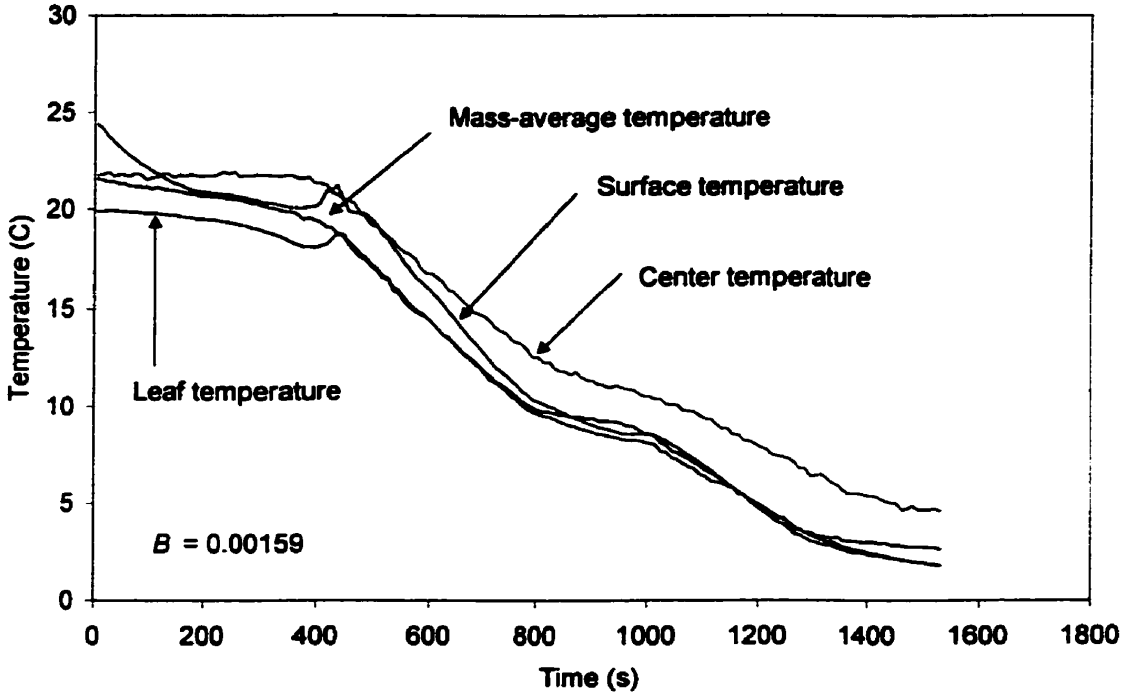

Figure 4.2: Typical temperature versus time for lettuce cooled with a B value of 0.00159.

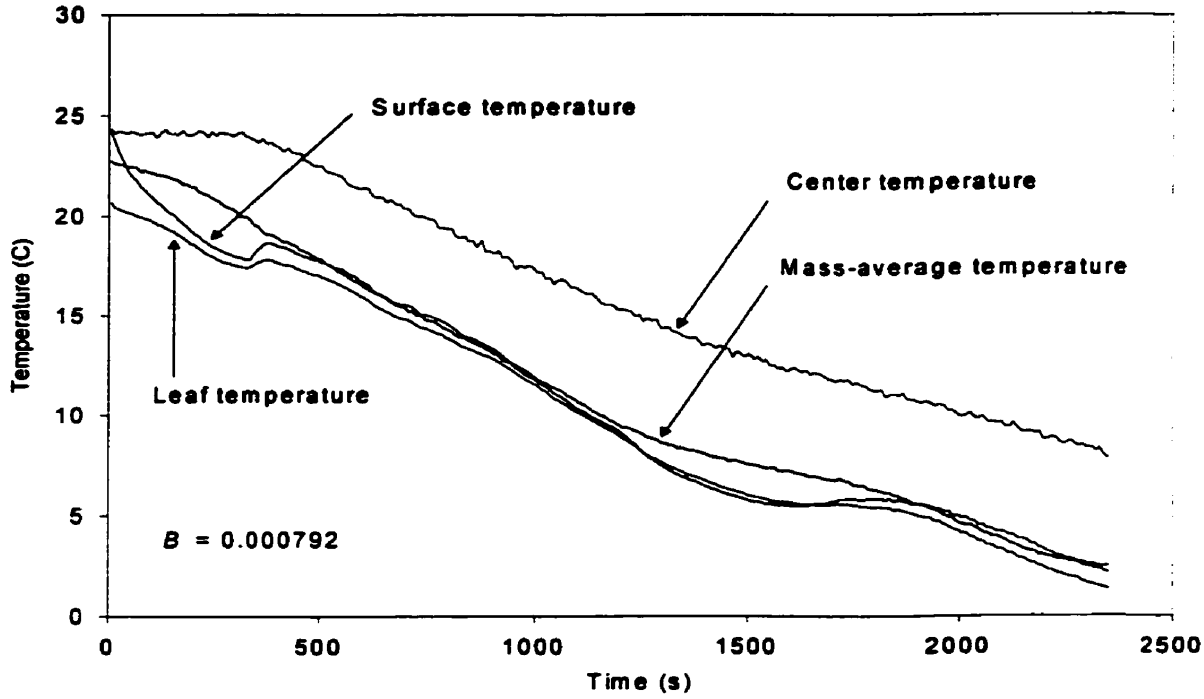

Figure 4.3: Typical temperature versus time for lettuce cooled with a B value of 0.000792.

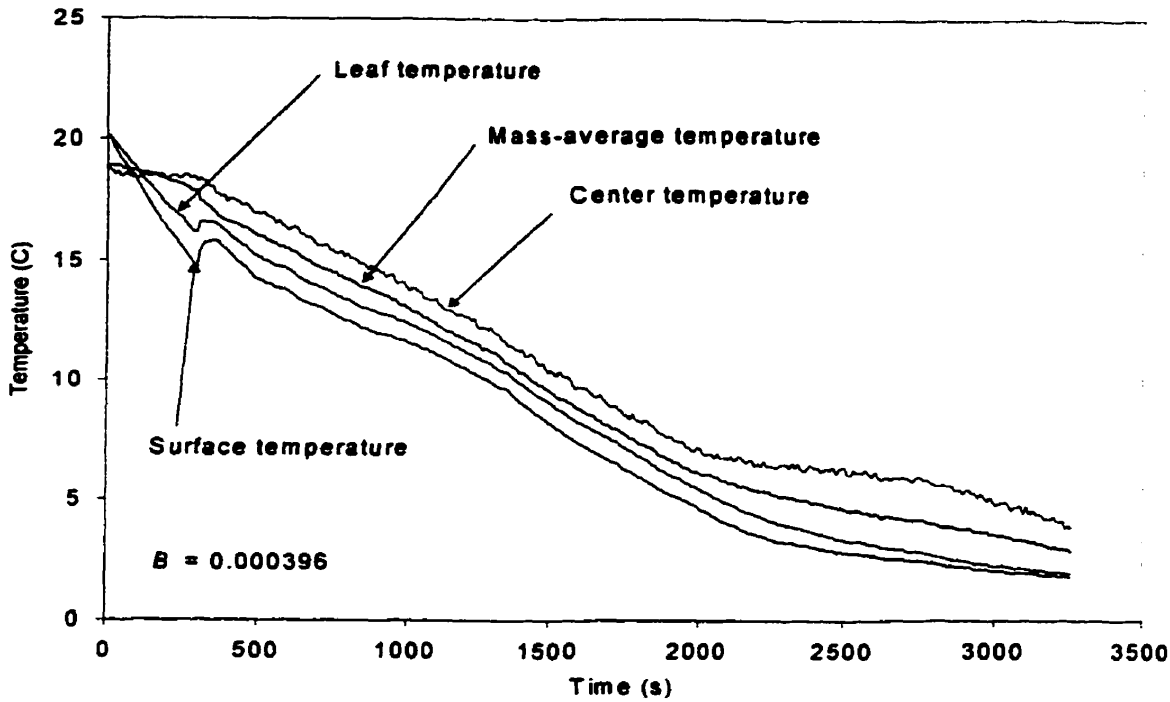

Figure 4.4: Typical temperature versus time for lettuce cooled with a B value of 0.000396.

CONNECTING TEXT

The cooling characteristics of the produce are only one step in determining if the use of a slower vacuum rate has application to the fresh fruit industry. Product quality and the maintenance of the quality are also of extreme importance for the industry. The next paper describes the quality aspects of the slow vacuum rate. The combination of these two papers will cover all the important produce cooling and physiology aspects with respect to the reduced vacuum rate.

V. EFFETCS OF VACUUM COOLING RATE ON LETTUCE QUALITY DURING STORAGE

5.1 Introduction

The prolongation of the storage life of fruits and vegetables is an important economic consideration in the agri-food business (Bakker-Arkema, 1999). The storing of fruits and vegetables for sufficient time allows the producer to sell the crop when the highest rates of return for the produce can be achieved. The price varies due to availability of the produce. During the peak harvest season, the prices of the produce are low then as the harvesting season ends, prices increase when it is necessary to buy imported produce. For the majority of fruits and vegetables, refrigerated warehouses are necessary to store the produce long enough to acquire higher prices. Controlled or modified atmosphere storage can further increase the storage life, or better maintain the produce quality during storage.

Produce quality is becoming increasingly important in the production and marketing of fresh commodities (Bakker-Arkema, 1999). Loss in quality can be caused by a number of factors, including moisture loss, microbial contamination, nutrient loss, and physiological breakdown (Bakker-Arkema, 1999, Mitchell *et al.*, 1972, Raghavan *et al.*, 1996). Lowering the ambient temperature can reduce all of these factors. The determination of the product quality is of importance in both industry and in research of fruits and vegetables.

Precooling of fruits and vegetables, which involves cooling the produce prior to storage or transportation has economic benefits for the postharvest operations of some produces. When precooled, the storage system has only to maintain the produce temperature, rather than cooling it as well, which reduces the peak refrigeration capacity for the warehouse. For very perishable produce, precooling will extend the storage length of the commodity as it is brought to storage conditions quickly after harvest, reducing the time that it remains at a high temperature, and hence reducing high respiratory activity that decreases the produce quality. Though precooling is an extra expense, it can decrease capital and operating costs of the refrigerated warehouse, and

increase the storage length of the commodity, thus adding economic value to the commodity.

Of the different methods of precooling, vacuum cooling is the best suited towards leafy green vegetables, such as lettuce, spinach, cauliflower, and endive (Kader, 1992). Other commodities that can be vacuum cooled include sweet corn, mushrooms, bean sprouts, and sweet peppers (Talbot *et al.*, 1991, Hardenburg *et al.*, 1986). The major disadvantages to vacuum cooling are the limited number of produce that can be cooled and the large capital costs associated with purchasing a vacuum cooling system. Thus, in many instances, small operations opt to use a different method to cool vegetables that would be best cooled by vacuum. Thus, a vacuum cooler that can be constructed at lower costs could have an economic benefit to small operations that wish to have a vacuum cooler but cannot justify the large capital expense for conventional systems.

5.2 Objective

The overall objective of this experiment is to evaluate the effects of vacuum cooling rate on lettuce quality during storage.

5.3 Materials and Methods

5.3.1 Vacuum cooling process and storage conditions

The tests were performed using a laboratory scale vacuum cooler. The cooler was a Model Y1 series 77-003 "Lyo-Tech" freeze-dryer (Lyo-San Inc., Lachute, Qc, Canada). Using only the vacuum pump and the refrigeration system allowed the freeze-dryer to perform the identical function as a vacuum cooler. The cooler was equipped with a belt-driven Welch duo-seal vacuum pump (Sargent-Welch Scientific Inc., Skokie, Illinois) operated with a 0.75 kW (1 hp), 120 V electric motor. The vacuum pump dropped the pressure from normal atmosphere to 25 mm Hg in an average time of 5 minutes and 53 seconds.

The cooler was instrumented with type-T thermocouples and a DIGIVAC 200 Conv (Fairfield/Digivac Company, Oceanport, NJ) vacuum gauge. The sensors were connected to a DATAshuttle Express (StrawberryTree Inc., Sunnyvale, CA) data

acquisition and control system. The DATAshuttle Express was controlled by a personal computer using WorkBench for Windows™ (StrawberryTree Inc., Sunnyvale, CA) software. The software allowed for the conversion of the voltage inputs of the vacuum gauge and the thermocouples to units of pressure and temperature, respectively. The vacuum gauge was supplied with voltage-pressure calibration points. From these points, empirical equations for pressure as a function of voltage was produced. Due to the highly non-linear relationship, three different equations were developed to describe three different portions of the pressure range. The thermocouples had an internal conversion of voltage to temperature supplied with the software.

Using the WorkBench for Windows™ software, a system to control the internal pressure of the chamber was devised. The pump was started and ran at the same speed for all the trials. An automated air leak was used to let air into the chamber so that the rate at which the pressure in the chamber dropped could be controlled by the amount of air going through the air leak. The air leak consisted of a tube attached to the chamber and three inlet solenoid valves of different diameters. Opening and closing the valves could allow different amounts of air in. An exponential decay equation for the pressure as a function of time was developed and used in the software to control the opening and closing of the solenoid valves. In theory, the rate at which the pressure is decreased follows an exponential decay function. In practice there is a slight deviation, generally when low pressures are achieved (Wang and Gitlin, 1964). The pressure could only be controlled when it had reached 200 mm Hg as the pump removed the air faster than the air leak could supply air at pressures higher than this. Thus, the equation used in the software was,

$$P = Ae^{-B\theta} \tag{5.1}$$

where A is 200 mm Hg, θ is time (s), and the B value (s^{-1}) represents the speed at which the pump can reduce the pressure. The control system began once the pressure was reduced to 200 mm Hg. By changing the B value, the rate at which the pressure dropped is changed. Once the pressure reached 6.0, the contol system was to maintain the pressure at 6.0 +/- 0.3 mm Hg by the opening and closing of the solenoid valves.

5.3.2 Quality evaluation

There are several methods to evaluate the produce quality. Visual observation, though subjective, has its merits as it is the same procedure that would be used by a consumer. The quality index scale that was used in this experiment is shown in Table 5.1. The drawback to this method is that it is limited primarily to the exterior quality. Internal injuries or damage can rarely be detected. Deterioration of the product is often accompanied by changes in the produce that is not readily detectable by visual observation. Colour changes, though sometimes slight, can indicate changes in the produce quality. Produce that is deteriorating may have increased respiration and transpiration, resulting in faster mass loss. Certain disorders may not be detected visually in their early stages, though the commodity is under stress. Other objective measurements, such as chlorophyll fluorescence, may be able to detect these stresses before the visual symptoms.

Table 5.1 : Visual quality evaluation scale

Score	Visual quality	Description
9	Excellent	Essentially free from defects
7	Good	Minor defects; not objectionable
5	Fair	Slightly to moderately objectionable defects; lower limit of sales appeal
3	Poor	Excessive defects, limit of saleability
1	Extremely poor	Not usable

Chlorophyll fluorescence has become an important analytical tool for analysing many environmental and physiological aspects of plants. Chlorophyll fluorescence is based on the amount of light that is emitted from chlorophyll in plant tissue when it is subjected to a light source. Chlorophyll fluorescence is a measure of the primary

processes of photosynthesis that occur in the chloroplasts, including light absorption. excitation energy transfer, and the photochemical reaction of photosystem II (PSII) (DeEll et al., 1999). Other levels of photosynthesis influence the primary level and thus chlorophyll fluorescence is effected by numerous factors in a very complex manner (Krause and Weis, 1991). Research has shown that the amount of light emitted (fluoresced) can be correlated to the stress that the plant is under (Krause and Weis, 1991, Corlett and Choudhary, 1993, Harbinson, 1995, Lichtenthaler, 1996). Water and cold stress in plants affect the normal operation of photosynthesis and these have been detected by chlorophyll fluorescence measurements (Schapendonk *et al.*, 1992). An important advantage to chlorophyll fluorescence is that it has the ability to detect stress before visual symptoms occur (Meir et al., 1997). There is an indication that chlorophyll fluorescence has potential to be used as a measurement to determine the storage quality of fruits and vegetables (Dull, 1986, Toivonen, 1992, DeEll *et al.*, 1995).

Under optimal conditions, the process of photosynthesis occurs with high efficiency. More than 90% of the absorbed light is utilised by photosynthesis (Krause and Weis, 1991). Some excitation energy is also released as fluorescence from chlorophyll *a* of PSII. When all the reaction centres of PSII are closed, that is, when the P680 cannot transfer any more electrons, the maximum fluorescence yield (ΦF_M) is observed. The maximum fluorescence is around 3% of the absorbed light (Krause and Weis, 1991). When all the reaction centres are open the fluorescence yield (ΦF_O) is about five times lower due to competition with photochemistry (Krause and Weis, 1991). Competition for the energy released from the deactivation of excited chlorophyll involves fluorescence along with photochemical reactions, thermal deactivation and excitation energy transfer to non-fluorescent pigments. Each of these processes is associated with a process rate constant. The constants k_F, k_P, k_D, and k_T are representative of the fluorescence, photochemical reactions, thermal deactivation, and excitation energy transfer, respectively. From these rate constants the general equation for fluorescence yield may be expressed as:

$$\Phi F = \frac{k_F}{k_F + k_D + k_T + k_P} \tag{5.2}$$

When all reaction centres are open, k_P is at its maximum, when all reaction centres are closed, k_P is zero. Thus, the maximum and minimum values of k_P correspond to the minimum and maximum fluorescence yields, respectively. In a similar manner, the potential yield (ΦP) of the photochemical reactions of PSII may be expressed as:

$$\Phi P = \frac{k_P}{k_F + k_D + k_T + k_P} = \frac{\Phi F_M - \Phi F_O}{\Phi F_M} = \frac{F_V}{F_M} \qquad (5.3)$$

F_M is the maximum total fluorescence and F_V is the variable fluorescence emission. The ratio of these two parameters is extremely important in the measurement of the physiological state of the photosynthetic structure of intact plant leaves. Environmental stress that affects the efficiency of the PSII process leads to a decrease in the F_V/F_M ratio (Krause and Weis, 1991).

To perform the above measurements, the plant tissue needs to be first dark adapted (no exposure to light) for roughly 20 minutes. The test is performed in the dark, with the activating light source coming from the instrument. Measurements of chlorophyll fluorescence can also be made when there is a background light. The measurements will not yield the maximum and minimum fluorescence but the maximum value under light exposure, ΦF_{MS}, and the steady state fluorescence, ΦF_S. Thus, a similar ratio, F_V'/F_M', can be made that is analogous to the F_V/F_M ratio (Opti-Sciences, 1994).

For this experiment, dark-adapted measurements were made for F_V, F_V/F_M, and $T½$. Measurements of the F_V' (variable fluorescence) and F_V'/F_M' were made after the lettuces were light adapted for 20-30 minutes.

Chlorophyll fluorescence was measured using a OS-500 modulated fluorometer (Opti-Sciences Inc., Tyngsboro, MA). The fluorometer was portable with four light sources (modulated, saturation, actinic, and far red), a photodiode detector, computer hardware and software, standard 3.5" diskette drive, user input keys, a LCD screen, a 12 V battery and charger, and a 9 mm measuring probe connected to the light sources and detector through a system of fiber optic cables. The modulated light was a 655 nm solid state source with adjustable intensity (< 1.0 $\mu mol \cdot m^{-2} \cdot s^{-1}$) which emitted radiation at wavelengths greater than 660 nm. Filters blocked all radiation above 700 nm. A 35 W halogen lamp provided the saturating pulse light with adjustable intensity up to 10 000 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for duration of 0.1 to 3.0 s. The actinic light is a solid state source whose

peak emission wavelength was roughly 670 nm with a variable intensity up to 450 $\mu mol \cdot m^{-2} \cdot s^{-1}$. The PIN silicon photodiode detector is filtered to receive radiation from 710 to 760 nm.

5.3.3 Experimental layout

Three different rates of vacuum application were used in this experiment. The *B* values used are listed in Table 5.2. Three replications were used for each treatment. Due to the length of time necessary to perform the treatments, each replicate was run on a different day. Thus, the experiment had each treatment performed on the same day, the order of the treatments being randomised within each replicate. As the characteristics of the lettuce could change from one day to the next, the reps were treated as block factors in the statistical analysis of the data. For the statistical analysis, a multivariate analysis of variance (MANOVA) was used with time as a repeated measure, as the data collected was always on the same subject over time. The statistical analysis was performed using SAS 6.1 for Windows™. This allowed for the determination of significance between the treatments for each day samples were taken, as well as the effects of the rep (block effect) and interactions between rep and time, rep and treatment, and treatment and time.

Table 5.2: *A* and *B* values used for the control of the pressure

Speed	A Value	B Value
Fast	***	0.00940[†]
Medium	200 mm Hg	0.00159
Slow	200 mm Hg	0.000396

[†] Natural *B* value of the vacuum pump.

5.3.4 Experimental procedure

Fresh 'iceberg' lettuce (*Lactuca Sativa*) was bought from a local distribution centre each morning. The lettuce had been freshly harvested and it was not precooled. The lettuce was transported to the Horticultural Research and Development Center of Agriculture and Agri-Food Canada (St. Jean-sur-Richelieu, Quebec, Canada). The outer wrapper leaves were removed from each of the ten heads, the heads were weighed,

visually evaluated for quality and placed into the vacuum chamber. Three of the ten heads were instrumented with thermocouples to read the mass-average temperature of the lettuce. The chamber door was closed and the vacuum pump started. When the average temperature of the three thermocouples reached 2.5°C the vacuum pump was stopped, the vacuum broken, and the lettuce removed. The lettuce were weighed again and then immediately placed into cold storage at 1°C and 85% relative humidity. The boxes were covered with a perforated bag to protect the lettuce from direct airflow and to maintain a high relative humidity in the boxes. Separate boxes were used for each of the reps and for each of the treatments. After being stored in the dark for 30 minutes, allowing the lettuce leaf temperature to equilibrate with the cold room and to provide the necessary dark adaptation, chlorophyll fluorescence measurements were made on the lettuce heads. The lights in the storage room were turned on and 20 minutes later the light chlorophyll fluorescence measurements were made. Chlorophyll fluorescence measurements were then made on days 1, 2, 6, 9, 13, and 16. On day 16, the lettuce were also allowed to warm up to room temperature and an additional measurement of chlorophyll fluorescence was made, both in the dark and in the light. On days 2, 6, 9, 13, and 16, visual evaluation and weighing of each head of lettuce was performed. On day 16, the lettuce heads were cut in half to observe the internal condition of the lettuce.

5.4 Results and Discussion

5.4.1 Mass loss

The mass of the lettuce was taken after cooling on days 2, 6, 9, 13, and 16. For each day, the percent mass loss as based on the initial mass was calculated. The average of the three reps is represented in Figure 5.1. The mass loss with respect to time was nearly linear. The mass loss followed a similar pattern for all three treatments, though the fastest vacuum rate resulted in greater mass loss and the slowest resulted in the least loss. From previous studies (Chapter IV), though not significant, it appeared that the faster rates might not lose as much moisture as the slower vacuum rates. Had more reps been performed it may have shown significance. If there is a slight difference then that could explain the greater mass loss from the faster vacuum rate, as there is more moisture

that can be removed. However, the difference is not that great between the different rates and considering that for this theory to work, the slowest vacuum rate would lose the most moisture during the cooling process. The end result, combining the loss during cooling and during storage, would be that the difference would be negligible at most.

5.4.2 Visual quality

Visual evaluation of the lettuce quality was performed on days 0, 2, 6, 9, 13, and 16. The results from the visual quality are shown in Figure 5.2. The three treatments all behaved in the same manner. The overall quality of the lettuce after 16 days of storage was classified between "fair" and "good". The differences between the different treatments were minimal and it may be concluded that the rate of vacuum application has no overall effect on the quality of the stored lettuce. On the final day the lettuce were cut in half and they were evaluated for internal rot. No incidences of internal rot were found. The visual internal quality of the lettuce was better than the outer quality and still had a freshly harvested appearance.

5.4.3 Chlorophyll fluorescence

Chlorophyll fluorescence measurements were made on days 0, 1, 2, 6, 9, 13, and 16. Measurements were made in both dark-adapted and light-adapted conditions. For the dark-adapted condition, three measurements were taken, $T½$, F_V, and F_V/F_M. Figure 5.3 shows a plot of $T½$ versus time for the three treatments. The $T½$ measurement is the measurement of the time required for the fluorescent measurement to increase from the minimum value to half the difference between the minimum and maximum fluorescence. Most fluorescence measurements are ratios, where $T½$ gives quantitative information. The plot shows that the $T½$ values all increased after the precooling and became somewhat constant after a few days in storage. Significant differences were observed on days 0, 1, 9, 13, and 16 (Table 5.3), as $T½$ measurements for the fastest vacuum application rate did not recover as well as for the slower applications rates. One possible reason that $T½$ was lower is that the variable fluorescence was also lower for the fastest application rate. Figure 5.4 shows a plot of the variable fluorescence F_V versus time.

From this plot, it is seen that indeed the variable fluorescence of the fastest application rate is lower as it did not recover as well as with the other two rates. This suggests that

Table 5. 3: Statistical analysis results for treatment main effects using chlorophyll fluorescence measurements

Test	Day						
	0	1	2	6	9	13	16
F_V	S	S	S	NS	S	NS	NS
F_V/F_M	S	S	S	S	S	S	S
T½	S	S	NS	NS	S	S	S
F_V'	S	S	S	S	S	S	NS
F_V'/F_M'	S	NS	S	NS	S	NS	S

S = Significant, NS = Not Significant, at $\alpha = 0.05$

the faster application rate may have stressed the lettuce at the molecular level, but not enough to cause visual deterioration of the lettuce quality. Significant differences amongst the treatments were found on days 0, 1, 2, and 9 (Table 5.3). Figure 5.5 is a plot of F_V/F_M versus time. The plot shows that the slowest application was the most affected and it took longer to recover than the other rates. All three rates recovered and although there was significant differences for all the sampling days (Table 5.3), the order did change periodically. In all cases, the F_V/F_M ratio was over 0.8, indicating that the tissue was healthy immediately after the precooling and throughout the storage period, thus even if significance is found between treatments it should not affect the overall storage condition of the lettuce; unlike the T½, the F_V/F_M ratio suggests that the slow application stressed the lettuce. It is possible that for slower vacuum rates, the longer exposure to vacuum and evaporation of water could cause a stress, whereas with faster rates the duration of the stressful situation is not enough to affect the plant tissue. With the three different dark-adapted measurements, no conclusive deductions can be made as to the magnitude of the stress due to different vacuum rates.

For the light-adapted condition, F_V' and F_V'/F_M' measurements were made. For the F_V' measurements, significance was detected between the treatments throughout the storage period (Table 5.3), with the lowest value associated with the fastest vacuum rate and the highest value with the slowest rate. These results are shown in Figure 5.6 and are similar to those of the F_V' which showed a similar trend. Significance was detected on all the sampling days except for the final day (Table 5.3). Figure 5.7 shows the plot of F_V'/F_M' versus time. Though significance was detected on some days, the variation of the values from day to day does not allow for any conclusions to be made on the effect of the vacuum rate on the ratio.

5.5 Conclusions

An experiment was performed to determine if changing the vacuum rate of a vacuum cooler would have any effect on the quality of the lettuce after cooling and during storage. Lettuces were cooled at three different rates and stored for 16 days at 1°C and 85% relative humidity conditions. Mass loss, visual quality, and chlorophyll fluorescence measurements were made throughout the storage period. The results from the mass loss and visual quality evaluation suggest that there is no difference in the overall quality when cooled with different rates. The chlorophyll fluorescence measurements suggested that the faster rate of vacuum application may stress the lettuce more than the slower rate, and that the lettuce under the faster rate did not recover from the stress as well. But in all cases the lettuce tissue was still healthy and that the level of stress was minimal and did not affect the overall quality of the lettuce. Thus, supporting the results from the visual quality evaluation.

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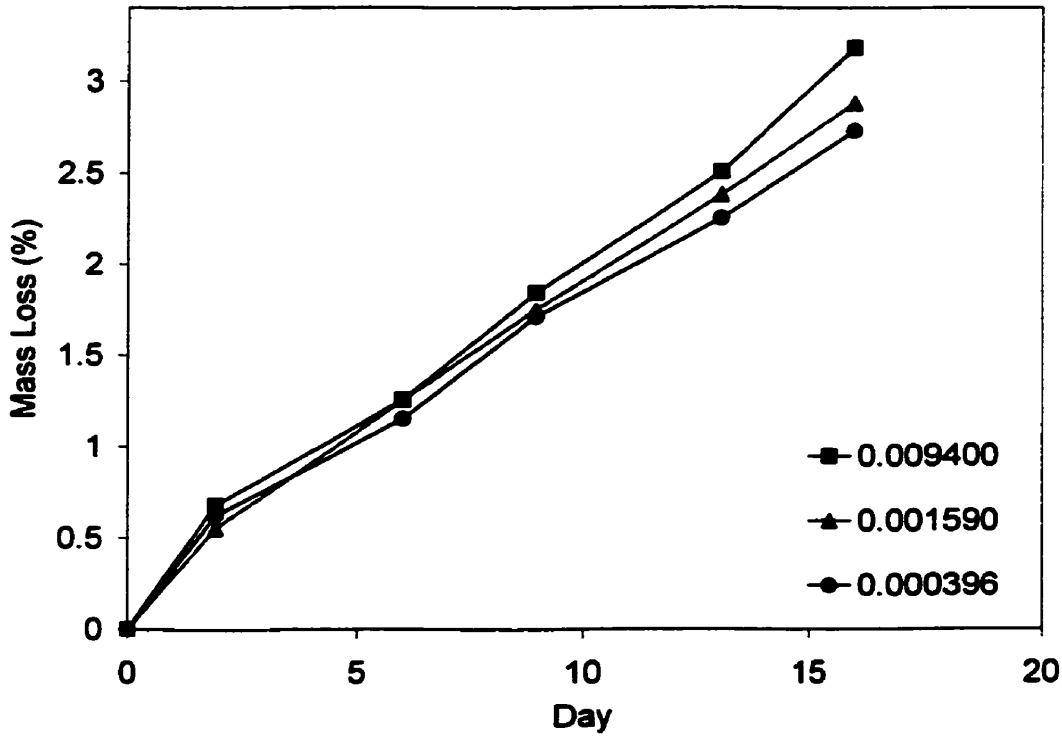

Figure 5.1: Mass loss of lettuce vacuum cooled under different *B* values and held at 1° for 16 days.

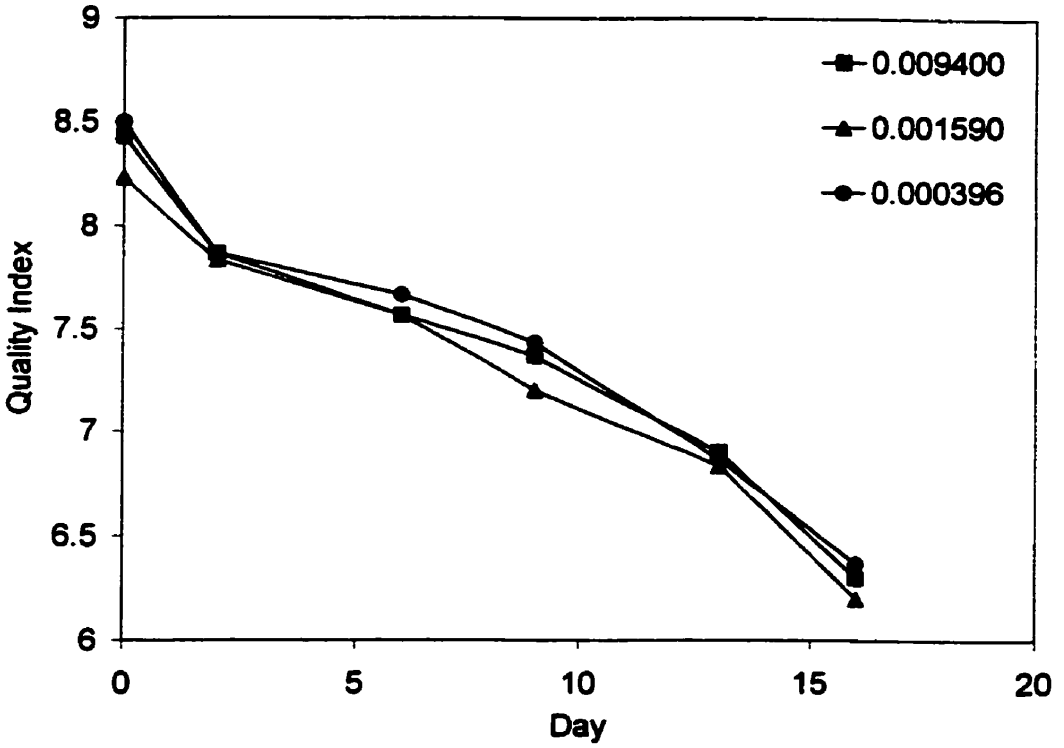

Figure 5.2: Visual quality of lettuce vacuum cooled with different *B* values and held at 1°C for 16 days.

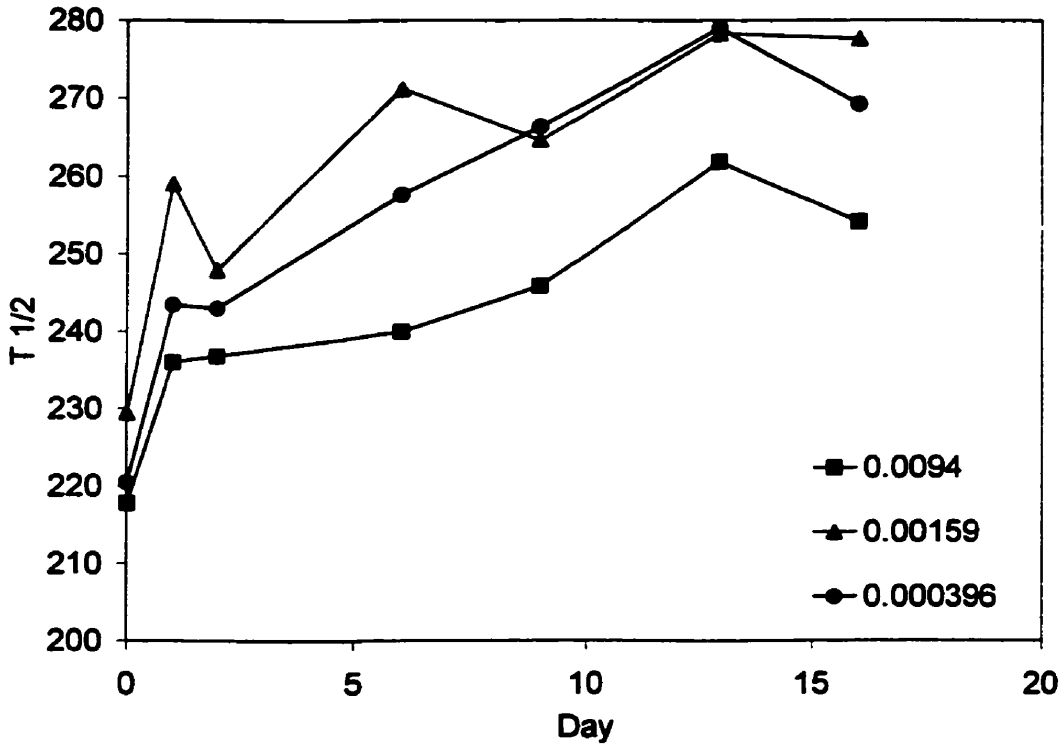

Figure 5.3: Chlorophyll fluorescence T ½ values for lettuce vacuum cooled with different *B* values and held at 1°C for 16 days.

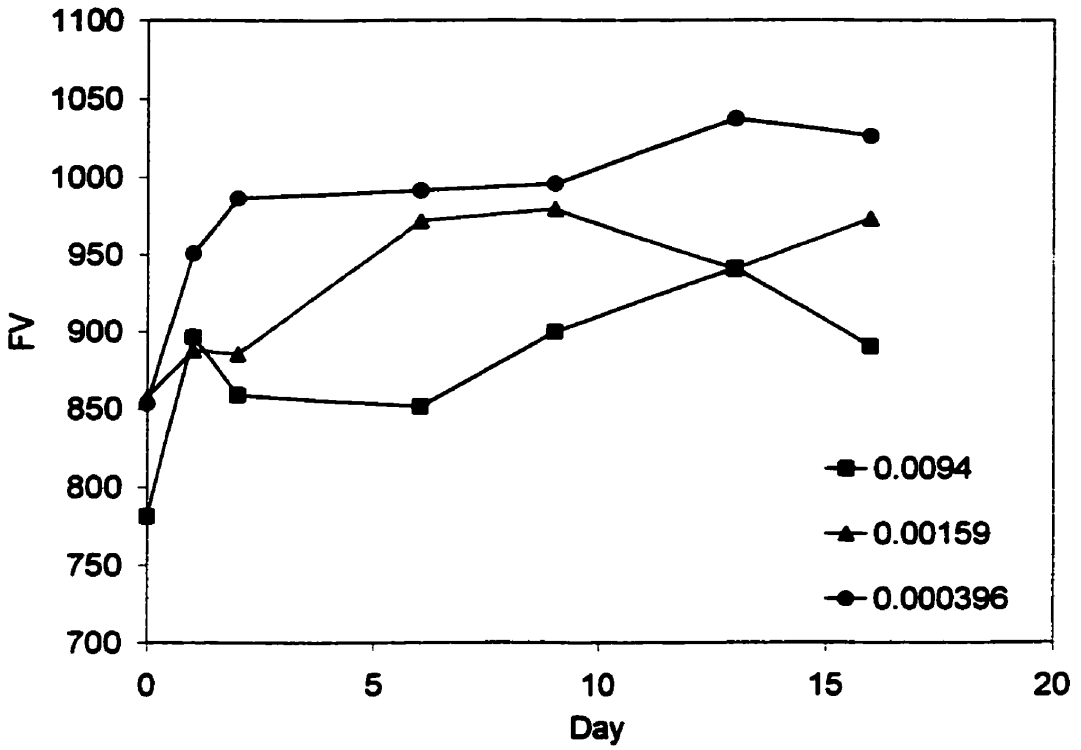

Figure 5.4: Variable fluorescence values for lettuce vacuum cooled with different *B* values and held at 1°C for 16 days.

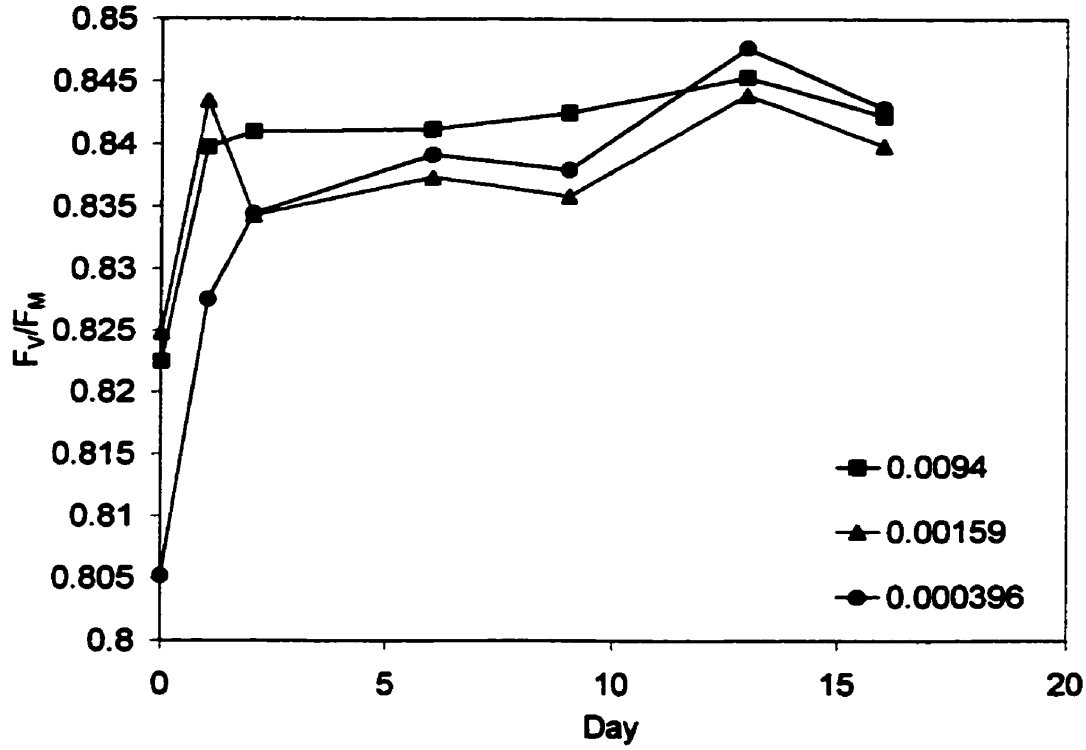

Figure 5.5: Variable to maximum fluorescence ratio values for lettuce vacuum cooled with different *B* values and held at 1°C for 16 days.

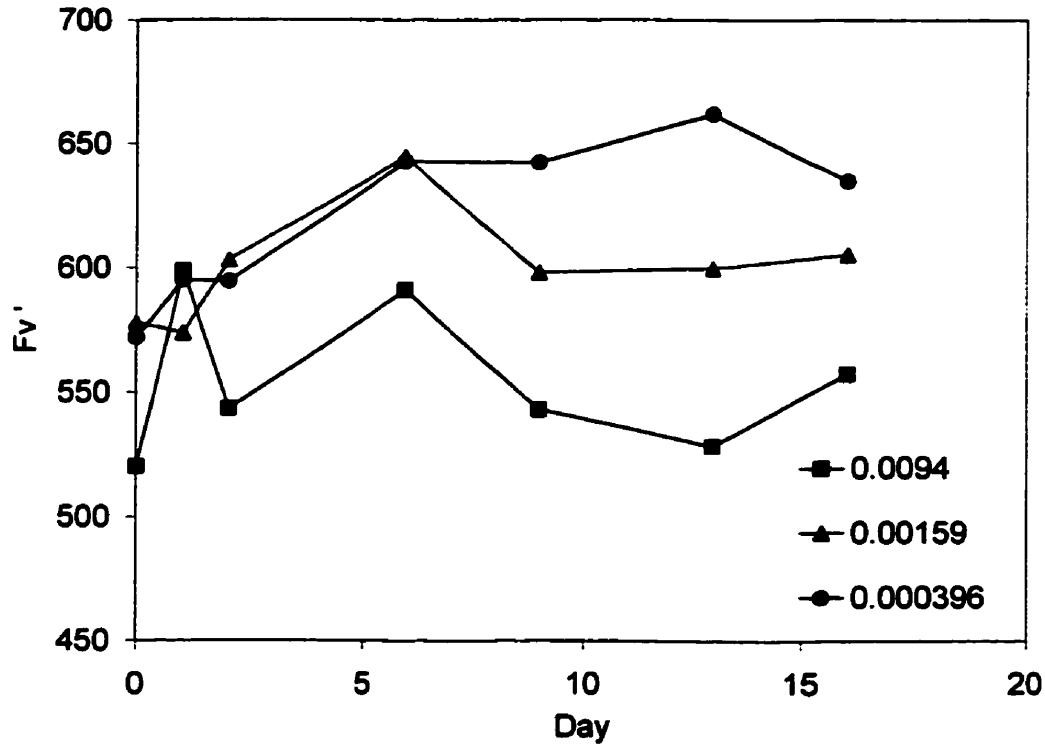

Figure 5.6: Variable fluorescence (light) values for lettuce vacuum cooled with different *B* values and held at 1 °C for 16 days.

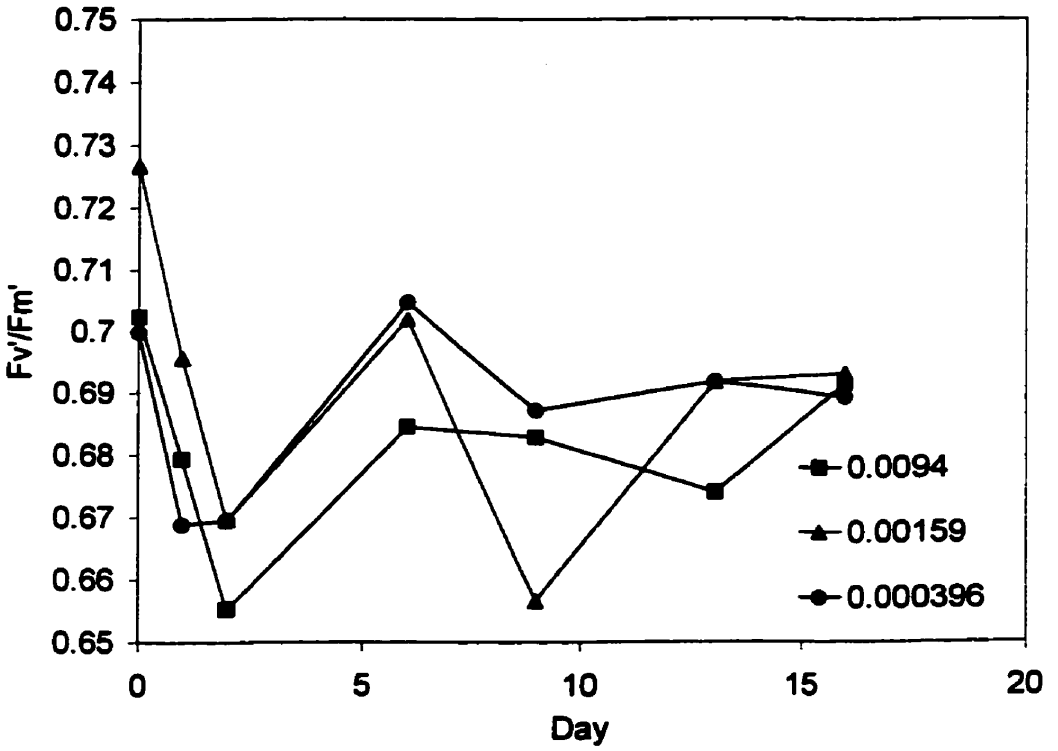

Figure 5.7: Variable to maximum fluorescence ratio (light) values for lettuce vacuum cooled with different *B* values and held at 1°C for 16 days.

CONNECTING TEXT

The previous two chapters dealt with the cooling characteristics and the quality of lettuce cooled with various vacuum rates. These results show that there is no drawback for using a slower vacuum rate. To truly investigate the possible benefits of using a slower vacuum rate, not only the effect on the lettuce needs to be studied, but also the affect on the overall system. Thus, for economic and design purposes, the relationship between the pumping rate and the product refrigeration load needs to be determined. The following paper deals with this relationship.

VI. DETERMINATION OF THE PRODUCE REFRIGERATION LOAD IN VACUUM COOLING OF LETTUCE

6.1 Introduction

The storage life of perishable fruits and vegetables can be prolonged by refrigerated storage of the commodities (Kader, 1992). Though refrigerated storage can increase the shelf life of some commodities, the storage rooms tend to be large and the refrigeration systems can not effectively cool the produce quickly. Equipping a refrigerated storage room with a refrigeration system that would produce the necessary cooling is costly, as the refrigeration unit would be running at peak performance for only a short period of time. As well, cooling in storage often causes excessive moisture loss in produce as they are exposed to higher than normal airflow rates during the cooling (Raghavan *et al.*, 1996). For some produce, they can deteriorate as much in one hour at 26 °C as they would if stored at 0 °C for one week (Boa and Lindsay, 1976). In such situations, refrigerated storage alone is not adequate to maintain quality as it could take several hours for the produce temperature to reach desired levels. Thus, for some produces, it is imperative that they are quickly cooled prior to refrigerated storage. Processes that are separated from refrigerated storage and are used to quickly remove the field heat of the produce before storage or transportation are known as precooling processes.

The type of precooling method used is dependent on the type of produces being cooled and the size of operation. Some produces can be cooled by a number of methods, though one or two specific methods might yield better results than others, either in produce quality or operating and maintenance expenses. Other produces may be limited as exposure to some conditions, such as high airflow rates or cold, wet environments which may adversely affect the quality of the produces.

Vacuum cooling is an effective method of cooling produce with a high surface to mass ratio, such as lettuce, spinach, and other leafy vegetables (ASHRAE, 1998, Haas and Gur, 1987). Vacuum cooling is a specific application of evaporative cooling, as the cooling of the produce comes from the evaporation of water from the surface (Griener

and Kleis, 1962). Produce is placed in an airtight retort and the pressure is reduced using a vacuum pump. As the pressure is reduced, the boiling point of water is also lowered. When the boiling temperature of water reaches the produce temperature, rapid evaporation begins. The evaporation of water requires large inputs of energy, which is obtained from the thermal energy of the produce, thus effectively cooling the produce. A refrigeration system is required to condense the water vapour rather than attempting to send it through the vacuum pump.

The design of the refrigeration system requires the knowledge of the following three processes: (1) cooling of the produce, (2) respiration heat of the product, and (3) the cooling of the chamber (Wang and Gitlin, 1964). Wang and Gitlin developed the following equation to determine the refrigeration load of the produce based on the heat capacity, c_p ($kJ \cdot kg^{-1} °C^{-1}$), the mass, m (kg), of the produce to be cooled, and the change in temperature that the produce has to undergo, T_1-T_2 (°C):

$$q = \frac{\frac{2}{3} c_p (T_1 - T_2) m}{1/2 \text{ actual cooling time}} \tag{6.1}$$

The equation is based only on cooling that takes place after flash and assumes that two thirds of the cooling occurs in the first ten minutes of cooling, considering a twenty minute cooling time. This assumption is based on an exponential decay type temperature drop. Though this temperature drop is considered standard for vacuum cooling produce in the classical sense, the cooling curve may change as the vacuum application rate is lowered.

The produce respiration load is a function of the temperature of the produce and the time before the flash point is reached. As no cooling occurs before the flash point, the refrigeration system needs to remove this heat. Until the flash point is reached, the refrigeration load due to the respiration is constant and at its maximum. Once the flash point is reached and the produce temperature begins to drop, the respiration heat load decreases. In normal operations, the refrigeration load due to respiration is about 3 percent of the produce heat load for lettuce (Wang and Gitlin, 1964).

The refrigeration load of the retort can be kept to a minimum if it is possible to restrict the condensed water from coming in contact with the retort walls. If this is

achieved, the refrigeration load due to cooling of the retort can be restricted to 2 or 3 percent of the product load (Wang and Gitlin, 1964). If this is not possible, then the cooling load can be calculated using the following expression based on the mass of the chamber (kg), m_c, the temperature difference and the heat capacity, c_{pc} of the chamber:

$$q = m_c(T_1 - T_2)c_{pc} \tag{6.2}$$

It should be noted that the first run, considering constant ambient temperatures, may have the highest refrigeration load as the chamber would be warm on the first run but would be relatively cool on subsequent runs. Though the amount of cooling of the retort walls depends on the amount of condensed water allowed to contact the inside retort walls.

The main disadvantages of vacuum cooling are the limited number of produce that can be cooled quickly and the large capital cost of vacuum coolers. Reducing the size of the vacuum pump can reduce the capital cost of the pump but time required for the operation is increased. The reducing the rate at which the vacuum is applied will decrease the peak refrigeration capacity needed, but little published material exist on the extent the capacity can be decreased.

6.2 Objective

The objective of this study was to determine what effect the change of the rate of vacuum application has on the peak refrigeration requirements in the vacuum cooling of head lettuce. This was achieved by the following:

1. Development of a model to determine the peak refrigeration requirements based on the pumping rate and the initial produce temperature.
2. Test the model against experimental trials

6.3 Materials and Methods

6.3.1 Determination of the theoretical temperature decrease

The maximum supply of refrigeration necessary during the vacuum cooling cycle will determine the size of various components of the refrigeration unit. The surface area of the condenser and evaporator coils will depend on the peak refrigeration and on the

operating temperatures of the refrigerant and the surrounding ambient conditions. Appropriate knowledge of the peak refrigeration need is important in correctly sizing the refrigeration unit.

With the assumption that there is no lag between the water vapour saturation temperature and the temperature of the produce, the rate at which the temperature of the produce drops can be modelled as a function of the pressure, as the pressure depicts the water vapour saturation temperature. Theoretically, the pressure in a vacuum cooler should follow an exponential decay function. In practical situations there is a slight deviation from this function as the efficiency of a vacuum pump decreases slightly as the pressure is lowered (Wang and Gitlin, 1964). The pressure, p, in the vacuum cooler is thus modelled by the following expression:

$$p = 760e^{-B\theta} \tag{6.3}$$

where the pressure is expressed in mm Hg, B (s^{-1}) is a value related to the speed of the applied vacuum, and θ is the time (s) with a zero value when the vacuum pump is started. The B value is a function of the volumetric removal rate of the pump and the volume in the retort.

The desired function needs to express product temperature as a function of time. Before this can be reached, an expression that relates the temperature as a function of pressure is needed. ASHRAE (1997) provides a relationship between the saturated vapour pressure and temperature. The saturated vapour pressure is expressed as a quadratic function of the absolute temperature between 0 to 200 °C. Results from this equation between temperatures of 0 to 35 °C were used to define a model of temperature, T_p, as a function of pressure, p. The resulting model was a MMF model, a member of the growth family, with the following form:

$$T_p = \frac{ab + cp^d}{b + p^d} \tag{6.4}$$

where a, b, c, and d are constants having the following values:

a = -9.150

b = 506.3

c = 146.2

d = 0.6085

The temperature and the pressure in the above model were expressed in degrees Celsius and mm Hg, respectively. The model was used in the ranges between 0 and 35 °C as these would be considered as the two extremes for the temperature of the produce. The model fit the original curve (ASHRAE, 1997) with a standard error of 0.013 and a correlation coefficient of 0.99. Substituting the expression of pressure into the above model yielded the following theoretical expression of the temperature of the produce as a function of time in the cooler, starting with a time of zero when the vacuum pump is started:

$$T_p = \frac{-602.5 + 1646(e^{-B\theta})^{0.197}}{7.349 + 3.684(e^{-B\theta})^{0.197}} \tag{6.5}$$

This equation is only applicable if the produce temperature is below a temperature of 35 °C as this expression was based on the saturation vapour pressures corresponding to saturation temperatures between 0 and 35°C. It is expected that this equation would become more valid as the rate of vacuum application is slowed, as there would be less of a lag time in heat transfer.

What is of concern to the design of the refrigeration system is not the temperature of the produce, but at what rate the temperature of the produce is dropping. Hence the above equation is of little use, but the derivative of the function is the main interest. The derivative of the above expression is as follows:

$$\frac{dT_p}{d\theta} = -\frac{C_1 B(e^{-B\theta})^{C_2}}{C_3 + C_4(e^{-B\theta})^{C_2}} + C_7 \frac{B(-C_5 + C_6(e^{-B\theta})^{C_2})(e^{-B\theta})^{C_2}}{(C_3 + C_4(e^{-B\theta})^{C_2})^2} \tag{6.6}$$

where,

$C_1 = 323.6$

$C_2 = 0.197$

$C_3 = 7.349$

$C_4 = 3.684$

$C_5 = 602.5$

$C_6 = 1646$

$C_7 = 0.724$

Thus, knowing the initial produce temperature (and hence the initial evaporation pressure), and the B value of the pump, the time at which the evaporation would theoretically begin can be calculated by equation 6.3. This time, along with the B value, can then be inserted into equation 6.6, resulting in the rate of change of the temperature. Due to the type of function of the temperature with respect to time, the slope of this function will always decrease with time, thus the greatest rate of evaporation will correspond to when the greatest temperature change of the produce occurs. This greatest change will therefore occur when the saturated temperature reaches the actual temperature of the produce.

6.3.2 Experimental set-up

To determine the cooling rate of the lettuce, experimental trials were performed in a laboratory scale vacuum cooler. The laboratory vacuum cooler was a Model Y1 series 77-003 "Lyo-Tech" freeze-dryer (Lyo-San Inc., Lachute, QC, Canada). Using only the vacuum pump and the refrigeration system, the freeze-dryer operates as a vacuum cooler. A 0.75 kW (1 hp), 120V electric motor was operated a belt driven Welch duo-seal vacuum pump (Sargent-Welch Scientific Inc., Skokie, IL). The vacuum pump could reduce the vacuum in the empty retort from normal atmospheric pressure to 25 mm Hg in an average time of 5 minutes and 53 seconds.

The cooler was instrumented with seven type-T thermocouples and a pressure sensor. The pressure sensor was a DIGIVAC 200 Conv (Fairfield/Digivac Company, Oceanport, NJ) with a voltage output. The calibration points supplied with the sensor were used to perform a regression to model the pressure as a function of voltage. Since the voltage-pressure relationship was highly non-linear, three equations were developed, each for a different pressure range. These equations were used in the data acquisition program to transform the voltage readings to pressure measurements.

The data acquisition and control system consisted of a DATAshuttle Express (Strawberry Tree Inc., Sunnyvale, CA) hardware unit and a portable computer using WorkBench PC for Windows™ (Strawberry Tree Inc., Sunnyvale, CA) software to control the data acquisition system. The data was recorded in ASCII format so that it could be manipulated later in a standard spreadsheet program.

Since the objective was to simulate different vacuum pump sizes, the cooler had to be modified to be able to control the pressure in the retort. The same pump was used for all the experimental trials, but an air leak was introduced to control the pressure. The pressure was allowed to drop naturally until a retort pressure of 25 mm Hg was achieved. At this pressure, the control system for the pressure began. Using an air leak regulated the pressure. The air leak consisted of three tubes attached to the cooler, each tube connected to a solenoid valve. The computer controlled the operation of the solenoid valves. The rate of vacuum was modelled based on an exponential decay function in the form of:

$$p = Ae^{-B\theta} \tag{6.7}$$

where p is the pressure of the retort (mm Hg), θ is the time (s) starting when the control began, A is the pressure at which the control began (mm Hg) and B is a process variable representing the speed of the vacuum application (s^{-1}). When the pressure reached 6 mm Hg, the control system was used to keep the retort pressure at 6 ± 0.4 mm Hg. The B value was changed to simulate different vacuum pump sizes. The values are listed in Table 6.1.

Table 6.1: B values used for the controller

Time (25 mm Hg to 6 mm Hg)	B Values (s^{-1})
Natural speed	0.00940
15 min	0.00159
30 min	0.000793
60 min	0.000396
120 min	0.000198

6.3.3 Experimental procedure

The experimental design was a completely random design. It consisted of five levels of treatment and three replicates per treatment. Each replicate consisted of three lettuce heads. The treatment factor was the rate at which the vacuum was applied. The

replicates were done on three consecutive days with fresh head lettuce bought from a local market each morning.

Three heads of lettuce were selected, their diameter measured and instrumented with two thermocouples each. One thermocouple was placed to read the centre temperature and the other thermocouple was placed to record the mass-average temperature. Mass-average temperature is defined as the temperature of an object, undergoing transient cooling, that would become the temperature of the object if it were allowed to come to a uniform temperature in adiabatic conditions (Smith and Bennett, 1965). The mass-average temperature was located at a depth of one-fourth of the radius. This depth assumes a spherical object with homogenous physical and thermal properties and cooling that follows Newton's law of cooling as described in Smith and Bennett (1965). The lettuces were placed in the cooler and the vacuum applied. The vacuum pump was stopped and the vacuum broken when the average mass-average temperature of the three lettuces reached 2.5 °C. The lettuces were removed from the cooler. During the cooling process, the temperature data was recorded every second. This data was then averaged out for every ten seconds of operation to remove some of the effects of noise.

6.3.4 Determination of the observed rate of temperature drop

Using the temperature data, the slope of the temperature curve was calculated for every ten seconds of operation. For the slope calculation, two temperature measurements were taken, with one-minute interval between the two temperature measurements for the B values of 0.00940 and 0.00159. For the B values of 0.000793, 0.000396 and 0.00198, the time interval used was 90 seconds. The maximum slope that occurred between the operating conditions of 25 mm Hg to the end of the test run was recorded.

The observed slope was also measured by plotting the data. The greatest visual slope was then fitted with a linear fit using the least squares method. These slopes were considered to be more accurate as they were less likely to be affected by noise fluctuations of the thermocouple readings.

6.4 Results and Discussion

The peak produce refrigeration load, q_p, needed in a vacuum cooling operation is a function of the mass of produce, m_p, its specific heat, c_p, and the rate of temperature change, $dT_p/d\theta$, given by the expression:

$$q_p = m_p c_p \frac{dT_p}{d\theta} \tag{6.8}$$

This experiment was conducted to compare the theoretical peak refrigeration load to the observed peak load for different rates of vacuum application. A theoretical model was developed as a function of the rate of vacuum application. The basis of this model assumes that the temperature of the produce follows the saturation temperature of water vapour as the pressure is reduced.

The peak produce refrigeration load based on this model is presented in Table 6.2. Three different values have been calculated. The first value is based on an initial produce temperature of 35°C. This would correspond closely to the maximum initial produce temperature that would be experienced in industry, though it is dependent on geographic location. The second rate calculated is the linear slope of the temperature-time relationship between 0 and 35°C. These slopes are lower than the slopes at 35°C but do not differ greatly as the temperature-time relationship is fairly linear. For the B value of 0.00940, corresponding to the natural vacuum rate, the linear slope is 21.4% lower than the slope at 35°C. Correspondingly, the linear slope for a B value of 0.000198 is also 21.4% lower than the 35°C slope.

The theoretical rate of temperature drop was also calculated based on the initial produce temperature for each of the lettuces that was used in the experiment. These could then be compared directly to the observed rates of temperature drop.

The observed maximum slopes based on the interval method produced results that were below the maximum at high B values, above the predictions at low B values and fairly accurate for medium B values. As these temperature measurements were taken at the mass average temperature, they should represent the rate of heat loss fairly accurately. Though some errors would be associated with the lower B values as the noise level of the thermocouples would become more apparent as the temperature-time slope became

smaller. Thus, this method of measuring the maximum slope at low *B* values may have overestimated the temperature-time slope. This was overcome by viewing the plots of temperature versus time and applying a linear fit to the steepest part of the curve. The results showed lower slopes compared with those of the interval method. The results between the two methods for the larger *B* values had comparable results, suggesting that the linear fit was a better method for the lower *B* values.

Table 6.2: Predicted and observed rates of temperature decrease ($°C \cdot s^{-1}$)

B Values	Maximum (@35 °C)	Linear slope (0-35 °C)	Slope at initial temperature	Observed maximum slope (linear fit)	Observed maximum slope (calculated)
0.00940	0.188	0.148	0.178	0.109	0.0924
0.00159	0.032	0.025	0.030	0.024	0.025
0.000793	0.016	0.013	0.015	0.012	0.014
0.000396	0.008	0.006	0.008	0.007	0.009
0.000198	0.004	0.003	0.004	0.005	0.007

As the *B* values were lowered, the plot of the observed temperatures versus time became more linear. Thus the refrigeration load became more evenly distributed over the operating period as the *B* value was lowered. With lower *B* values, the cooling curve would fit the theoretical cooling curve more closely. The lag factor would become less apparent. This can be seen in the observed data where at high *B* values, the theoretical peak refrigeration was being over estimated with respect to the measured values. As the *B* values were lowered, these differences became less. The temperature lag was observed during the trials. For small *B* values, the temperature of the lettuce reached 2.5°C shortly after the pressure in the chamber reached the lower limit of 6.0 mm Hg, and in a few instances it reached this temperature before the lower limit was reached. In contrast, with the higher *B* values, some time was needed after the lower limit was reached before the lettuce reached an average temperature of 2.5°C.

Figure 6.1 shows the plot of the observed temperature decrease rates versus the predicted rates. The graph is shown in a semi-log format to better show the distinction between the different B values. This graph clearly shows that for higher B values, there is an over prediction for the values of the slopes as the observed values are under the one to one correspondence for larger B values. It was found that the relationship between the observed and the predicted slopes was best approximated using a power law with the following values:

$$y = 0.43x^{0.83} \tag{6.9}$$

where x is the predicted value and y is the observed value. As the predicted value increases with an increasing B value, this type of function would under predict the slope at low B values and over predict the slope at higher B values.

A plot of the predicted and observed slopes versus the B values is shown in Figure 6.2. The predicted values were based on the initial temperature of the lettuce, which varied between 18.1 and 21.5°C. This graph also illustrates the over prediction at higher B values. Though the predicted values are nearly linear in relation with the B values, the observed values tend to follow a power law of the form:

$$\frac{dT}{d\theta} = 4.91B^{0.83} \tag{6.10}$$

with an R^2 value of 0.971. This equation does not take into account the change in the initial temperature of the produce, which would slightly change the slope at a given B value. The slope is not greatly affected by the change in temperature. This is illustrated in Figure 6.3, where the predicted slopes by three methods are plotted against the B values. The three predictions are the slopes corresponding to 35°C, 0°C, and the initial temperature of the lettuce, which was between 18.1 and 21.5°C. The 0 and 35°C temperatures cover a very large area as the initial temperature will seldom be below 15°C and only occasionally could reach temperatures of 35°C. Even using these two extremes, there is little variation in the slope as affected by the temperature when compared to the effects of the B value.

Using equation 6.10 for the temperature slope, the peak refrigeration load due to the produce cooling can be expressed in terms of the B value as follows:

$$q_p = 4.91 m_p c_p B^{0.83} \tag{6.11}$$

It should be noted that when determining the B value, the volume of the retort needs to be taken into account. Haas and Gur (1987) expressed the pumping rate, S ($m^3 \cdot s^{-1}$), as being:

$$S = \frac{V}{\theta} \ln \frac{P_1}{P_2} \tag{6.12}$$

Where V is the volume to be evacuated and P_1 and P_2 are the change in pressure that occurs over a time θ. The B value is the ratio of the pumping rate to the volume to be evacuated. Thus, using this definition of the B value, the peak refrigeration load can then be adjusted for different volumes of loads in the cooler. The free volume of the retort is the total volume, V_t (m^3), minus the total mass of the produce divided by the density, ρ_p ($kg \cdot m^{-3}$), and it is this volume that needs to be evacuated with the pump. Therefore, empirically, the peak refrigeration load from the produce can be expressed as:

$$q_p = 4.91 m_p c_p \left(\frac{S}{V_t - \frac{m_p}{\rho_p}} \right)^{0.83} \tag{6.13}$$

This equation takes into account the peak refrigeration load for head lettuce only. Other produces may vary, as often they will lose moisture more slowly or faster than head lettuce. It must be emphasised that even though the equation was developed using lettuce with an initial temperature between 18.1 and 21.5°C, it is unlikely that temperature variation would have an appreciable effect on the peak load. There was sufficient variation in the experimental temperature drops and these cannot be explained by differences in initial temperature alone. It is expected that variation in produce density, shape, and size would also have an effect on the rate of cooling.

6.5 Conclusions

This paper studied the effects of reducing the rate of vacuum application on the peak produce refrigeration load for vacuum cooling of head lettuce. An empirical model for determining the peak refrigeration load was developed and compared to observed data. The observed data fit the model well except for situations where the vacuum was applied very quickly. In those situations, the model over predicted the rate at which the temperature of the produce dropped. This deviation can be explained by considering the effects of heat transfer and mass transfer restrictions. The faster the pressure is dropped, the greater the heat and mass transfer must occur. Above a certain rate, heat conduction and/or moisture transfer become limiting, thus causing the produce to cool slower than predicted, as the theoretical model does not take into consideration any time lags.

The peak refrigeration load was modelled based on experimental data as a function of the rate of vacuum application. This model excluded the variation due to the initial temperature of the produce, as this parameter was rather insensitive to temperature changes. The model was modified to take into account the volume of the cooler that was occupied by produce. Thus, knowing the rate of the pump, the volume of the cooler, and the mass of produce to be cooled, the peak produce refrigeration load can be predicted.

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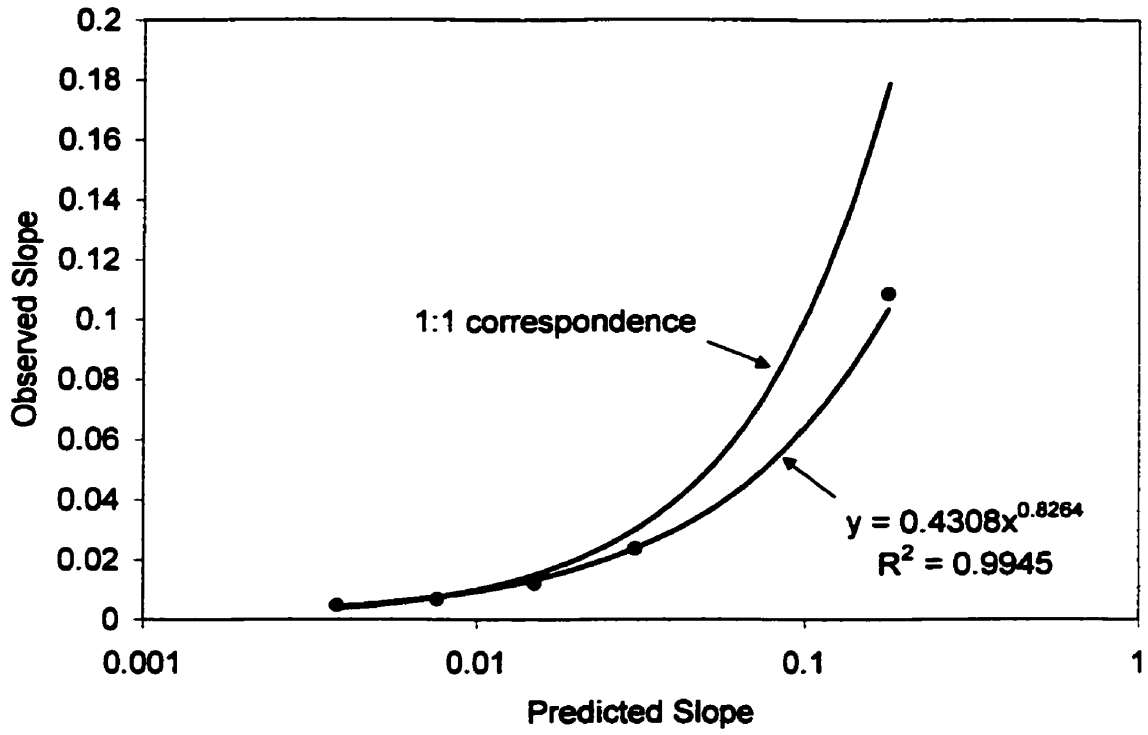

Figure 6.1: Observed rate of temperature decrease (slope) versus predicted rate of temperature decrease (slope)

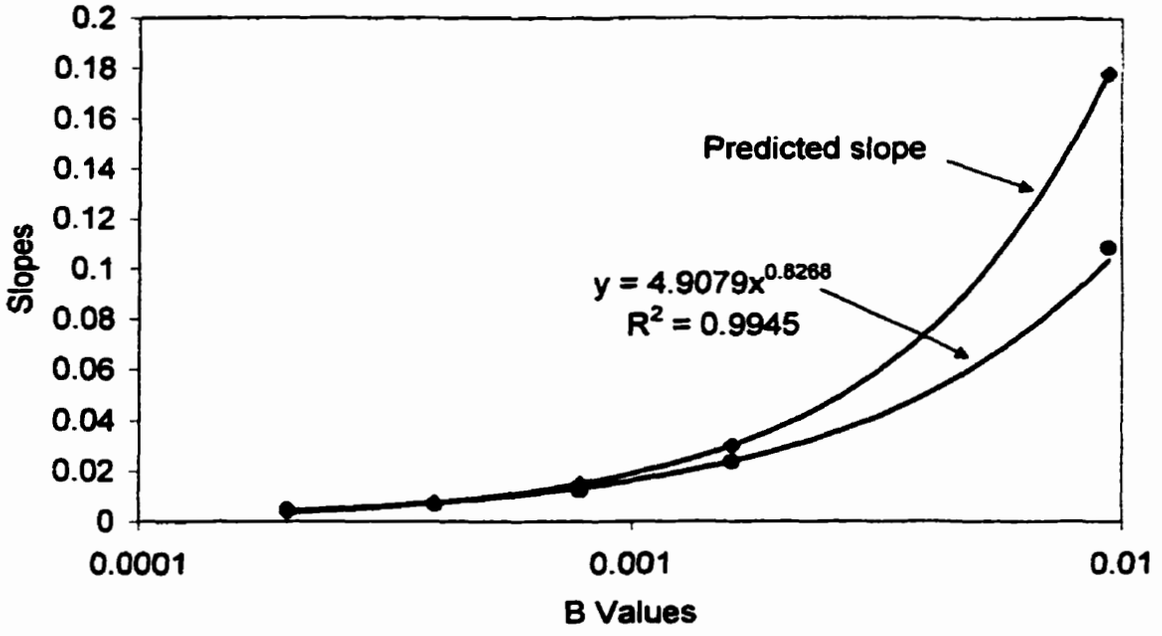

Figure 6.2: Predicted and observed rates of temperature decrease (slope) versus *B* values

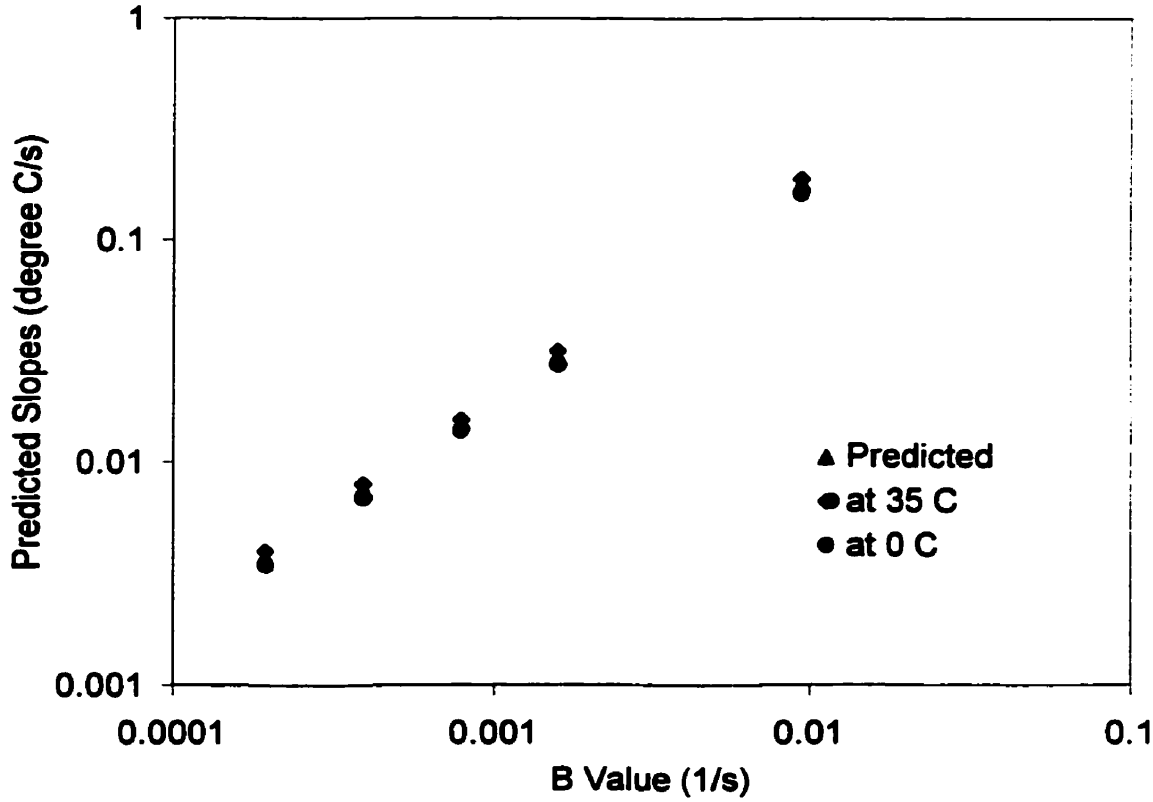

Figure 6.3: Predicted rate of temperature decrease (slope) versus *B* values.

VII. GENERAL DISCUSSION AND CONCLUSIONS

Precooling can benefit postharvest operations in two manners. The first is to reduce the size of the refrigeration system necessary for the storage facility, and the second is to increase the storage duration of perishable commodities. Vacuum cooling works well for cooling leafy vegetables but has the drawback of requiring high capital costs and is therefore limited to large-scale production operations or co-ops. Two of the components that are costly are the vacuum pump and the refrigeration system. Reducing the size of both these components would decrease the capital costs of the system, but would increase the time of cooling. In some instances, especially for small-scale operations, the slower cooling time is a small price to pay compared to the savings in the capital cost of the system. Thus, experiments were carried out to determine the changes in the cooling characteristics, quality, and peak produce refrigeration load for a system with different vacuum rates.

Temperature distributions were measured in lettuce cooled with different vacuum rates. For the rates used, no change in the temperature distribution was noticed. The surface temperature measured by infrared temperature sensors was not different from the surface temperature or the mass-average temperature as measured by thermocouples. These temperature measurements were significantly lower than the temperature measured at the centre of the lettuce head. The temperature change per percent mass loss was not affected by changing the rates of applied vacuum, though a trend seemed to be present. Possibly using more replicates could indicate a slight difference but the difference is likely not important.

Chlorophyll fluorescence measurements on the lettuce indicated that vacuum cooling causes lettuce to undergo some stress, but not enough to affect the health of the plant tissue or the overall quality of the lettuce. This was supported by visual evaluation of the lettuce quality using a quality index. The chlorophyll fluorescence measurements indicated that the rate of vacuum did have an effect on the rate at which the lettuce recovered and to what extent they recovered. But as the stress induced was not severe, there is no particular benefit to changing the rate of vacuum to avoid or reduce this

minimal stress. For all practical purposes, the rate of vacuum application did not affect the lettuce quality.

An empirical model for determining the peak refrigeration load was developed and compared to observed data. The observed data fit the model well except for situations where the vacuum was applied very quickly. In those situations, the model over predicted the rate at which the temperature of the produce dropped. This deviation can be explained by considering the effects of heat transfer and mass transfer restrictions. The faster the pressure is dropped, the greater the heat and mass transfer must occur. Above a certain rate, heat conduction and/or moisture transfer becomes limiting, thus causing the produce to cool slower than predicted, as the theoretical model does not take into consideration any lag times.

The peak refrigeration load was modelled based on experimental data as a function of the rate of vacuum application. This model excluded the variation due to the initial temperature of the produce, as this parameter was rather insensitive to temperature changes. The model was modified to take into account the volume of the cooler that was occupied by produce. Thus, knowing the capacity of the pump, the volume of the cooler, and the mass of produce to be cooled, the peak produce refrigeration load can be predicted. The existing method of determining the produce refrigeration load for vacuum cooling does not take into account the rate of the pump. Thus, this new method should enhance the correct sizing of the refrigeration unit for vacuum coolers.

With these experiments, it can be concluded that designing a vacuum cooler with a slower vacuum rate will reduce the size of the vacuum pump and the refrigeration system without seriously changing the cooling characteristics of lettuce or affecting the quality of the lettuce. The relationship between the rate of vacuum and the peak produce refrigeration load was determined for lettuce, which will aid in the design of vacuum coolers. Lettuce is the most used produce in vacuum cooling and one of the fastest to be cooled. Thus, if any other produces are used, the size of the refrigeration system, if designed with the method as described in this thesis, should be adequate.

This work opens up other areas of investigation. All the work done here was based on lettuce, the easiest produce to cool with vacuum cooling. Other produce may benefit from the changing of the vacuum rate, and may enhance their cooling or quality

aspects. As well, the determination of the physical size of the evaporator in the vacuum chamber needs to be determined to enhance the rate of moisture removal in the chamber such that it does not affect the rate of cooling. A complete economic analysis of the system, as a function of the rate of cooling, would need to be performed to determine the operating costs, capital costs, and investment potential of such systems.

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