DEVELOPMENT AND EVALUATION
OF A LIQUID-ICE SYSTEM

by

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ABSTRACT

M. Sc. BERNARD GOYETTE Agricultural Engineering

DEVELOPMENT AND EVALUATION OF A LIQUID-ICE SYSTEM

The deterioration of freshly harvested horticultural crops prior to storage can be minimized by rapid pre-cooling. This deterioration occurs for two reasons: i) the respiration rate is typically high due to high ambient temperatures at harvest, and ii) physiological activity of the produce is at peak levels. Thus, precooling is essential.

Many precooling techniques are used in the horticulture industry today. Their main purpose is to rapidly extract heat from the produce by using a suitable fluid for the heat extraction/rejection process.

The efficiency of a cooling method depends on many factors: the cooling fluid used, the morphological characteristics of the product, the type and shape of packing, the system design, etc.. It is therefore relatively difficult to compare the efficiencies of cooling systems or to evaluate the effect of each parameter on system efficiency. A new method for assessing cooling system efficiency was therefore developed. The technique was based on the capacity of the system to maintain the product temperature at the surface as low as possible without affecting the morphological characteristics of the product. It was shown that this method of assessing efficiency was effective under field conditions.

A low cost liquid-ice system was designed and tested for broccoli precooling. It is based on ice particle injection into a water stream, the mixture then being pumped into the box of produce to be precooled. The effects of different ice particle sizes and ice-water ratios on the medium temperature of broccoli, the mass of ice remaining in the boxes of produce and the icing efficiency were analyzed. The results led to the establishment of optimum conditions for the parameters of the proposed system.

RÉSUMÉ

M. Sc. BERNARD GOYETTE Agricultural Engineering

CONSTRUCTION ET ÉVALUATION D'UN SYSTÈME DE GLACE LIQUIDE

La détérioration des produits horticoles récoltés frais est un problème commun qui demande une attention particulière. Dès la récolte, les produits se détériorent pour deux raisons: i) un taux de respiration élevé à température ambiante ii) l'activité physiologique est à son niveau le plus élevé. Il est donc nécessaire de prérefroidir les produits horticoles.

Présentement dans l'industrie, plusieurs méthodes de prérefroidissement existent. Leur principe de base est d'extraire rapidement la chaleur du produit à l'aide d'un fluide caloporteur.

L'efficacité d'une méthode de prérefroidissement dépend de plusieurs paramètres dont le type de fluide caloporteur utilisé, les caractéristiques morphologiques des produits, le type et la forme d'emballage, le design du système, etc. Il est donc relativement difficile de comparer l'efficacité de différents systèmes de prérefroidissement ou d'évaluer l'effet de chaque paramètre sur l'efficacité d'un système. Une nouvelle méthode d'évaluation de l'efficacité des systèmes de refroidissement a été développée. Cette méthode est basée sur la capacité d'un système à maintenir la température à la surface d'un produit au plus bas niveau possible. Cette méthode n'est pas affectée par les paramètres morphologiques des produits. Elle permet d'évaluer l'efficacité d'un système dans des conditions de champ.

Un système d'injection de glace liquide a été développé et évalué pour le prérefroidissement du brocoli. Le procédé consiste a injecté les particules de glace dans un courant d'eau pour ensuite le pomper dans les boîtes de produits. L'effet de différentes grosseurs de particules de glace et du ratio glace-eau sur la température du milieu environnant du brocoli, la quantité de glace restant dans les boîtes de produits et l'efficacité du glaçage ont été analysés. Les résultats ont permis d'optimiser les paramètres opérationnels du système.

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FORMAT OF THESIS

This thesis is submitted in the form of original papers suitable for journal publications. 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:

> "The candidate has the option, subject to the approval of the Department, of including as part of the thesis the text, or duplicated published text (see below), or original paper, or papers. In this case the thesis must still conform to all other requirements explained in Guidelines Concerning Thesis Preparation. Additional material (procedural and design data as well as descriptions of equipment) must be provided in sufficient detail (e.g. in appendices) to allow a clear and precise judgement to be made of the importance and originality of the research reported. The thesis should be more than a mere collection of manuscripts published or to be published. It must include a general abstract, a full introduction and literature review and a final overall conclusion. Connecting texts which provide logical bridges between different manuscripts are usually desirable in the interests of cohesion.
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> It is acceptable for thesis to include as chapters authentic copies of papers already published, provided these are duplicated clearly on regulation thesis stationery and bound as an integral part of the thesis. Photographs or other materials which do not duplicate well must be included in their original form. In such instances, connecting texts are mandatory and supplementary explanatory material is almost always necessary.
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The work reported here was performed by the candidate and supervised by

Dr. G.S.V. Raghavan and **Dr. C. Vigneault**, Department of Agricultural Engineering, Macdonald Campus of McGill University, Montréal. **Dr. C. Vigneault** is also researcher at the Chemistry and Engineering Section of the Agriculture and Agro-Alimentaire Canada Research Station, Saint-Jean sur Richelieu, where the entire research project was conducted.

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NOMENCLATURE

Bi	=	Biot number
CC	=	cooling rate coefficient
d	=	half-width of the desired confidence interval
D	=	broccoli stalk diameter, mm
d_i	=	diameter of sieve openings of the i'th sieve, mm
d_{i+1}	=	diameter of openings in next larger than i'th sieve, mm
d_{gw}	=	geometric mean size, mm
D_i	=	geometric mean size of particles on i'th sieve, mm
FA	=	forced-air
h	=	convective heat transfer coefficient, $W \bullet m^{-2} \bullet K^{-1}$
HC	=	hydrocooling
HCT	=	half-cooling time
k	=	thermal conductivity of the solid, $W \bullet m^{-1} \bullet K^{-1}$
ln(T)	=	logarithmic transformation of the temperature ratio
n	=	number of samples
PI	=	package icing
R	=	room cooling
R^2	=	coefficient of correlation
s	=	sample standard deviation
S_{gw}	=	geometric standard deviation, mm^2
s_r	=	volume to surface ratio of the body, m
t	=	tabulated value for the desired confidence level and degree of freedom
T	=	temperature ratio
t_b	=	temperature inside the body, K
t_i	=	initial temperature inside the body, K
t_0	=	temperature of the medium surrounding the produce, K
t_0'	=	apparent medium temperature of the produce

VC	=	vacuum cooling
W_i	=	weight fraction on i'th sieve, g
α	=	level of significance
θ	=	time, min

I. GENERAL INTRODUCTION

Postharvest losses of fresh fruits and vegetables are estimated to be 5 to 25 percent of the total harvest in developed countries and 20 to 50 percent in developing nations, depending upon the commodity (Kader, 1992). The difference in range is mainly the result of: (i) more widespread application of technologies aimed at reducing post-harvest losses in developed countries, and (ii) a greater percentage of crops harvested in cool conditions in northern regions. A number of other differences in field production, harvesting and handling, crop physiology and so on are involved.

Fresh horticultural crops are living organisms that must remain alive and healthy until they are either processed or consumed (Fraser, 1991). After harvest, metabolic energy comes from the food reserves in the produce itself stored prior to harvest (Mitchell *et al.*, 1972). The process by which these reserves are converted into energy is called respiration (Kader, 1992). Respiration involves the breakdown of organic material with the liberation of CO_2, water with latent heat, and sensible heat, thus entraining minor dehydration of the produce. The rate of deterioration of the produce is closely connected to the rate of respiration after harvest.

The respiration level varies with the species, the variety, the level of maturity, the level of injury incurred during growth, harvest and handling, and the temperature (Fraser, 1991). The product temperature has a great influence on the degree of respiratory activity and therefore, on the amount of heat released and rate of deterioration, i.e. wilting, discoloration, fermentation, textural softening and weight loss (Ryall and Lipton, 1972; Ryall and Pantzer, 1974). Table 1.1 shows the heat of respiration of some freshly harvested crops held at various temperatures. A temperature reduction of about 10°C reduces the rate of respiration by a factor of 2 to 3 depending on the type of produce. Hence, for highly perishable commodities, a few hours' delay in cooling can cause damage which cannot be overcome by subsequent good handling practices (Mitchell *et al.*, 1972). Precooling is generally defined as the removal of field heat from freshly harvested products in sufficient time to prevent spoilage and maintain all possible pre-harvest freshness and flavour (ASHRAE, 1986). Precooling is essential to lowering

Table 1.1: Heat of respiration of fresh fruits and vegetables held at various temperatures. (ASHRAE, 1981).

	Heat of respiration, (kJ•Mg^{-1}•day^{-1})				
Commodity	0°C	5°C	10°C	15°C	20°C
Apple	922	1802	2682	5028	6285
Asparagus	20531	34945	78102	83926	128214
Broccoli	4777	8841	---	44498	71272
Cabbage	2095	3562	4609	6914	10475
Carrot	3939	5028	8045	10140	18059
Celery	1844	3268	6997	10726	---
Lettuce	2682	3394	5573	9218	14581
Strawberry	4525	8506	---	23632	50196
Sweet Corn	10894	19903	28702	41732	73912

the rate of deterioration and increasing the product shelf-life (Fraser, 1991), particularly under conditions where the delay between harvest and final storage can lead to significant initial deterioration.

Among the many precooling techniques, liquid-icing is that which is most widespread in application to broccoli and is also recommended for root vegetables, artichokes, brussels sprouts, green onions, leek, peas, some melons and sweet corn (Kasmire and Thompson, 1992). The main advantage of liquid-icing is that a cool and moist environment for the produce is maintained during transport from the packing house to the market place (Mitchell, 1992). However, although liquid-icing is a well-established technique in large production units, small and medium production units cannot justify its use because of high initial and operating costs (Kader, 1992). Finally, the uniformity of the ice distribution in the boxes of produce is a very important factor in achieving rapid and uniform cooling (Prussia and Shewfelt, 1984). Ice particle size and ice-water ratio are suspected to affect ice distribution in the boxes but information on these two factors is absent from the literature.

Cooling rate coefficient (CC) and half cooling time (HCT) have been used for comparing precooling techniques (Baird *et al.*, 1988; Fraser and Otten, 1992; Bartsch *et al.*, 1990). These factors are useful in determining suitable ice particle size for the liquid-ice system being developed in this study. It should be further noted that these evaluation methods depend very much on the morphological characteristics of the cooling body.

II. GENERAL OBJECTIVES

The main objectives of this research are:

A) To develop a low cost liquid-ice system which has a lower power requirement than the system now in use, thus making it accessible to small and medium scale operations.

B) To optimize the new liquid-ice system based on the effects of ice particle size and ice-water ratio of the liquid-ice mixture on: (i) the apparent medium temperature of the produce, and (ii) the ice remaining in the boxes of produce and the icing efficiency.

The secondary objectives of this research are:

A) To develop and test a granulometric method to evaluate ice particle sizes.

B) To develop a method to obtain the apparent medium temperature of the produce during the precooling process in order to be able to compare different precooling systems.

III. LITERATURE REVIEW

There are many methods of cooling horticultural products before storage or loading for shipment: room cooling, forced-air cooling, vacuum cooling, hydrocooling, package icing and top icing (Kader, 1992). Some commodities can be cooled by several methods, but most commodities respond best to one cooling method. The precooling requirements of a given commodity, and therefore the method used, are largely determined by product physiology in relation to harvest maturity and ambient temperature at harvest time, (ASHRAE, 1986). Highly perishable commodities must be precooled as soon and as rapidly as possible after harvest. In general, such commodities are those harvested in late spring, summer and early fall. Precooling is not as important for late-season crops such as winter apple varieties, or low-repiration commodities. Table 1.2 represents the most widely used cooling method for a few horticultural crops, and their needs for rapid cooling.

3.1 <u>Room Cooling</u>

Room cooling is probably the most widely used refrigeration technique due to its versatility and low cost. However, room-cooled produce must be tolerant of slow heat removal, since much of the cooling is by heat conduction through the container walls. This technique is not considered to be a true precooling method. It involves placing field containers into a room cooled by a refrigeration system. The ventilation system must provide good air circulation through and around the containers (Fig. 3.1). Cold air from the evaporator enters the room near the ceiling, moves horizontally under the ceiling, and then sweeps past the produce containers in returning to the evaporator. For adequate heat removal, the air-flow speed must be at least 1 to 2 $m \bullet sec^{-1}$ and the moving cold air must be in good contact with all container surfaces, otherwise the centre produce in the containers is not cooled rapidly enough (Kader, 1992). Container disposition is therefore very important in the handling sequence.

Room cooling is best applied to produce having a low respiration rate, a low harvest temperature, and a relatively long storage life and/or which is harvested at the

Table 1.2: Cooling methods suggested for horticultural commodities (Kader, 1992).

Commodity	Size of operation		Remarks
	Large	Small	
Citrus	R[1]	R	
Garlic	R		
Asparagus	HC	HC	
Broccoli, brussels sprouts	HC, FA, PI	FA, PI	
Celery, rhubarb	HC, VC	HC, FA	
Cabbage	VC, FA	FA	
Cucumbers, eggplant	R, FA	FA	Fruit-type vegetables are chilling sensitive but at varying temperatures.
Leaf lettuces, spinach, endive	VC, FA, HC	FA	
Cut flowers	FA, R	FA	When packaged, only use FA.
Potted plants	R	R	
Sweet Corn	HC, VC, PI	HC, FA, PI	
Melons	HC, FA, PI	FA	
Dry onions	R	R, FA	Should be adapted to curing.
Berries	FA	FA	
Tomatoes	R, FA		

[1] R = Room Cooling; FA = Forced-Air; HC = Hydrocooling; VC = Vaccum Cooling; PI = Package Icing.

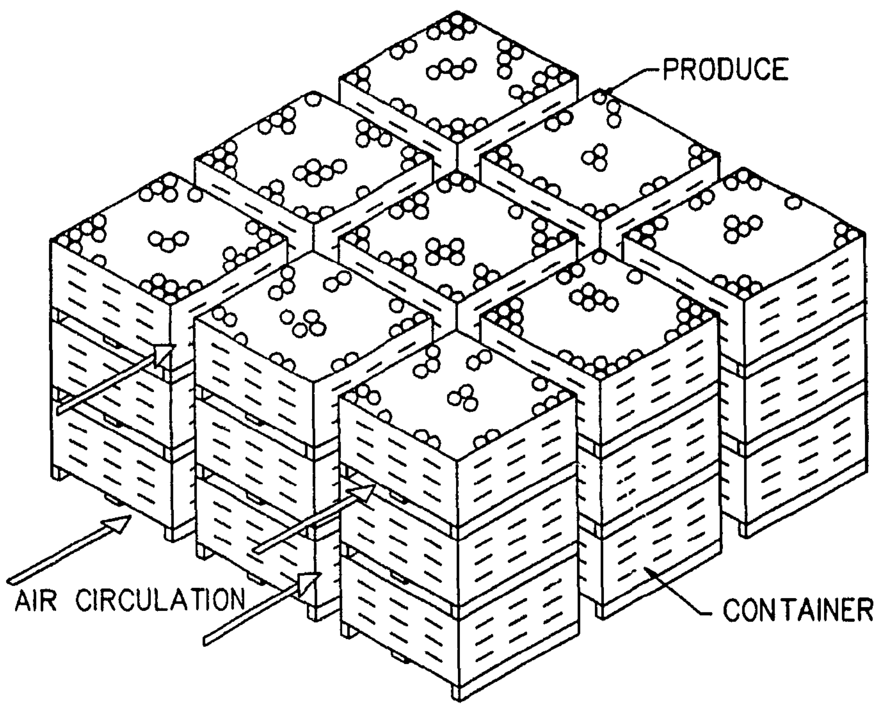

Figure 3.1: Schematic of the air circulation during room cooling.

end of the season (Kader, 1992). The main advantage of room cooling is that produce can be cooled and stored in the same room without being transferred. However, it is too slow for most commodities and can result in excessive water loss. Rehandling may be needed for better use of the storage space after cooling is achieved (Mitchell, 1992). Furthermore, the addition of warm produce into a cold room may result in condensation on already cooled produce (Mitchell *et al.*, 1972).

3.2 Forced-Air Cooling

Forced-air cooling consists of using fans to pull refrigerated air through the container vents by vacuum such that warm air is swept away by the cold airflow (Fraser, 1991). Two basic designs are used: the forced-air tunnel (Fig. 3.2) and the cold wall (Fig. 3.3). Mitchell *et al.* (1972) observed that forced-air pressure cooling is four to ten times faster than conventional room cooling but two to three times slower than hydrocooling or vacuum cooling.

The product cools as a result of the convective action of refrigerated air sweeping away warm air. "Pulling" rather than "blowing" air through the containers is a better option since "short-circuiting" (ie. refrigerated air that flows directly to the fan without first going around the product, when the containers are under vacuum) is reduced. Ideally, the ventilation system must produce between 0.5 and 3 $L \cdot s^{-1} \cdot kg^{-1}$ of warm product (Fraser, 1991).

The forced-air tunnel system (Fig. 3.2) consists of a row of palletized containers or bins placed on either side of an exhaust fan, leaving an aisle between the rows. The aisle and the open end are then covered to create an air plenum tunnel. The exhaust fan creates negative air pressure within the tunnel. Cold air from the room then moves through the openings in and between containers toward the low-pressure zone, thus sweeping heat from the product (Kader, 1992). Investment for this method is minimal: a ventilation unit and a covering linen. However, it also returns warm air into the room which may condense on the produce. It is possible to eliminate the use of a fan and the condensation problem if one end of the tunnel is put directly on the air intake of the cooling system. In this case, the produce containers must be rearranged in order to prevent dehydration after precooling is achieved.

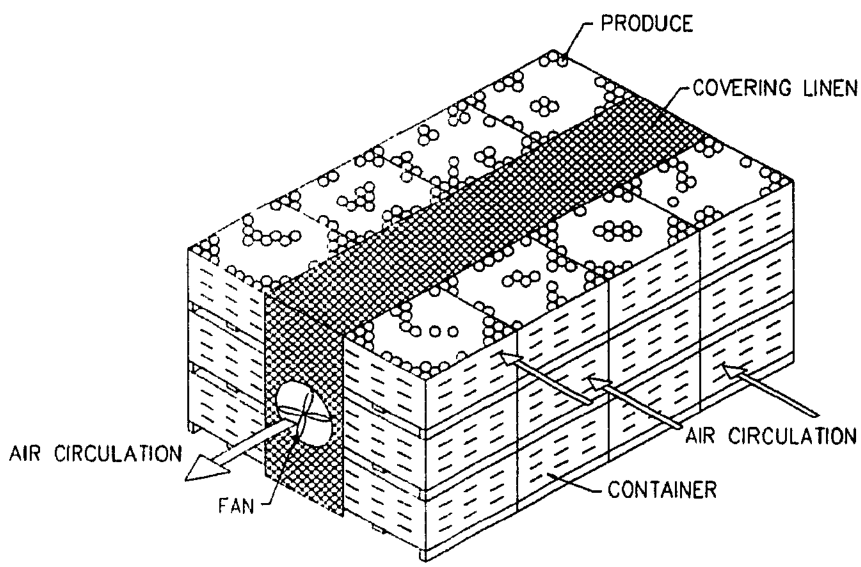

Figure 3.2: Schematic view of a forced-air cooling tunnel.

The cold wall cooling system (Fig. 3.3) uses a permanent air plenum, formed by the construction of a "dummy wall", equipped with exhaust fans. It is often located at one end or side of a cold room, with the exhaust fans designed to move air over the cooling system. Openings are located along the room side of the plenum against which stacks or pallet loads of containers can be placed. Various damper designs ensure that air flow is blocked except when a pallet is in place. Each pallet starts cooling as soon as it is in place, thus eliminating the need to await deliveries to complete a tunnel (Mitchell, 1992). This is a good system for operations in which the produce arrives at variable times. It is also versatile, in that the treatment time can be adjusted for each product; however rehandling of the containers is also necessary as soon as cooling is achieved.

3.3 Vacuum Cooling

Thompson and Chen (1987) summarized the energy use efficiency of cooling systems. Vacuum coolers were the most efficient, followed by hydrocoolers and then forced-air coolers. Vegetables having surface-to-mass ratios favouring rapid transpiration, (eg. leafy vegetables), are especially suited to vacuum cooling (Kader, 1992). Vegetables are cooled on a large scale by enclosing them in air-tight chambers and pumping out air and water vapour, thus cooling by water evaporation at low temperature and very low air pressure (Fig. 3.4). For example, at a pressure of 0.6 kPa, water evaporates at 0°C (ASHRAE, 1986). This type of cooling is accomplished in two phases (Fig. 3.5). The first phase (A-B) represents the time required by the vacuum pump to lower the chamber pressure to the vapour pressure of the product to be cooled. No cooling occurs during this phase and the chamber pressure drops from 101 kPa to about 3 kPa. The time required is about 5 to 8 minutes depending on the pump capacity (Belzile, 1982). When the chamber pressure is lower than the product vapour pressure, water evaporation occurs and the product cools down. Cooling continues until the inside pressure is re-established (point C). Cooling time depends on the system capacity and the mass of product to be cooled. A target cooling time of 20 minutes is generally achievable. Vacuum cooling causes about 1% product weight loss (mostly water) for each 6°C of cooling (ASHRAE, 1986). In some cases, an atomizer system is used to humidify the product in order to reduce dehydration.

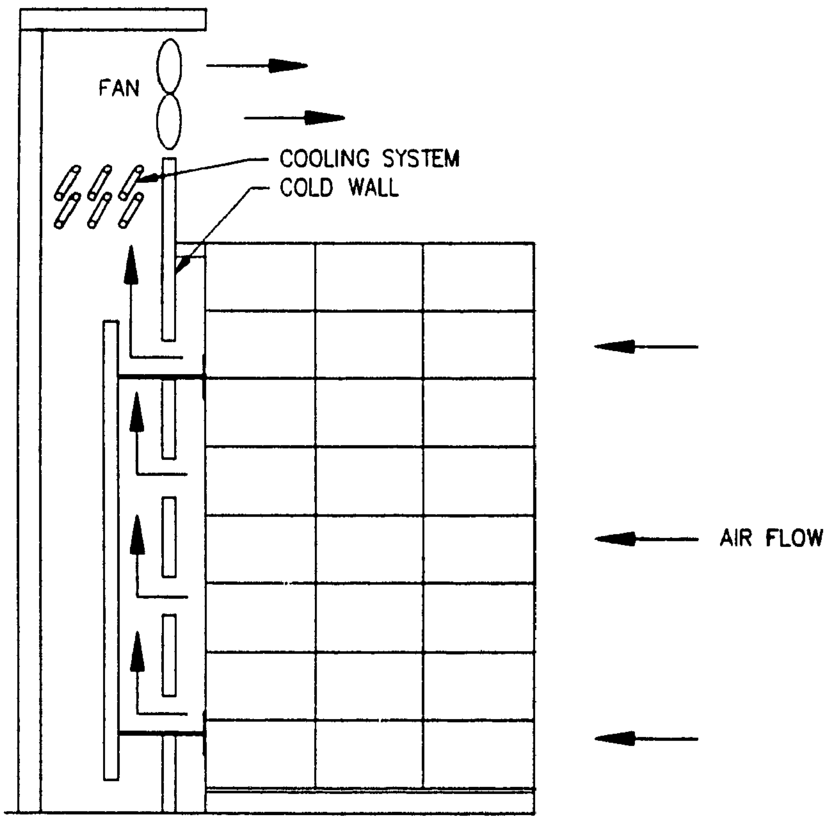

Figure 3.3: Schematic of the cross section of a cold-wall type forced-air cooler.

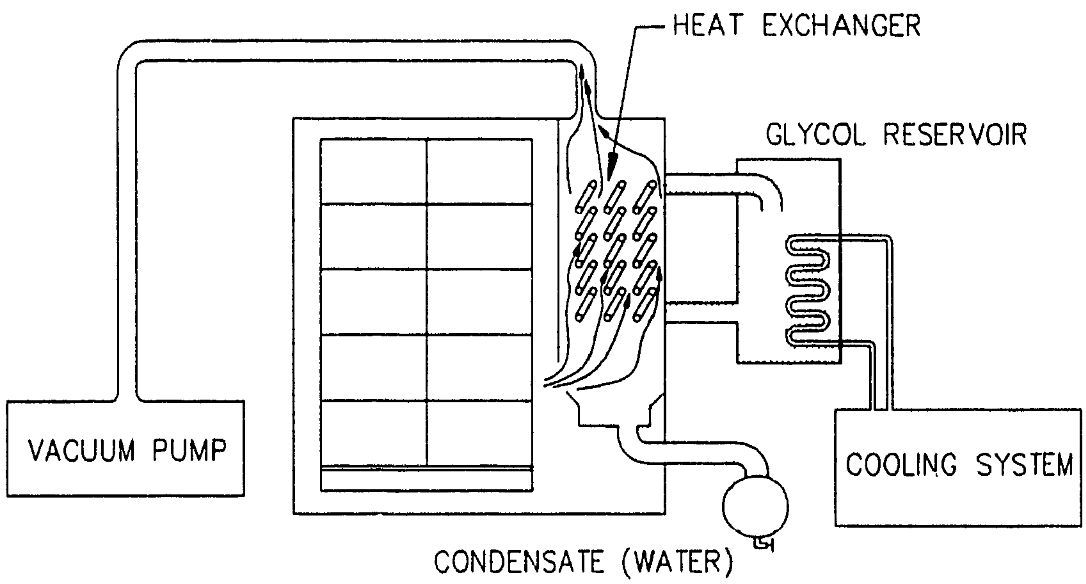

Figure 3.4: Schematic view of a vacuum cooler.

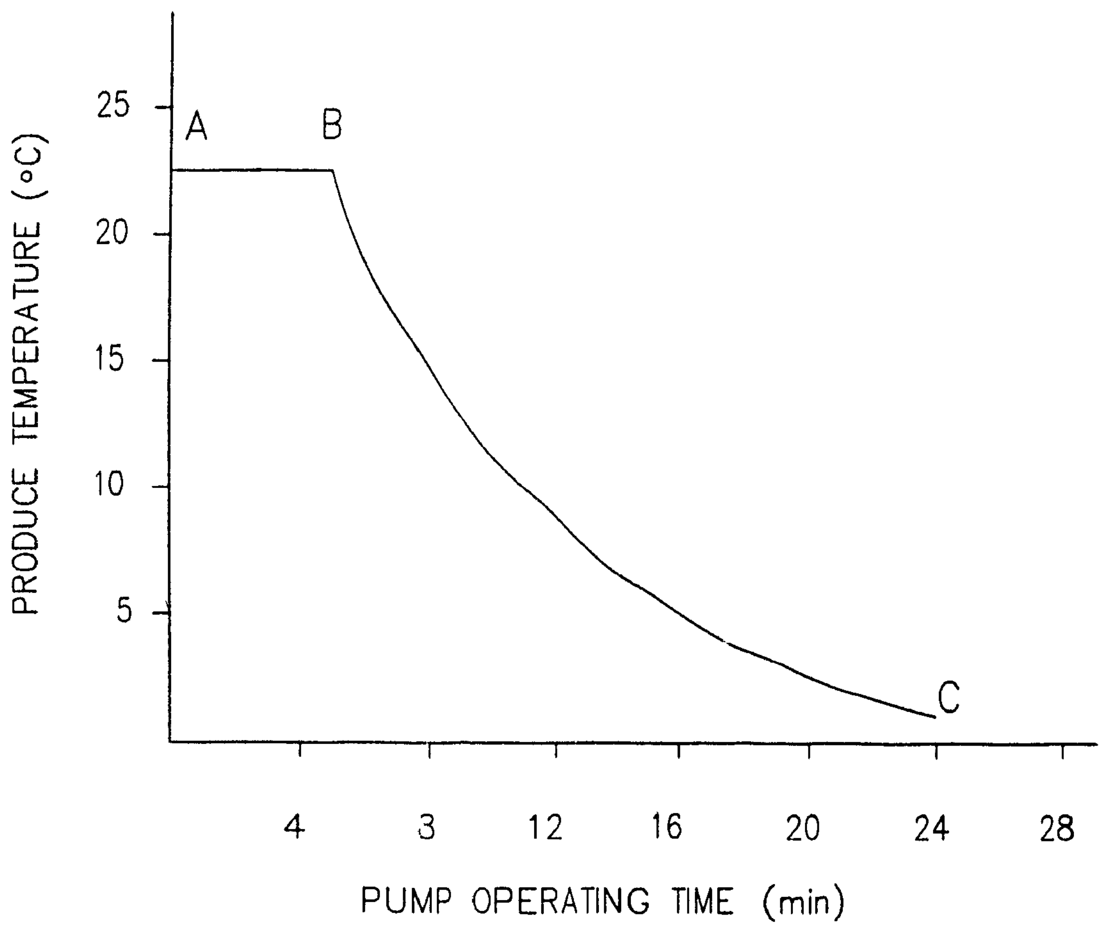

Figure 3.5: Typical temperature variation during vacuum cooling process.

A refrigeration system is necessary to condense the water vapour removed from the produce to prevent it being circulated to the vacuum pump since most vacuum pumps cannot withstand water vapour condensation (ASHRAE, 1986). Two types of refrigeration equipment will trap water inside the vacuum system: (i) the evaporator of a mechanical refrigeration system, and (ii) a glycol heat exchanger. The glycol system is most popular since it can more easily handle the great variations in refrigeration demand needed in vacuum cooling.

3.4 Hydrocooling

Cold water is an old and effective method for quickly precooling a wide range of fruits and vegetables in bins or in bulk. Hydrocoolers can be based on immersion or showering (Kader, 1992). In a typical shower-type hydrocooler (Fig. 3.6), cold water is pumped from a bottom reservoir to an overhead perforated pan. The water showers over the commodity, which may be in bins or boxes, or loose on a conveyer belt passing beneath. Water leaving the product may be filtered to remove debris, then passed over refrigeration coils (or ice) where it is recooled (Kader, 1992).

The evaporator of the refrigeration system recools used water. It is usually located in one of the two reservoirs of the precooler. When it is on the top reservoir, it frees the bottom reservoir, thus facilitating cleaning which must be done regularly due to the amount of dirt washed off the produce. Since the top reservoir is empty when the pump is off, it can not be used as an ice reservoir. If the evaporator is located in the bottom reservoir, it can accumulate ice between cooling periods and thus considerably increases the refrigeration capacity for a given compressor capacity; it is a great advantage when the produce deliveries vary considerably. Ice may also be used if it can be added to water when the cooling capacity of the system is not enough to keep water temperature near 0°C (Kader, 1992). Cooling speed is generally greater using a water system instead of an air system, and there is no product dehydration.

The produce and the packing and packaging materials must be tolerant to wetting, resistant to water impact, and tolerant of chlorine or other chemicals that are used to sanitize the hydrocooling water (Kader, 1992). The produce must also be tolerant to

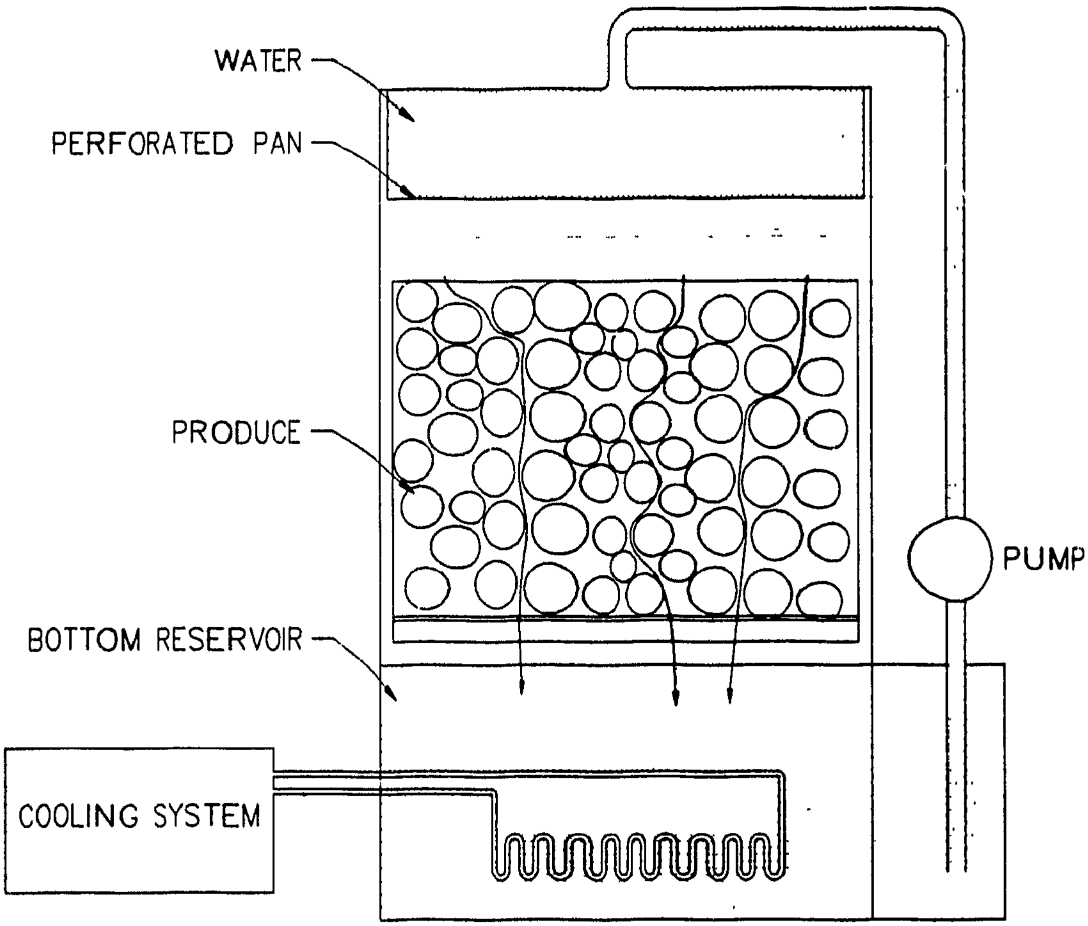

Figure 3.6: Schematic view of a hydrocooler.

prolonged exposures to a temperature of 0°C. Hydrocooling operations can require rehandling of the produce before packing or storage, thus increasing labour costs.

3.5 Package-Icing

Before the development of vacuum cooling, many leafy vegetables were packed using crushed ice placed between layers of produce and an addtitional layer of ice on the top of the package. The quantities of ice used depended partially on the initial product temperature, but was usually applied at a rate of 1 kg of ice for 4 kg of produce (Belzile, 1982). Icing is now done by placing ice on top of containers with already precooled produce. In small operations, the ice is hand raked or shovelled into containers; large operations use mechanical icers (Kader, 1992). A mechanical or automatic icer creates a uniform ice distribution (Fig. 3.7). The automatic system requires extra manipulation to place boxes on the conveyor and to repile them after icing is completed. Sensors detect the boxes as they are conveyed into position and the signal initiates the icing process.

Package-icing requires more expensive, water-tolerant packages. The packages should be fairly tight but with enough holes to drain meltwater (Kader, 1992). Rehandling of the boxes after icing increases costs. This system is effective at keeping produce temperature near 0°C, even during transportation in non-refrigerated trucks or in a storage room having an ambient temperature of 10°C. However, icing is not recommended for precooling of horticultural crops since heat exchange between the product and the ice is too slow due to the small contact surface area.

3.6 Liquid-Ice

Liquid-ice (mixture of ice and water) is used to achieve better contact with the product. Ice can be produced during off-peak hours when electricity is cheaper (in some countries) and stored for daytime use (Kader, 1992).

A liquid-ice system consists of mixing ice particles with water and injecting this mix into the boxes of produce to be precooled (Fig. 3.8). Water allows a greater quantity and better distribution of ice in the boxes of produce. This decreases the cooling time

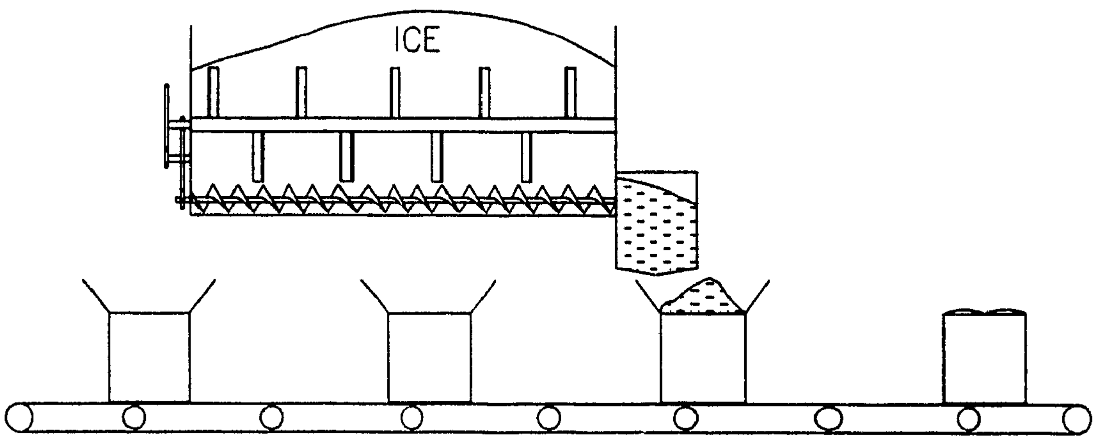

Figure 3.7: Automatic icing package system.

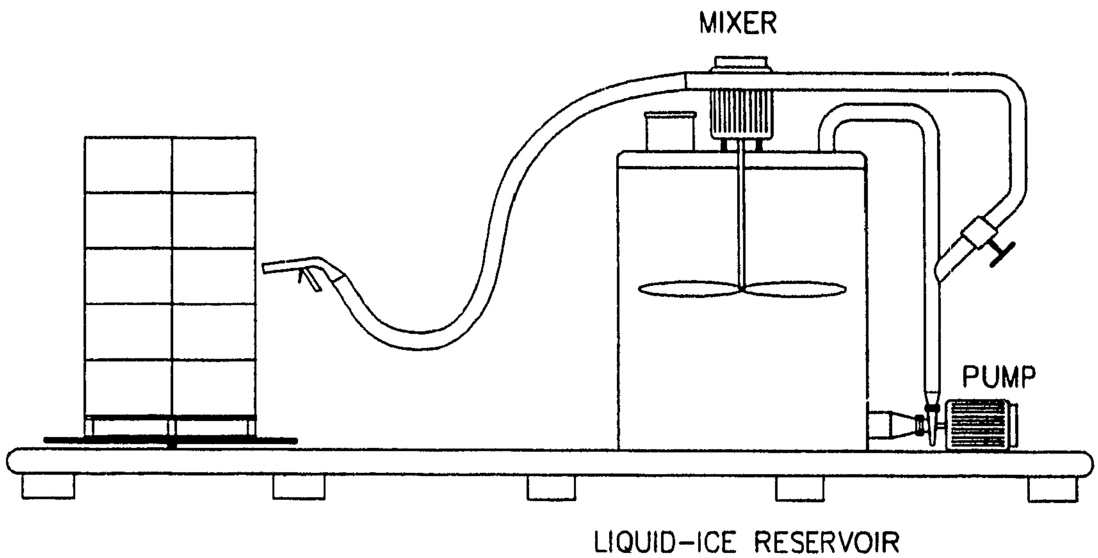

Figure 3.8: Conventional liquid-ice system producing 180 boxes per hour.

relative to a crushed ice system. Water can flow out of the boxes and leave the ice in contact with the produce. This system also allows the injection of ice through the handles of the containers, cutting the time previously required to open and close the boxes when icing was performed.

Two types of icing methods are used: 1) icing one box at a time, or 2) icing a pallet of 36 to 48 boxes all at once. The "one by one" technique (Fig. 3.8) consists of mixing finely crushed ice with water to obtain an easily pumped mix. A mixing system maintains the mixture's uniformity. A pumping system, pipes and valves, permits the injection of ice-water through the opening in the box handle. Water flowing out is recycled for ulterior use. When the ice-water mix is depleted, the reservoir is refilled.

This is a batch system, and requires rapid refilling to maintain high productivity. Thus, the required motor capacity to crush ice and pump water is typically high. Furthermore, a powerful mixer is required to prevent the ice from floating to the top of the mixing tank. This system allows accumulation of ice to keep up with the peaks in the precooling demand (125 to 250 boxes per hour). The necessary time for treatment is relatively short and the effect is long-lasting.

In a "pallet-icing" system, the walls of the chamber are equipped with grooves aligned with the box handle slots such that liquid-ice can be pumped into the boxes. This type of system allows icing of 2000 to 4000 boxes per hour. It is very efficient but is expensive to install and therefore viable only in large operations.

IV. APPARENT MEDIUM TEMPERATURE METHOD TO EVALUATE PRECOOLING SYSTEMS

4.1 Introduction

Proper cooling and temperature management practices are critical to the inhibition of the physiological deterioration of harvested fruits and vegetables (Ryall and Lipton, 1972). Produce harvested in warm periods and produce having an inherently high respiration rate must be slowed down by prompt, rapid and uniform cooling immediately after harvest by what are generally called rapid cooling (Fraser, 1991) or precooling (ASHRAE, 1986) processes. Broccoli is a highly perishable vegetable which must be precooled to preserve its quality during the storage, transport and distribution phases. The recommended precooling process for broccoli is the liquid-ice technique (Kasmire and Thompson, 1992) because it creates a cool and moist environment.

The liquid-ice method consists of pumping a mixture of crushed-ice and water into the boxes of produce (Mitchell, 1992). Since the ice distribution in the container is a very important factor in achieving rapid and uniform cooling (Prussia and Shewfelt, 1984), particle size should affect the distribution of ice in the container and should be considered when designing a liquid-ice system. However, there is no information regarding the quantitative effects of ice particle size on system performance.

Cooling rate coefficient (*CC*) and half-cooling time (*HCT*) have been used for comparing precooling techniques (Baird *et al.*, 1988; Fraser and Otten, 1992). These methods quantify the rate of heat removal from the produce (Bartsch *et al.*, 1990) and was presented in detail by Guillou (1958). *CC* and *HCT* are influenced by the morphological characteristics of the produce and these methods ignore an important variable for quantifying the performance of cooling system. This variable is the temperature uniformity achieved throughout the mass of produce being cooled. For example, in liquid-ice cooling of broccoli, the ice distribution within the boxes might be uneven resulting in a non-uniform temperature distribution. In this case, the use of temperature probes located on the surface of broccoli stalks is not an appropriate solution because the surface is not uniformly covered with ice. As will be discussed, the use of temperature probes inserted in the produce is more appropriate. This approach allows for both, a measure of the CC and the calculation of the apparent medium temperature.

4.2 Objectives

The objectives of this study are: (i) to develop a method for evaluating the performance of precooling methods which is not influenced by the morphological characteristics of the produce and, (ii) to use the method to be described to determine the optimum mean size of ice particles used in a liquid-ice system.

4.3 Literature Review

If a solid body is suddenly subjected to a change in environment, some time must elapse before an equilibrium temperature distribution is reached inside the body. Of the various criteria and parameters for evaluating and comparing cooling efficiency, the CC and HCT are usually considered to be the most convenient measures of the characteristics of a cooling system (Guillou, 1958). Predicted values may be derived from theoretical relationships or actual values can be calculated from experimental temperature-time response data.

Theoretically, the heat transfer process can be divided into three categories depending on the Biot number (*Bi*) (Mohsenin, 1980). *Bi* is defined as the ratio of the internal resistance to the external resistance to heat transfer. The internal resistance is the inverse of the thermal conductivity of the solid (k) and the external resistance is the resistance to convective heat transfer (h) at the body surface. The ratio is non-dimensionalized by the volume to surface ratio (Eq. 4.1).

$$Bi = \frac{h\ s_r}{k} \tag{4.1}$$

where,

Bi	=	Biot number;
k	=	thermal conductivity of the solid, $W{\bullet}m^{-1}{\bullet}K^{-1}$;
h	=	convective heat transfer coefficient, $W{\bullet}m^{-2}{\bullet}K^{-1}$;
s_r	=	volume to surface ratio of the body, m;

When $Bi > 10$, the convective heat transfer coefficient is large enough to make the thermal conductivity of the product the limiting factor to heat transfer. The temperature at the surface of the product is assumed equal to the environment temperature. On the other hand, when $Bi < 0.2$, the internal thermal conductivity of the product is so important that the temperature is considered uniform throughout the volume of the produce and it is therefore the cooling medium that is considered limiting to heat transfer. This is often the case in very slow cooling processes, eg. when tons of warm fruits and vegetables are introduced in a refrigerated room with a relatively limited cooling capacity (combination of air temperature and airflow rate), it can take several days for the produce to cool down. For a *Bi* of between 0.2 and 10, which applies to precooling processes for fruits and vegetables, there is a finite internal and external resistance to heat transfer.

The equations used for calculating predicted values of CC and HCT depend on ***Bi***. Singh and Heldman (1984) presented the Heisler charts used to predict CC and HCT values when *Bi* is between 0.1 and 40. However, in order to calculate the actual values of CC and HCT one uses the dimensionless temperature (T) which is obtained by monitoring the temperature profile of the cooling body. T is the unaccomplished temperature change at any time in relation to the total temperature change for the cooling conditions and can be calculated using Eq. 4.2 (Holman, 1986).

$$T = \frac{t_b - t_0}{t_i - t_0} \tag{4.2}$$

where,
- T = temperature ratio;
- t_b = temperature inside the body, K;
- t_0 = temperature of the medium surrounding the produce, K;
- t_i = initial temperature inside the body, K.

The natural log of T, ln(T), is plotted versus time giving a straight line whose slope is CC (ASHRAE, 1986), i.e. the change in product temperature per unit change of cooling time. Guillou (1958) defined CC as a function of the time (θ, minutes) and ln(T), as follows:

$$CC = \frac{\ln(T_2) - \ln(T_1)}{(\theta_2 - \theta_1)} \tag{4.3}$$

By definition, HCT is the time required to reach T=0.5 and is obtained by the following equation:

$$HCT = \frac{\ln(0.5)}{CC} \tag{4.4}$$

Even if CC and HCT has been used for comparing precooling techniques, these two methods cannot be used to evaluate the uniformity of ice distribution. These two methods are largely influenced by the morphological characteristics of the produce and the temperature of the medium surrounding the produce. This medium temperature could largely variate throughout the mass of produce being cooled. However, the temperature at any position inside of a product attempts to reach the medium temperature (t_0') through heat transfer. During precooling of a deformed produce, such as broccoli, the temperature of the medium surrounding the product can be evaluated and used to compare different cooling processes.

Based on the literature review, it was hypothesized that the apparent temperature of the medium surrounding the product (t_0') can be determined by an iterative method called the best fit straight line. First, t_0' is considered equal to the environment temperature, ln(T) is plotted against time and the regression coefficient of the straight line is calculated. Then, t_0' is iteratively adjusted in order to get the greatest regression coefficient of the straight line. The t_0' finally obtained is considered to be the apparent medium temperature of the product during the precooling period. The main advantage of using t_0' rather than the CC in comparing cooling performances is that t_0' should not be affected by the morphological characteristics of the produce.

4.4 Materials and Methods

4.4.1 Evaluation of the Apparent Medium Temperature Method

Evaluation of the hypothesis concerning the feasibility of calculating the apparent medium temperature from the straight line obtained with ln(T) plotted against time was tested on broccoli. This test was performed under laboratory condition in order to get the precision required. Since the stalk has the smallest surface-to-volume ratio among other parts of the broccoli head, it is assumed to be the critical part during precooling (Jiang *et al.*, 1987). Broccoli stalks of five different diameters ranging from 0.02 to 0.04 m and of equal length were used. A temperature probe was inserted at the centre of the stalk. The broccoli, initially at room temperature, was placed in a 10 L reservoir filled with ice and water. Water was circulated around the broccoli stalk using a pump. Ice was added in order to maintain the temperature of the water as low as possible inside the reservoir creating the best hydrocooling conditions. The temperatures of the water and at the centre of the broccoli stalk were recorded every minute, until the broccoli temperature reached about 4°C, using a ±0.5°C accuracy thermocouple. Both t_0' and CC were calculated and compared among broccoli stalks of different diameters.

4.4.2 Determination of the Mean Ice Particle Size

In a "liquid-ice" system, the ice particle size affects the uniformity of ice distribution in the boxes of produce. Different ice particle sizes were obtained by crushing polyshaped ice flakes of about 50 mm maximal length and 2.5 mm thickness. The ice crusher used (Fig. 4.1) consists of a square casing containing a drum driven by a 0.75 kW electric motor. The ice crushing drum is built from a 300 mm diameter, 300 mm long aluminum cylinder. Forty-six, 6 mm diameter × 45 mm long doll pins are uniformly inserted at a 45^0 angle pointing towards the rotational direction of the drum and protruding 6 mm above the drum surface. The tips of these pins were sharpened at a 45^0 angle to form the crushing teeth. Below the drum, two grids (A and B) were constructed using 9 mm × 25 mm flat iron bars to sieve the ice particles and further reduce their size. The bars of grid A were spaced at 22 mm, covering half of the total surface

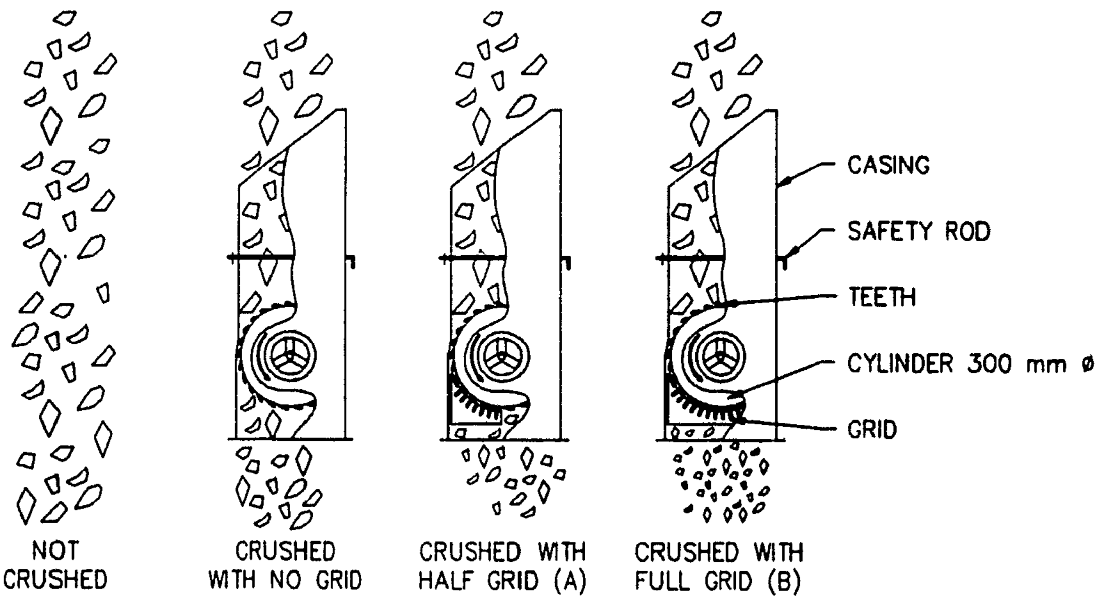

Figure 4.1: Schematic of the crusher assembly used to obtain the four different ice particle sizes.

underneath of the crushing drum. The bars of grid B were spaced at 18 mm, covering the total surface underneath of the crushing drum. Four ice particle sizes were produced to optimize the operating parameters of the liquid-ice system when using grid B, grid A, no grid and finally not using the crusher by unprocessed ice flake.

A granulometric method of analysis was developed to determine the mean size of the four samples of ice particles by adapting the sieving method for feed ingredients reported in ASAE (1992). The purpose of this sieving method was to derive a test procedure for determining and expressing the fineness of particles. In the case of ice particles, the tests were performed in a freezer where the ice was kept at -5 to -7°C to prevent ice particles from sticking together and forming large ice chunks. The equipment required consists of a set of woven-wire cloth sieves having diameters of 203 mm. The openings of the sieves used were of the following sizes: 1.25, 5, 10, 14, 20 and 28 mm. A Ro-tap† sieve shaker and a ±0.1 g accuracy balance were used as recommended (ASAE, 1992).

Preliminary tests were performed to determine the shaking time and the weight and number of samples required to obtain significant results. Large samples usually require longer shaking time to separate the ice particles but smaller samples require extra care to recover all material from the sieves (ASAE, 1992). Samples of 200, 400 and 600 g were tested.

The shaking time is determined by placing an ice sample on the top sieve of the set of sieves and shaking until the mass of material, on the smallest sieve, reaches equilibrium (ASAE, 1992). Equilibrium is said to be reached when the mass of material of this sieve changes by less than 0.2% of the total mass. Each sieve was weighed after 30, 60, 90 and 120 s shaking time.

There were four different ice particle sizes. All four were tested with the sieving method. The number of samples required to differentiate the different ice particle sizes was calculated using Eq. 4.5 (Steel and Torrie, 1980):

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† Registered trade name.

$$n = \frac{t^2 * s^2}{d^2} \qquad (4.5)$$

where, n = number of samples;

t = tabulated value for the desired confidence level and degree of freedom;

s = sample standard deviation, mm;

d = half-width of the desired confidence interval, mm.

Based on the results obtained, five samples of about 400 g were required for each ice particle size with a shaking time of 60 s. Each sieve was weighed before and after the shaking process.

The mean sizes of the ice particles were calculated and reported in terms of geometric mean size (d_{gw}) and geometric standard deviation (S_{gw}) by weight as recommended by ASAE (1992). These results were obtained using Eqs. 4.6 and 4.7,

$$d_{gw} = \log^{-1}\left[\frac{\sum (W_i \log D_i)}{\sum W_i}\right] \qquad (4.6)$$

$$S_{gw} = \log^{-1}\left[\frac{\sum W_i(\log D_i - \log d_{gw})^2}{\sum W_i}\right]^{1/2} \qquad (4.7)$$

where,

$$D_i = (d_i \times d_{i+1})^{1/2} \qquad (4.8)$$

d_i = diameter of sieve openings of the i'th sieve, mm;

d_{i+1} = diameter of openings in next larger than i'th sieve, mm;

d_{gw} = geometric mean size, mm;

D_i = geometric mean size of particles on i'th sieve, mm;

S_{gw} = geometric standard deviation, mm^2;

W_i = weight fraction on i'th sieve, g.

4.4.3 Optimization of a Liquid-Ice System Based on the Ice Particle Size

The optimum ice particle size was determined by comparing the calculated apparent medium temperature (t_0') obtained using the four ice particle sizes. For each of the four ice particle sizes, three boxes of fresh broccolis were filled using an ice-water mixture containing 50% of ice on a mass basis. This liquid-ice was injected through the handle of the boxes at a flow rate of 150 kg•min^{-1}. In each of the boxes, the temperature was monitored by inserting a thermocouple inside of broccoli stalks positioned at three different locations (Fig. 4.2). The three locations were: near the ice-water inlet (position 1), on top of the pile of broccolis at the opposite side of the ice-water inlet (position 2), and at the bottom of the pile of broccolis at the opposite side of the ice-water inlet (position 3). Liquid icing was performed at an ambient temperature of 20 to 25°C. Approximately 10 minutes after the end of the treatment, the boxes of broccoli were placed inside of a refrigerated storage room maintained at 5°C. The temperatures of the broccoli and the surrounding air were recorded every minute during the 100 minutes following the treatment. The apparent medium temperature was calculated by the best fit straight line method.

4.5 Results and Discussion

4.5.1 Evaluation of the Apparent Medium Temperature Method

Figure 4.3 shows the results obtained by plotting ln(T) against time during the hydrocooling of broccoli stalks of different diameters. The water temperature data was constant at 0.1°C throughout the whole cooling process; the ice melting heat sink compensated for the heat lost from the broccoli. The calculated apparent medium temperature of the broccoli (t_0') was 0.2°C for each of the five broccoli diameters tested, which is not significantly different from the measured water temperature considering the accuracy of the temperature monitoring system. The R^2 of each best fit regression line was 0.998 and higher. The concordance between the water temperature and the t_0' was expected since the *Bi* of this hydrocooling process was fairly high (around 20).

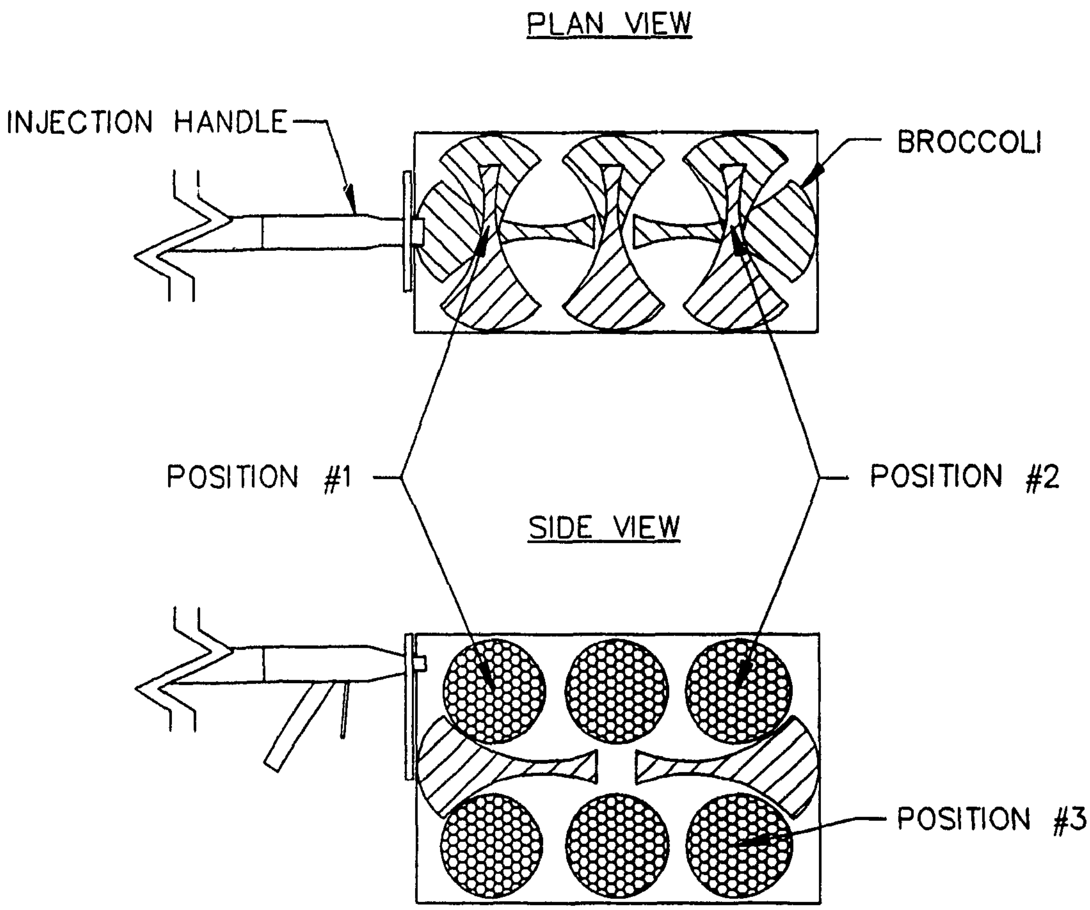

Figure 4.2: Typical box of 14 bunched broccolis bunched where the three positions of the thermocouples are shown.

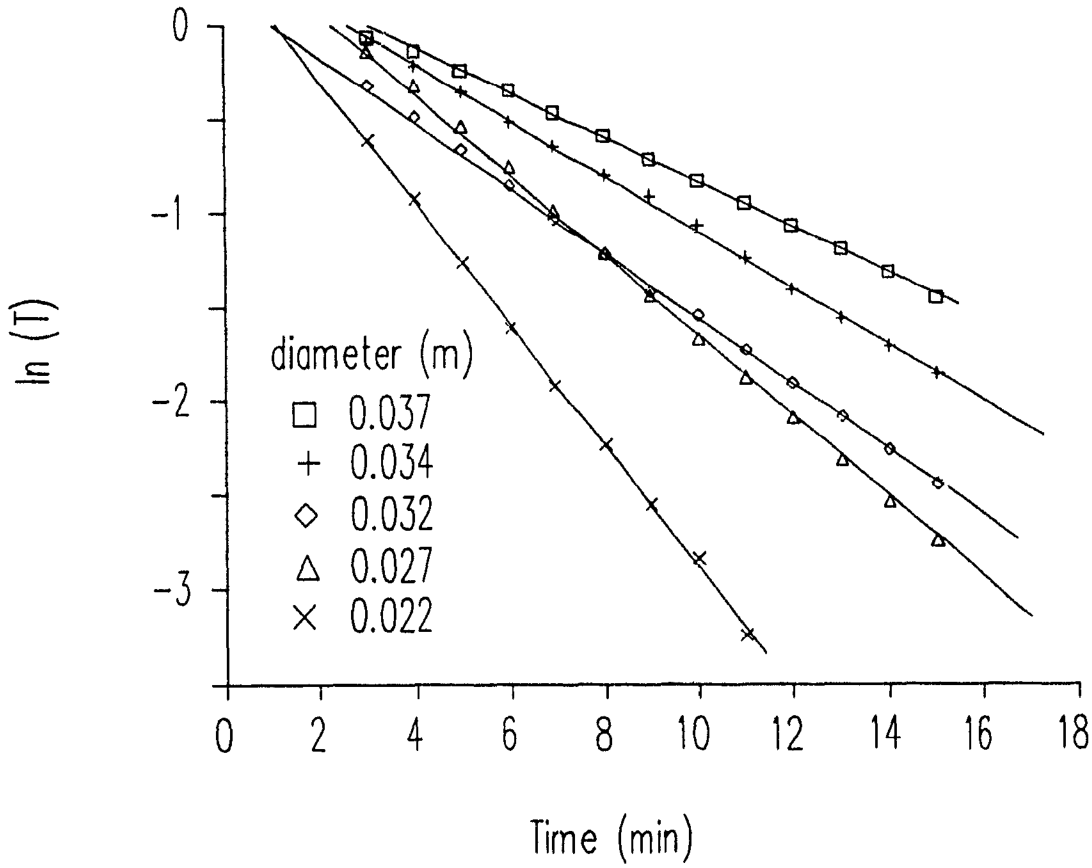

Figure 4.3: Ln(T) as a function of time for broccoli stalks of different diameters during the hydrocooling process.

Figure 4.4 shows the importance of the relation between CC and broccoli stalk diameter (D) during the hydrocooling process: $CC = -1.7\times10^{-4} D^{-2}$. From Eq. 4.4, HCT can also be related to D. Based on these results, it is more convenient to compare t_0' than to compare CC or HCT when laboratory conditions are not possible since these two parameters depend on the morphological characteristics of the produce and the temperature of the medium surrounding the produce.

4.5.2 Determination of the Mean Ice Particle Size

The maximal ice flow rate of the ice crusher was 180 $kg\bullet min^{-1}$ when no grid was used and 130 $kg\bullet min^{-1}$ with the half grid installed at the bottom of the crusher. When using the full grid, ice particles stuck together between the steel bars and occasionally plugged the ice crusher outlet.

The following results led to the procedure for the ice particle granulometric analysis. The weight difference of the smallest sieve containing material between the time 60 s and 90 s did not exceed 0.3 g for a sample of 400 g. Equilibrium considered to have been reached after a 60 s shaking period. The 600 g samples did not equilibrate within the 120 s shaking period. It appeared that this sample size was too large and the sieve was too full. The 200 g sample also required 60 s to reach equilibrium, but a much longer time was required to clean the sieve to maintain acceptable precision for the weight measurement. The method was then standardized to a 400 g sample and a shaking time of 60 s.

Preliminary tests were performed to calculate the number of replicates (using Eq. 4.5) required for the granulometric method. Results showed s of the crushed ice sample ranging from 0.47 mm when the ice was not crushed to 0.14 mm for the finest ice crushed. A number of five replicates were required as calculated using Eq. 4.5, while $d = 0.6$ mm and $t_{4,\,0.025} = 2.78$.

The results of sieving of the five samples of each of the four ice particle sizes allowed differentiation between their d_{gw} (Eq. 4.6) and S_{gw} (Eq. 4.7) (Table 4.1). S_{gw} decreases as d_{gw} decreases, meaning that the size of the individual particles is more uniform as the mean size of these particles decreases.

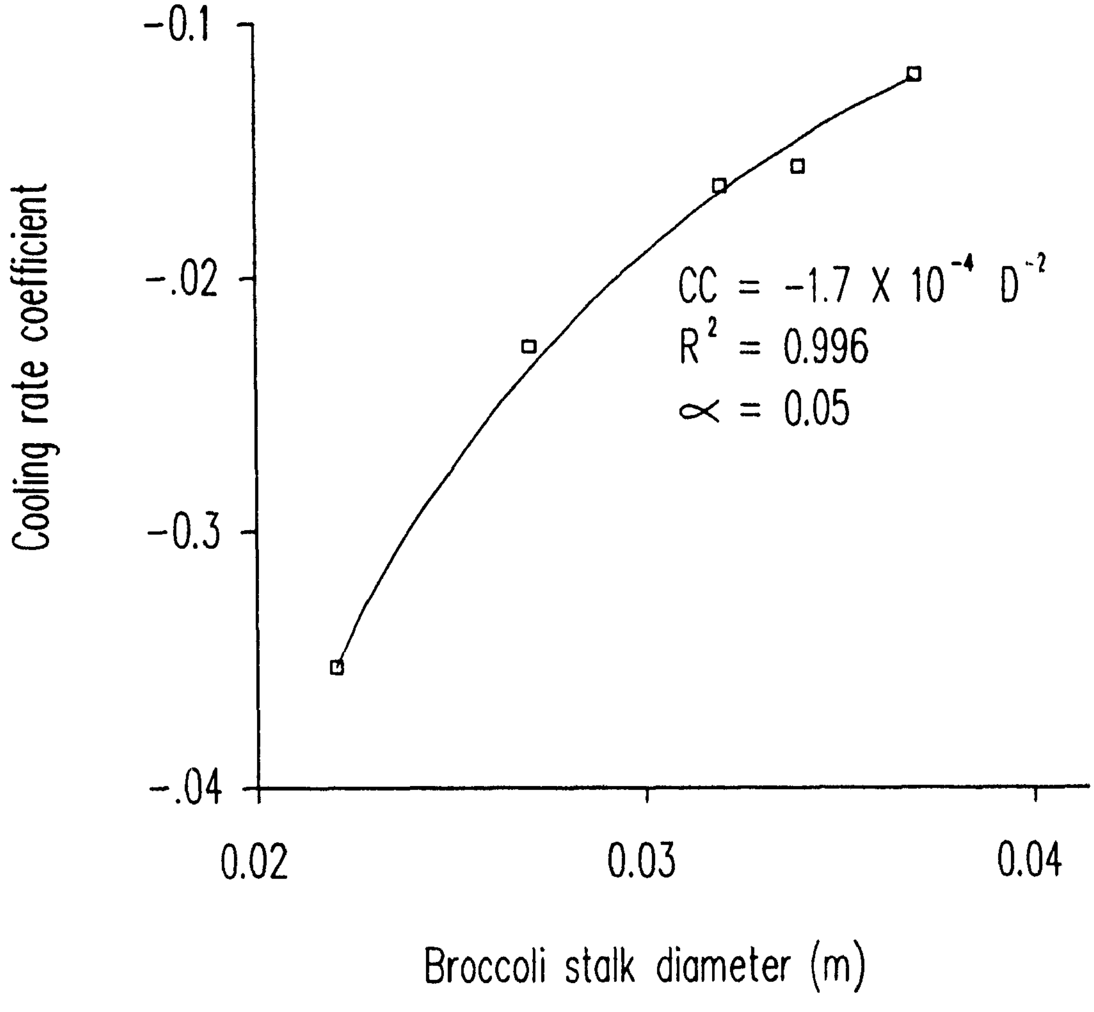

Figure 4.4: Cooling coefficient as a function of the diameter for broccoli stalks during the hydrocooling process.

Table 4.1: Geometric mean size (d_{gw}) and geometric standard deviation (S_{gw}) of the ice particle sizes obtained from the different crushing method.

	Not crushed	Crushed no grid	Crushed 1/2 grid	Crushed full grid
d_{gw} (mm)	6.92	5.10	4.42	3.22
S_{gw} (mm)	0.46	0.40	0.22	0.14

4.5.3 Optimization of a Liquid-Ice System Based on the Ice Particle Size

The t_0' of each broccoli was calculated by the best fit straight line method as described above. At first, t_0' was assumed to be 0°C and $\ln(T_0)$ was plotted against time. Typical results presented in Fig. 4.5 exhibit a non-linear relationship between $\ln(T_0)$ and time. In this particular case, adjusting t_0' resulted in a highly correlated linear relationship ($R^2 = 0.997$, $\alpha = 0.05$) between $\ln(T_{adjusted})$ and time. Overall, the linear correlations between $\ln(T_{adjusted})$ and time were very high ($R^2 > 0.995$, $\alpha = 0.05$). t_0' of broccoli are presented at Table 4.2 as a function of the ice particle size and the position. These temperatures were expected to be related to the size of the ice particles. A smaller size should result in a better contact between the ice and the product and a better distribution through the box. As shown in Table 4.2, lower t_0' of treated broccoli were observed while using the 4.4 mm ice particles followed by the 5.1 mm and then by the 3.2 mm particles. However, t_0' were higher using the 6.9 mm ice particles. This result could be explained by the fact that a large proportion of ice particles injected into the boxes was flowing out while using the 3.2 mm ice particles resulting in a poor ice distribution. According to this result, it is recommended that an ice particle size of 4.4 mm be used for liquid-ice precooling of broccoli.

4.6 Conclusion

A calculated apparent medium temperature (t_0') method has been developed and tested to determine the effect of ice particle size on precooling of broccoli. This t_0' method is convenient even when laboratory conditions are not possible. The method is also independent of the morphological characteristics of the produce.

A granulometric method was adapted to measure ice particle sizes. It permitted the determination of the geometric mean size of ice particles produced using four

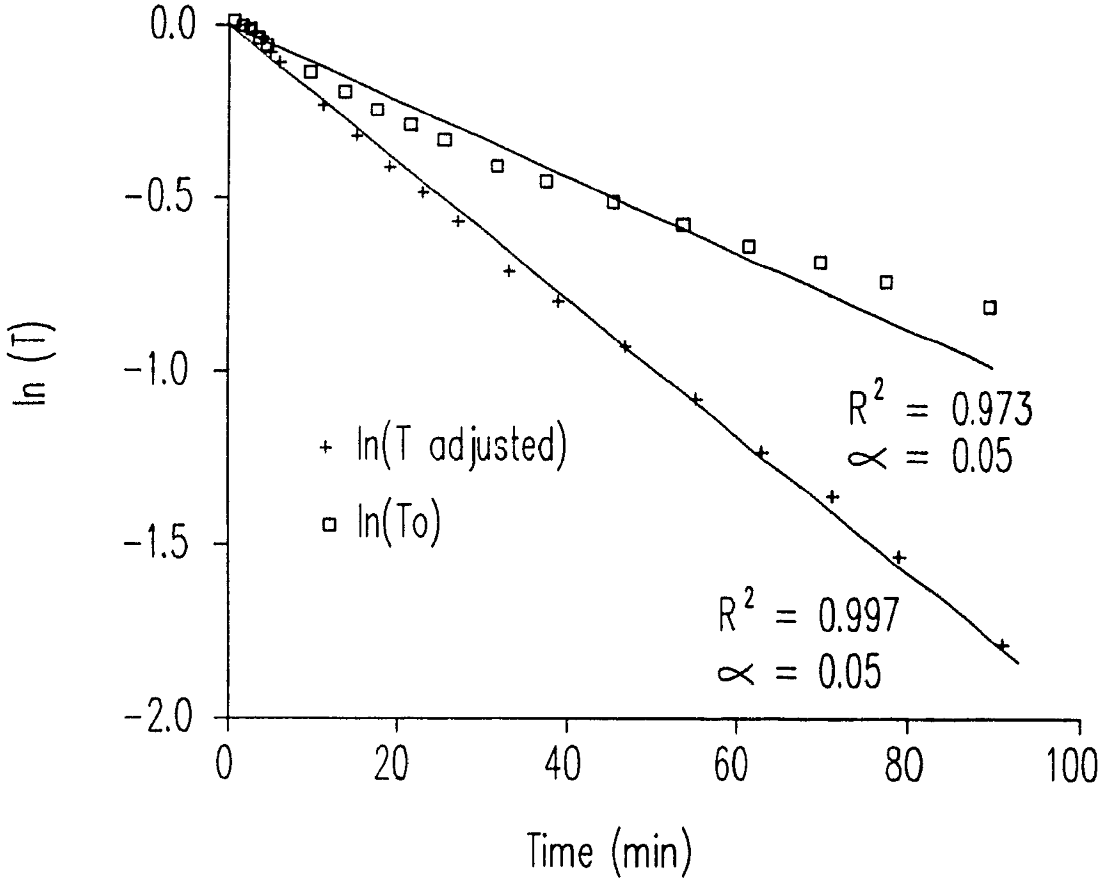

Figure 4.5: $Ln(T_0)$ and $ln(T_{Adjusted})$ as a function of time for a broccoli stalk during the cooling process.

Table 4.2: Mean apparent medium temperatures (°C) of the broccolis as a function of their position inside of the box and the average of these temperatures as a function of the ice particle size.

Ice particle size (mm)	Position 1	Position 2	Position 3	
	Mean temperature (°C)			Average†
3.2	3.2	4.0	3.8	3.7[CB]
4.4	1.1	1.7	2.5	1.8[A]
5.1	2.4	3.0	3.3	2.9[B]
6.9	3.5	3.7	4.6	3.9[C]

†Averages with the same letters are not significantly different at $\alpha=0.05$.

different crushing methods. The effect of particle sizes on t_0' of broccolis during precooling was measured. The results show that t_0' is related to the ice particle size used; the mean t_0' decreases with the decrease of particle size. However, the 3.2 mm ice particle size was too sticky, plugging the crusher outlet and flowing out of the boxes during liquid-icing, thus resulting in a higher t_0' of the produce.

The t_0' method showed that the 4.4 mm ice particle size was best for liquid-ice precooling of broccoli.

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CONNECTING TEXT

The next chapter deals with the construction and optimization of the liquid-ice system. Since the tests are performed under field conditions, the method generally used to compare different cooling processes is not accurate enough for this experiment. The apparent medium temperature method developed and tested in Chapter IV is used to perform this optimization. The granulometric analysis presented in Chapter IV is also used in the development and the evaluation of the new liquid-ice system.

V. LOW COST LIQUID-ICE SYSTEM TESTED ON BROCCOLIS

5.1 Introduction

Respiration must be slowed down by rapid cooling (Fraser, 1991) or precooling (ASHRAE, 1986) immediately after harvest to delay the physiological deterioration of produce (fruits or vegetables) (Ryall and Lipton, 1972). For example, the broccoli respiration rate at 20°C is 15 times larger than that at 0°C (ASHRAE, 1981).

Among many precooling techniques, liquid-icing is extensively used in broccoli postharvesting (Kader, 1992). It is also recommended for root vegetables, artichokes, brussels sprouts, green onions, leek, peas, some melons and sweet corn (Kasmire and Thompson, 1992).

Up to now, liquid-icing has been achieved by mixing crushed-ice with water in a large insulated reservoir (Fig. 5.1). The liquid-ice slush is pumped and introduced in the produce boxes by the holes made for handling. The advantages of liquid-icing include the maintenance of a cool and moist environment for the produce between the packing house and the market place and, the elimination of additional handling of the stacked boxes (Mitchell, 1992).

However, liquid-icing has many drawbacks. The produce and the packaging must be tolerant to water contact and prolonged exposure to 0°C. Furthermore, although liquid-icing is well established for large production units, small and medium production units cannot justify its utilisation because of a high initial and operating costs. Due to the ice's buoyancy, the ice-water slush must be stirred continuously to obtain a uniform mixture. The system is also generally operated in batch mode to maintain a constant ice-water ratio. Batch operation requires fast ice and water feeding systems to reduce the off-time during filling of the liquid-ice reservoir. The stirring process and the batch operation procedure result in a high power requirement (22 kW and more) to operate the system. Finally, the uniformity of the ice distribution in the boxes of produce is important in achieving rapid and uniform cooling (Prussia and Shewfelt, 1984). Ice particle size affects the ice distribution (Chapter IV). The ice-water ratio is also suspected to affect ice distribution in the boxes but information on this factor or the combined effects of

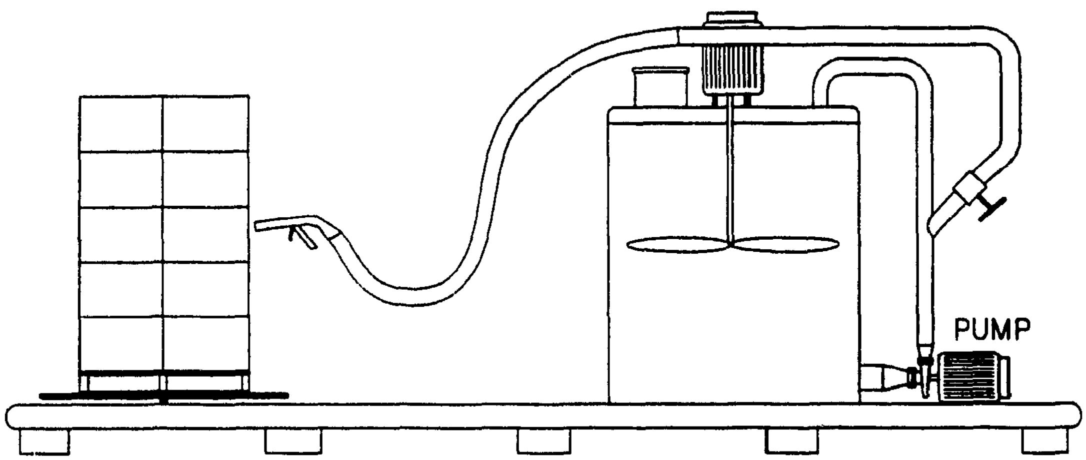

Figure 5.6: Conventional liquid-ice system producing 180 boxes per hour.

ice-water ratios and ice particle sizes is absent from the literature.

The cooling rate coefficient of a produce is generally used to evaluate the cooling efficiency of a given cooling system. The cooling rate varies as a function of the specific mass, the heat capacity, the heat conductivity, the shape of the cooling body (the produce to be cooled) and the temperature differential between the cooling body and the cooling fluid. However, it is possible to eliminate the effect of each of these parameters. The efficiency of a cooling system may be evaluated based on its capacity to maintain the temperature at the surface of the cooling body at the lowest temperature it could tolerate for a long period of time without adversely affecting quality parameters. It has been demonstrated (chapter IV) that the medium temperature at the surface of a product can be calculated from the change of its inside temperature during the cooling process. The produce mean apparent medium temperature can therefore be used as a convenient method to optimize the operating parameters of the liquid-ice system.

5.2 Objectives

The objectives of this project are to develop a liquid-ice system which has a lower power requirement than the system now in use and to determine the optimum operating parameters of the new system for precooling broccoli.

5.3 Description and Calibration of the System

The proposed liquid-ice system consists of a continuous ice flow feeding system which does not include any temporary ice-water reservoir. This way, the ice cannot separate from the water. The ice-water slush is used immediately after the ice and water are mixed to a homogeneous state. The different components of the new system are presented in Fig. 5.2. Starting from the flaker, the ice goes through the storage room, the auger, the crusher, the crushed ice reservoir, the ice-water mixing chamber, the diaphragm pump and, the injection and control handle. Finally, the excess water goes to the recycling reservoir where it is pumped to the mixing chamber.

Each component of the system was chosen and calibrated to ice 150 to 200 boxes per hour. Preliminary tests were performed to determine the maximum diaphragm pump flow rate, to calibrate the ice and water flow rate as a function of the control system and to establish the maximum ice-water ratio for plug-free operation.

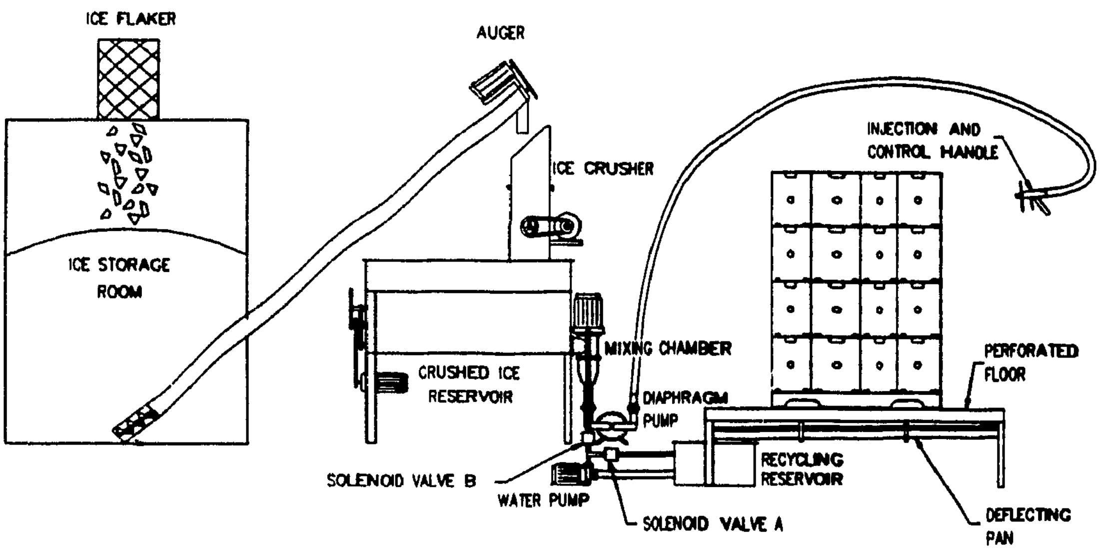

Figure 5.7: Schematic of the liquid-ice system developed during the project.

5.3.1 Ice Flaker and Storage Room

The ice used in the development the liquid ice system described herein is produced using a conventional ice flaker. This flaker produces the ice by spraying water onto the inside surface of an insulated freezing drum. The ice is removed using a helicoidal compression reamer rotating at a constant speed along the surface of the freezing drum. The flakes obtained are about 2.5 mm thick and 10 to 50 mm in length. The ice is produced continuously and stacked into an insulated storage room. An ice detector stops ice production when the storage room is filled.

5.3.2 Ice Feeder Auger

A 100 mm diameter × 3.66 m long auger is used to feed the ice crusher. A funnel-shaped stand is required to permit full capacity operation of the auger when using manual feeding. A 0.35 kW electric motor activates the auger.

5.3.3 Ice Crusher

An ice crusher (Fig. 5.3) was built to reduce and standardize the ice particle size. It consists of a square casing containing a drum driven by a 0.75 kW electric motor. The ice crushing drum is built from a 300 mm diameter, 300 mm long aluminum cylinder. Forty six, 6 mm diameter × 45 mm long doll pins are uniformly inserted at a 45° angle pointing towards the rotational direction of the drum and protruding 6 mm above the drum surface. The tips of these pins are sharpened at a 45° angle to form the crushing teeth. A grid is mounted below the drum to sieve the ice particles and further reduce their size. Two grids (A and B) were constructed using 9 mm × 25 mm flat iron bars. The bars of grid A were spaced at 22 mm, covering half of the total surface underneath of the crushing drum (Fig. 5.3). The bars of grid B were spaced at 18 mm and covered the total surface underneath the crushing drum. The four different ice particle sizes that can be produced by the crusher are: 3.2, 4.4, 5.1, 6.9 mm when either using grid B, grid A, no grid or finally not using the crusher but using ice directly from the flaker (Chapter IV).

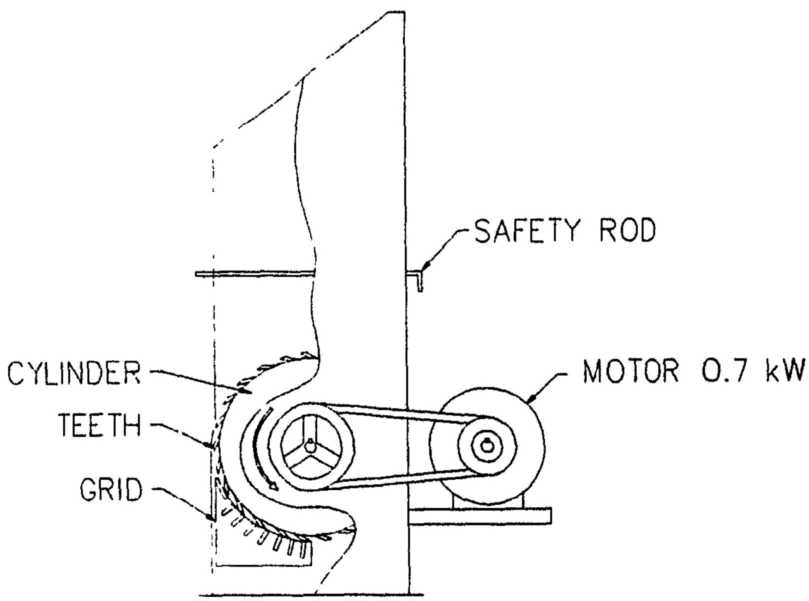

Figure 5.8: Ice crusher mounted with the type A grid.

5.3.4 Crushed Ice Reservoir

The crushed ice reservoir supplies a uniform ice flow rate to the mixing chamber (Fig. 5.4). This 1.8 × 0.9 m rectangular, open top reservoir is 0.3 m in height and has a V-shaped bottom section with 2 walls at 45° angle. Its volume is approximately 0.75 m^3. A bridge breaker and a 90 mm diameter, 1.8 m long auger supply the ice into the mixing chamber. A 0.75 kW variable speed DC electric motor operates the auger and the bridge breaker. A transmission reduces the speed of the DC motor by a ratio of 8.75:1 for the auger and 25:1 for the bridge breaker. The speed of the motor can be adjusted from 0 to 1750 RPM to supply the ice at the desired flow rate.

The ice flow rate of this auger, which feeds the mixing chamber, was calibrated as a function of the rotational speed of the DC motor. The ice flow rate entering the mixing chamber was sampled and weighed for each 10% gradation, between 30% to 100%, of the control panel of the DC motor. The tests were replicated twice. The mass flow ranged from 0.13 $kg \bullet s^{-1}$ to 1.48 $kg \bullet s^{-1}$. The results were not stable when operating the DC motor at slow speeds (under 50%), since a 17% variation between replicates was measured. This variation decreased very quickly with increased speed reaching 3% of the measured flow rate at full speed.

The bridge breaker is made of a central axle on which 17 blades are uniformly distributed. The blades are mounted at a 20° angle to push the ice backwards. This orientation of blades is necessary to prevent packing of the ice in front of the crushed ice reservoir at the inlet of the mixing chamber.

5.3.5 Mixing Chamber

The ice-water mixer (Fig. 5.4) consists of a cylindrical chamber placed at the exit of the crushed ice reservoir. The water and ice are introduced into the mixing chamber by two separate inlets (Fig. 5.5). A 90 mm diameter, 150 mm long vertical auger is placed inside of the mixing chamber to prevent blocking. A direct drive 0.25 kW electric motor activates this vertical auger. The ice-water slush exits the mixing chamber and flows down through the 90 to 50 mm diameter funnel to the diaphragm pump.

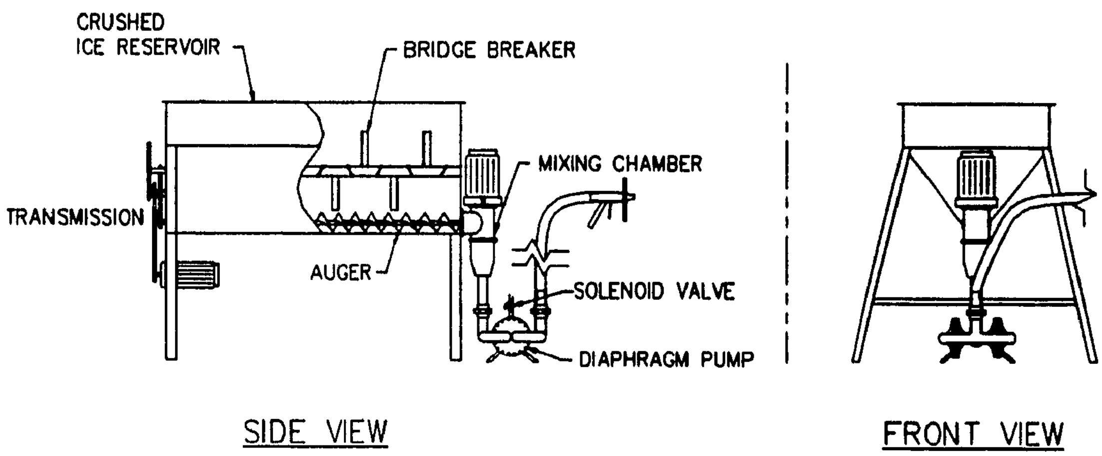

Figure 5.9: Schematic of the crushed ice reservoir and the mixing chamber.

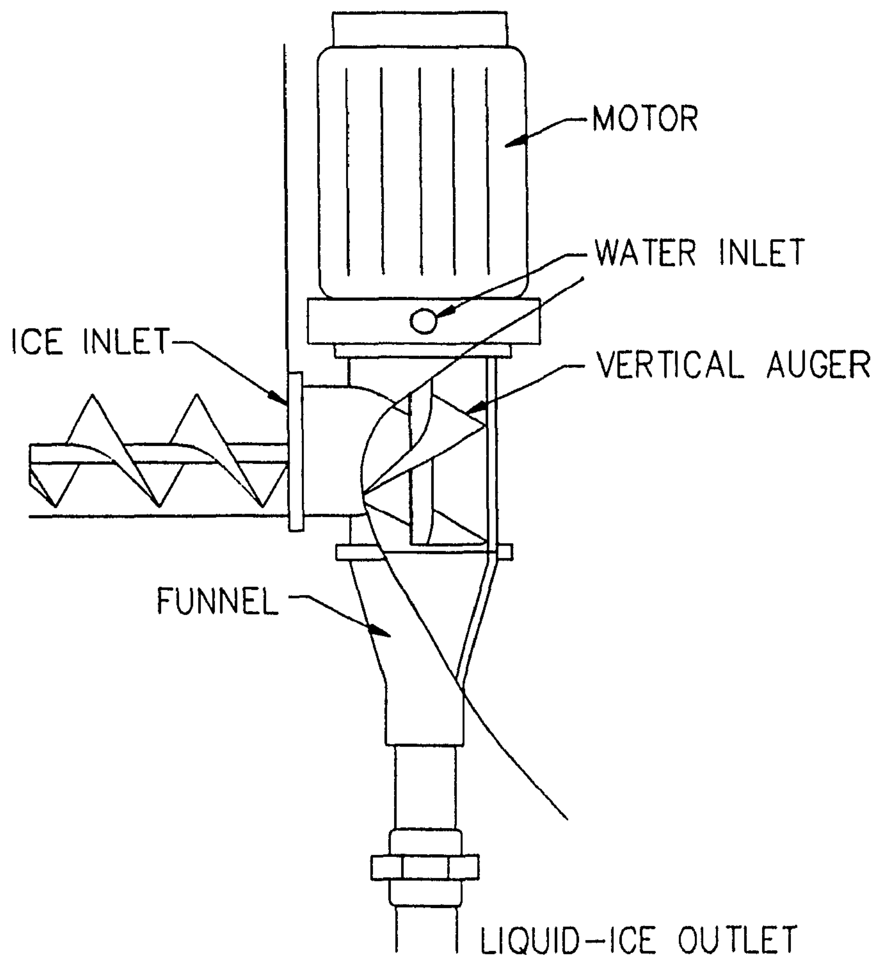

Figure 5.10: Schematic of the mixing chamber used with the liquid-ice system.

5.3.6 Diaphragm Pump

A double action pneumatically activated diaphragm pump circulates the ice-water slush into the boxes. The compressed air required is produced by a 3.5 kW compressor which has a 360 L air reservoir. A manual gate valve and a normally close solenoid valve are installed on the air supply line. The manual valve regulates the air flow rate which controls the operating speed of the diaphragm pump. When the solenoid valve is activated, the compressed air is free to circulate and activates the diaphragm pump. This pump, with 50 mm diameter inlet and outlet channels allows for the circulation of non uniform solids like ice and can take in air without discharging.

The maximum continuous flow rate at which the diaphragm pump can operate was determined. The air compressor operates the diaphragm pump until the pressure inside of the compressed air reservoir reaches equilibrium. The flow rate of the diaphragm pump and the compressed air pressure were recorded after pressure inside the compressed air reservoir was constant for 10 minutes. A water flow rate of 3.3 $L \bullet s^{-1}$ was obtained when operating at 150 kPa.

The maximum ice-water mass ratio for plug-free operation was determined as follows. The diaphragm pump was operated at its maximum continuous flow rate. The ice was fed at 1.48 $kg \bullet s^{-1}$. The water flow rate was adjusted to supply 1.8 $kg \bullet s^{-1}$, which resulted in a 45% ice-water ratio. The water flow was then decreased by steps of 5% of ice-water ratios until the liquid-ice system plugged up. This test was repeated several times and showed that the plugging problems occurred when the system was operated using an ice-water ratio of 70%. These tests were performed using the 5.1 mm ice size, but it was considered that the smaller ice particles would perform better. The 6.9 mm ice particles, produced without using the ice crusher, were also tested. These particles contained some large ice chunks which plugged up the system irrespective of the ice-water ratio. The maximum operating ice-water ratio was then fixed at 60% to avoid any plugging problem during the icing operation.

5.3.7 Injection and Control Handle

An injection handle is used to inject the liquid-ice into the boxes of produce. The handle tip is designed to fit the handle holes of the boxes. An electric switch is mounted on the injection handle to activate the solenoid valves of the system and the electric motor operating the crushed ice auger. For safety, the voltage used on the handle switch is 24 V.

5.3.8 Water Flow Components

During liquid-icing, a pallet of produce is placed on an elevated perforated floor (Fig. 5.2). A 300 L water reservoir and three deflecting pans located under the perforated floor collect the water that flows out of the boxes after the icing process. The water is recirculated from this reservoir by a 0.7 kW direct driven turbine pump to the ice-water mixing chamber. A manual valve placed on the exhaust line of the pump allows adjustment of the water flow rate. Two solenoid valves, one normally opened (A) and one normally closed (B) are also placed on the exhaust line (Fig. 5.2) to direct the water flow. When activated, these valves direct the water towards the mixing chamber; otherwise, the water is directed towards the recycling reservoir. The flow rate of the water pump was calibrated as a function of the manual valve aperture. The water flow rate was measured at each one eighth of a turn from half a turn to fully open. The measurements were repeated twice. The flow rate ranged from 0.315 $kg \bullet s^{-1}$ to 2.2 $kg \bullet s^{-1}$ and showed a maximum variation between replicates of 5% of the measured flow rate.

5.4 Materials and Methods

The following series of tests was performed to evaluate the effects of the ice-water ratios and the ice particle sizes on the icing efficiency, maximum cooling rate of broccoli and distribution of ice in the box of produce.

The icing efficiency is defined as the ratio of the ice remaining in the box of produce compared to the ice that was circulated through the box. The ice remaining inside the box was determined by calculating the difference between the mass of the box containing the broccoli before being iced and five minutes after the end of the treatment. The ice circulated into the box is calculated by multiplying the time required to process a box by the ice flow rate. During the experiment, three ice-water ratios (40%, 50% and 60%) and four ice particle sizes (3.2, 4.4, 5.1 and 6.9 mm) were tested. The slush mixture flow rate was kept constant at 2.5 $kg \bullet s^{-1}$ during the experiment.

The cooling efficiency and the uniformity of the ice distribution inside the boxes was evaluated by monitoring the temperature using thermocouples inserted at the centre of broccoli stalks placed at three specific locations (Fig. 5.6) inside of the treated boxes. These positions were: 1) near the ice-water inlet, 2) the upper part of the box at the opposite side of the ice-water inlet and, 3) the bottom part of the box at the opposite side of the ice-water inlet. For each treatment, three boxes of 14 bunched broccolis were treated with liquid-ice and stored in a refrigerated room 10 minutes after the end of the treatment. The temperature of the storage room was maintained at 5°C.

The apparent medium temperatures of the 108 tested broccolis (3 positions, 3 replicates, 3 ice-water ratios, 4 ice particle sizes) were calculated and compared. Considering that a larger surface of contact between the ice and the broccolis generates a lower apparent medium temperature, the uniformity of the ice distribution inside the box was evaluated by comparing the apparent medium temperature of the broccolis (Chapter IV).

5.5 Results and Discussion

Table 5.1 shows the mean apparent medium temperature of broccoli for the different positions as a function of the ice particle sizes. Table 5.2 shows the mean apparent medium temperature of broccoli for the different positions as a function of the ice-water ratios. Only one ice particle size (4.4 mm) and one ice-water ratio (50%) showed a significant difference in mean apparent medium temperature as a function of its position inside of the box.

More ice was added inside of the box when using the 4.4 and 5.1 mm ice particle sizes (Table 5.3). The icing efficiency was significantly lower when using the 3.2 mm ice particle size. It was also observed that a large portion of the ice flowed out of the boxes with the water during the liquid-icing process when using the 3.2 mm ice particles. A significantly higher apparent medium temperature resulted from using the 50% ice-water ratio (Table 5.4) or the 3.2 mm and 6.9 mm ice particle sizes (Table 5.3). These results are likely related to the fact that less ice remained inside of the boxes when using these two particle sizes (Table 5.3). The ice-water ratio had no significant effect on the icing efficiency and the mass of ice remaining in the boxes (Table 5.4).

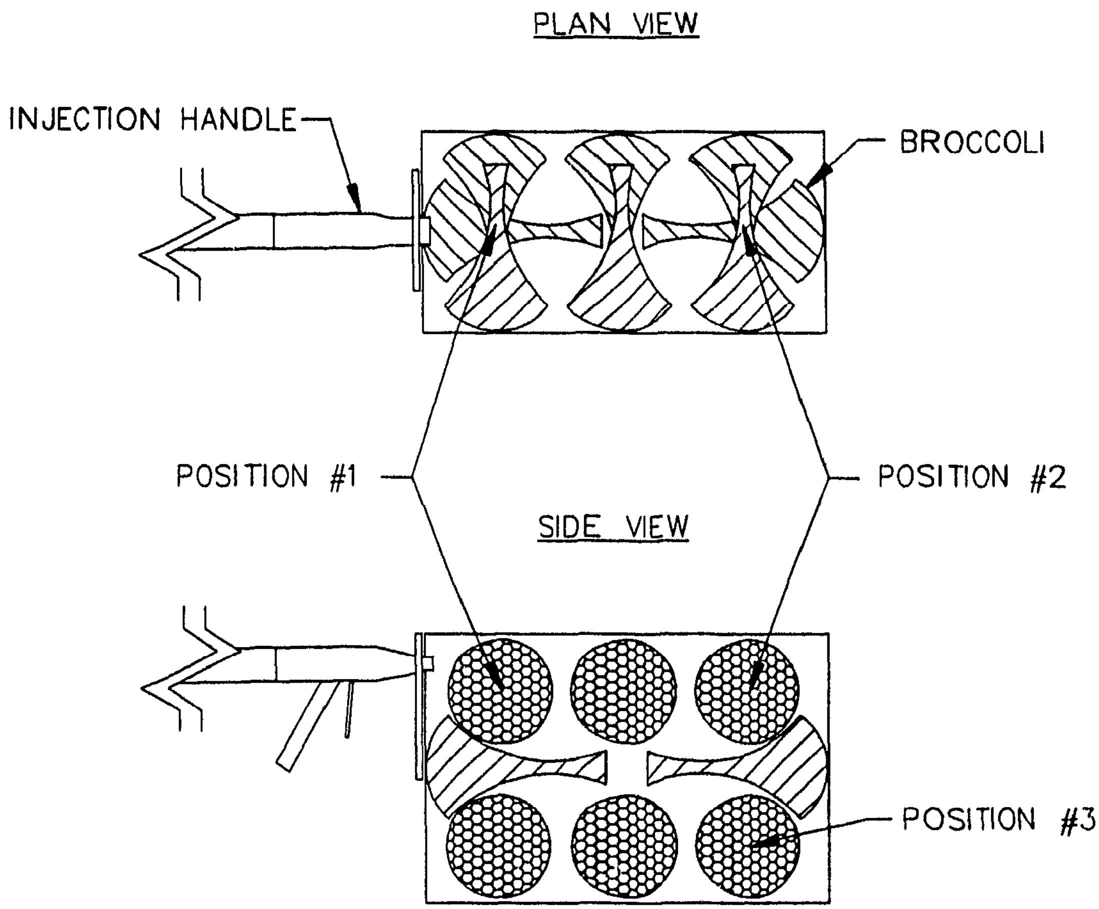

Figure 5.11: Typical box of 14 bunched broccolis where the three positions of the thermocouple are shown.

Table 5.1: Mean apparent medium temperature (°C) of the broccolis as a function of their position inside of the box and the ice particle size.

	Ice particle size (mm)			
Position	3.2	4.4	5.1	6.9
1	3.2^{A}	1.1^{A}	2.4^{A}	3.5^{A}
2	4.0^{A}	1.7^{AB}	3.0^{A}	3.7^{A}
3	3.8^{A}	2.5^{B}	3.3^{A}	4.6^{A}

Means with the same letters are not significantly different at α=0.05.

Table 5.2: Mean apparent medium temperature (°C) of the broccolis as a function of their position inside of the box and the ice-water ratio.

	Ice-water ratio(%)		
Position	40	50	60
1	2.5^{A}	3.0^{A}	2.2^{A}
2	2.7^{A}	4.1^{AB}	2.5^{A}
3	2.8^{A}	5.0^{B}	2.8^{A}

Means with the same letters are not significantly different at $\alpha=0.05$.

Table 5.3: Mean apparent medium temperature of the broccolis, mass of ice in the boxes and icing efficiency as a function of the ice particle size.

Ice particle size (mm)	Apparent medium temperature (°C)	Mass of ice in the boxes (kg)	Icing efficiency (%)
3.2	3.7^{CB}	11.8^{BC}	33^{B}
4.4	1.8^{A}	12.9^{AB}	61^{A}
5.1	2.9^{B}	13.5^{A}	62^{A}
6.9	3.9^{C}	11.1^{C}	66^{A}

Means with the same letters are not significantly different at $\alpha=0.05$.

Table 5.4: Mean apparent medium temperature of the broccolis, mass of ice in the boxes and icing efficiency as a function of the ice-water ratio.

Ice-water ratio (%)	Apparent medium temperature (°C)	Mass of ice in the boxes (kg)	Icing efficiency (%)
40	2.6^{B}	12.4^{A}	55^{A}
50	4.0^{A}	11.9^{A}	54^{A}
60	2.5^{B}	12.6^{A}	57^{A}

Means with the same letters are not significantly different at $\alpha=0.05$.

5.6 Conclusion

A liquid-ice system was developed requiring only 6.3 kW to operate compared to the 22 kW normally used for the same icing productivity. The productivity of this system was about 180 boxes per hour on a continuous operation basis. It was demonstrated that the ice particle sizes and the ice-water ratios affected the apparent medium temperature of the broccolis and hence the performance of the liquid-ice system. The optimal operating parameters of the new system were determined. Lower broccoli apparent medium temperatures were obtained using the 4.4 mm ice particle size. More uniform ice distribution, better icing efficiency and more ice addition were obtained when using the 5.1 mm ice particle size compared to 4.4 mm. There was no significant difference in the mass of ice remaining in the boxes of produce and the icing efficiency for the different ice-water ratios. The 40% and 60% ice-water ratio generated a lower apparent medium temperature than using 50%. However, for the same liquid-ice flow rate, with the ice-water ratio of 60% it requires about 33% less time to process one box of produce than using an ice-water ratio of 40% thus increasing the productivity. It is then recommended to use ice particle sizes ranging from 4.4 to 5.1 mm and the 60% ice-water ratio.

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VI. GENERAL DISCUSSION AND CONCLUSION

Proper temperature management is essential to extend the market life of freshly harvested produce. Precooling and cold storage are two esssential components of temperature management and they should be considered separately.

A liquid-ice system was developed based on a new concept. It consist of injecting ice into a water stream. The mixture is then pumped into the boxes of produce on a continuous basis. This new system required only 6.3 kW to operate compared to the 22 kW with the existing system. It was demonstrated that the ice particle sizes and the ice-water ratios affected the apparent medium temperature of broccolis and hence the performance of a liquid-ice system. The optimal ice particle size and ice-water ratio of the new system were determined.

Ice particles of different sizes were obtained by crushing ice flakes. A granulometric method was adapted to measure ice particle sizes. It allowed the determination of the geometric mean size and granulometric standard deviation of ice particles of four different sizes: 6.9 mm, 5.1 mm 4.4 mm and 3.2 mm. A problem occurred when crushing the 3.2 mm ice particles; they plugged the crusher outlet. This did not occur with the other sizes.

The apparent medium temperature of the product is an efficient way to compare the efficiency of precooling system. A comparative method based on the apparent medium temperature of the product has been developed and tested to determine the effect of ice particle size on precooling of broccoli. This method can be used even if laboratory conditions are not possible. This method is not affected by the physical characteristics of the produce.

Lower broccoli apparent medium temperatures were obtained using the 4.4 mm ice particle size. More uniform ice distribution, better icing efficiency and more ice addition were obtained when using particle size of 5.1 mm compared to 4.4 mm. There was no significant difference in the mass of ice remaining in the boxes of produce and the icing efficiency for the different ice-water ratios. The 40% and 60% ice-water ratio generated a lower apparent medium temperature than using 50%. However, for the same liquid-ice flow rate, the ice-water ratio of 60% requires about 33% less time to process one box of produce than when using an ice-water ratio of 40%. It is therefore recommended to use ice particle sizes ranging from 4.4 to 5.1 mm and a 60% ice-water ratio.

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