ASSESSMENT OF PRECOOLING TECHNOLOGIES
FOR SWEET CORN

by

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fulfilment of the requirements for the degree of
Master of Science

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ABSTRACT

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ASSESSMENT OF PRECOOLING TECHNOLOGIES FOR SWEET CORN

Sweet corn is classified among highly perishable horticultural commodities. Thus, it can be deteriorated rapidly after harvest resulting in high loss and poorer produce quality. Sweet corn’s sugar loss is about four times higher at 10°C compared to 0°C. Precooling, immediately after harvest, has shown to be an effective method to maintain the quality for a wide range of fresh fruits and vegetables during storage. Further, this method leads to reduction in metabolism and respiration rate of the produce, retardation of its senescence, and inhibition of growth of pathogens. In addition to diminishing postharvest losses of the produce, efficient precooling is required for increasing the length of duration of marketing time for better profitability.

Precooling of sweet corn was accomplished by three main methods including forced-air, water and vacuum cooling. Operating parameters such as temperature, pressure, orientation of corn cobs, air flow rate and water flow pattern were defined and studied for optimization. The assessment and comparison of the performance of precooling systems was achieved by determining the effect of these parameters on half cooling time and quality of the produce during storage for 7 and 21 days at 1°C and 90-95% RH. In addition, room cooling method was also tested and compared to the three precooling systems. The use of three sweet corn cultivars was important to compare their quality response to different cooling methods.

Experiments were performed on a lab-scale vacuum cooler and modified forced-air and water cooler systems. The results showed that changing the cob orientation perpendicular to the direction of flow medium, using higher air flow rate in forced-air cooling and immersed water flow pattern in water cooling, can significantly reduce the half cooling time of the produce. Finally, the best method to be recommended for precooling sweet corn is by using hydrocooling which results in superior quality produce and minimum time.
RÉSUMÉ

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ÉVALUATION DES TECHNIQUES DE PRÉREFROIDISSEMENT DU MAÏS SUCRÉ

Le maïs sucré est une denrée horticole extrêmement périssable. S’il n’est pas refroidi immédiatement après la récolte, le maïs sucré se détériore rapidement. Il a été démontré que les pertes en sucre sont quatre fois plus élevées à 10°C qu’à 0°C. Le prérefroidissement, tout de suite après la récolte, suivi de l’entreposage à de basses températures s’est avéré être une méthode efficace pour maintenir la qualité de plusieurs fruits et légumes frais. Cette méthode permet de réduire considérablement le métabolisme du produit, de retarder la sénescence et de ralentir la croissance des pathogènes. En plus de diminuer les pertes postrécolte, un prérefroidissement efficace permet de prolonger la durée de commercialisation.


Les résultats de l’étude ont indiqué que l’orientation des épis de maïs par rapport au courant d’air ou d’eau et que les débits d’air ou d’eau affectaient de façon marquée les demi temps de refroidissement. Pour le système à air forcé, les meilleurs temps de demi refroidissement ont été obtenus en plaçant les épis perpendiculaires au courrant d’air et en utilisant les débits d’air les plus élevés. Le refroidissement par immersion dans l’eau froide c’est avéré supérieur au refroidissement par douche. Lorsqu’on a tenu compte de la qualité après entreposage et du temps de demi refroidissement, la meilleure méthode s’est avérée être l’eau froide.
ACKNOWLEDGEMENTS

I would like to thank Dr. Vijaya Raghavan for his guidance, wisdom, and inspiration during the writing of this thesis and for giving me the opportunity to pursue my graduate studies with him. I am looking forward to any opportunities to work further with him in the future. To Dr. Clément Vigneault, I thank him for his insight and leadership during the time that I was working with him. It was a great pleasure to work together as a team. I would like also to give a sincere thanks to Dr. Marie-Thérèse Charles for her assistance during the quality planning and evaluation section in this study.

My full gratitude goes to Mr. Yvan Gariépy for all his help, direction and time during the statistical analysis and writing my scientific papers. I would like to thank Mr. Bernard Goyette for his help in the design and instrumentation of the experimental set-ups during my stay at the Research Centre of Agriculture and Agri-Food Canada. Further, I would really appreciate the help of Mrs. Dominique Roussel and Mrs. Isabelle Lemay during the time we spent together. It was my great pleasure to work with them both. To Mrs. Mélanie Cadieux for her time during the microbial analysis.

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I would like to thank my parents for their support and encouraging me to follow my own path in life. To my brother, Marc, and my sister, Pamela, they should follow their dreams; I will always support both of them.
**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 follow:

“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.

It is acceptable for the thesis to include as chapters authentic copies of papers already published, provided these are duplicated clearly on regulation thesis stationary 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 explanation material is almost always necessary.

The inclusion of manuscripts co-authored by the candidate and others is acceptable but the candidate is required to make an explicit statement on who contributed to such work and to what extent, and supervisors must attest to the accuracy of the claims, e.g. before the Oral Committee. Since the task of the Examiners is made more difficult in these cases, it is in the candidate’s interest to make the responsibilities of authors perfectly clear. Candidates following this option must inform the Department before it submits the thesis for review.”
CONTRIBUTIONS OF AUTHORS

The work stated here was completed by the candidate and supervised by Dr. G.S.V. Raghavan of the Department of Bioresource Engineering, Macdonald Campus of McGill University, Montreal, Dr. C. Vigneault and Dr. M.T. Charles of the Postharvest Quality Laboratory, Horticultural Research and Development Centre, Agriculture and Agri-Food Canada, Saint Jean-sur-Richelieu. The entire experiment was accomplished at the Horticultural Research and Development Centre. The authorship for the papers are 1) P. Cortbaoui, B. Goyette, Y. Gariépy, M.T. Charles, G. S. V. Raghavan and C. Vigneault; 2) P. Cortbaoui, C. Vigneault, B. Goyette, Y. Gariépy, M.T. Charles and G. S. V. Raghavan; 3) P. Cortbaoui, Y. Gariépy, B. Goyette, G. S. V. Raghavan, C. Vigneault and M.T. Charles in Chapters IV, V, and VI, respectively.
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>A</td>
<td>Produce surface area (m²)</td>
</tr>
<tr>
<td>ADP</td>
<td>Adenosine diphosphate</td>
</tr>
<tr>
<td>ATP</td>
<td>Adenosine triphosphate</td>
</tr>
<tr>
<td>Bi</td>
<td>Biot number</td>
</tr>
<tr>
<td>C₂H₄</td>
<td>Ethylene molecule</td>
</tr>
<tr>
<td>C₆H₁₂O₆</td>
<td>Glucose molecule</td>
</tr>
<tr>
<td>CC</td>
<td>Cooling coefficient (s⁻¹)</td>
</tr>
<tr>
<td>CFIA</td>
<td>Canadian food inspection agency</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide molecule</td>
</tr>
<tr>
<td>cₚ</td>
<td>Produce specific heat (J·kg⁻¹·°C⁻¹)</td>
</tr>
<tr>
<td>CR_{ins}</td>
<td>Instantaneous cooling rate (°C per unit time)</td>
</tr>
<tr>
<td>EC</td>
<td>Energy coefficient</td>
</tr>
<tr>
<td>ECR</td>
<td>Efficient consumer response</td>
</tr>
<tr>
<td>EFR</td>
<td>Efficient food service response</td>
</tr>
<tr>
<td>FCR</td>
<td>Farm cash receipts</td>
</tr>
<tr>
<td>F₀</td>
<td>Fourrier number</td>
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<tr>
<td>GDP</td>
<td>Gross domestic product</td>
</tr>
<tr>
<td>h</td>
<td>Convective heat transfer coefficient (J·m⁻²·°C⁻¹·s⁻¹)</td>
</tr>
<tr>
<td>H₂O</td>
<td>Water molecule</td>
</tr>
<tr>
<td>HCT</td>
<td>Half cooling time (s)</td>
</tr>
<tr>
<td>ICP</td>
<td>Interior crude products</td>
</tr>
<tr>
<td>k</td>
<td>Thermal conductivity (J·m⁻¹·°C⁻¹·s⁻¹)</td>
</tr>
<tr>
<td>kₜ</td>
<td>Transpiration coefficient (g·m⁻²·Pa⁻¹·s⁻¹)</td>
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<td>L</td>
<td>Latent heat of vaporization of water (kJ·kg⁻¹ water)</td>
</tr>
<tr>
<td>m</td>
<td>Mass of produce (kg)</td>
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<tr>
<td>MC</td>
<td>Moisture content (%)</td>
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<td>mₜ</td>
<td>Transpiration rate (g·m⁻²·s⁻¹)</td>
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<td>Water vapourised (kg water·kg⁻¹ produce)</td>
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<tr>
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<td>Description</td>
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<td>-------------</td>
</tr>
<tr>
<td>p&lt;sub&gt;a&lt;/sub&gt;</td>
<td>Water vapour pressure in the air (Pa)</td>
</tr>
<tr>
<td>P&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Inorganic phosphate</td>
</tr>
<tr>
<td>PLU</td>
<td>Price look up</td>
</tr>
<tr>
<td>ppm</td>
<td>Parts per million</td>
</tr>
<tr>
<td>p&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Water vapour pressure at surface (Pa)</td>
</tr>
<tr>
<td>P&lt;sub&gt;w&lt;/sub&gt;</td>
<td>Dynamic pressure (Pa)</td>
</tr>
<tr>
<td>Q</td>
<td>Heat produced (kJ·kg&lt;sup&gt;-1&lt;/sup&gt; produce)</td>
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<td>Q&lt;sub&gt;10&lt;/sub&gt;</td>
<td>Temperature quotient of respiration</td>
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<td>Q&lt;sub&gt;f&lt;/sub&gt;</td>
<td>Field heat load (kJ)</td>
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<tr>
<td>q&lt;sub&gt;g&lt;/sub&gt;</td>
<td>Heat generation rate (J·s&lt;sup&gt;-1&lt;/sup&gt;·m&lt;sup&gt;-3&lt;/sup&gt;)</td>
</tr>
<tr>
<td>QI</td>
<td>Quality index</td>
</tr>
<tr>
<td>r</td>
<td>Characteristic dimension (m)</td>
</tr>
<tr>
<td>RH</td>
<td>Relative humidity (%)</td>
</tr>
<tr>
<td>RI</td>
<td>Refractive index</td>
</tr>
<tr>
<td>RQ</td>
<td>Respiratory quotient</td>
</tr>
<tr>
<td>S&lt;sub&gt;0&lt;/sub&gt;</td>
<td>Characteristic dimension (m)</td>
</tr>
<tr>
<td>se</td>
<td>Sugary enhanced</td>
</tr>
<tr>
<td>sh2</td>
<td>Supersweet or shrunken-2</td>
</tr>
<tr>
<td>spp</td>
<td>Species</td>
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<tr>
<td>su</td>
<td>Sugary normal</td>
</tr>
<tr>
<td>t</td>
<td>Time (s)</td>
</tr>
<tr>
<td>T</td>
<td>Absolute temperature (°C)</td>
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<tr>
<td>T&lt;sub&gt;7/8&lt;/sub&gt;</td>
<td>Seven-eighth cooling time (min)</td>
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<tr>
<td>T&lt;sub&gt;a&lt;/sub&gt;</td>
<td>Cooling medium temperature (°C)</td>
</tr>
<tr>
<td>T&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Initial produce temperature (°C)</td>
</tr>
<tr>
<td>T&lt;sub&gt;in&lt;/sub&gt;</td>
<td>Instantaneous produce temperature (°C)</td>
</tr>
<tr>
<td>T&lt;sub&gt;i&lt;/sub&gt;-T&lt;sub&gt;ma&lt;/sub&gt;</td>
<td>Temperature reduction (°C)</td>
</tr>
<tr>
<td>T&lt;sub&gt;ma&lt;/sub&gt;</td>
<td>Mass-average temperature of produce (°C)</td>
</tr>
<tr>
<td>T&lt;sub&gt;p&lt;/sub&gt;</td>
<td>Produce temperature (°C)</td>
</tr>
<tr>
<td>TSS</td>
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<td>UPC</td>
<td>Universal product code</td>
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<td>V</td>
<td>Produce volume (m$^3$)</td>
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<td>x</td>
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</tr>
<tr>
<td>y</td>
<td>Spatial co-ordinate (m)</td>
</tr>
<tr>
<td>z</td>
<td>Spatial co-ordinate (m)</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Time (s)</td>
</tr>
<tr>
<td>$v$</td>
<td>Velocity (m·s$^{-1}$)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density (kg·m$^{-3}$)</td>
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I. GENERAL INTRODUCTION

Food problem has been a dangerous truth in this world since the beginning of life on the earth. Although, researchers have been thinking about two practical solutions which can be obviously defined either by reduction of population or by increasing the production of food; many people are suffering from insufficient food. Several reasons are attributable for this situation such as the delay occurring between the producer and the consumer and the postharvest practices including harvesting, handling, storage and processing of the produce.

Both quantitative and qualitative postharvest losses in fresh fruits and vegetables are significant due to their high values reaching up to 50% in developing countries (Kader, 2002). Therefore, postharvest conservation of the produce quality and quantity is an important measurement to enhance world food supplies in a largely effective manner (Salunkhe, 1984b). Certainly improved technologies in postharvest can at some extent overcome these losses.

Sweet corn is a very common horticultural crop in North America. Like other commodities, sweet corn is a living organism and continues to respire after harvest (Talbot et al., 1991). Its sweetness and quality can rapidly deteriorate after harvest if not maintained at low temperature (Boyette et al., 1990). Studies on sweet corn have shown that 60% of its sugar content can be lost in 24 hours if kept at 30°C; even at 10°C, this rate of sugar loss is four times that at 0°C (Herber, 1991). Freshly harvested sweet corn is best stored at 0°C and 90-98 %RH for maximum of 6 to 8 days and still retaining good marketing quality (Sargent et al., 1988); thus, temperature management is essential to maintain the quality of sweet corn during storage.

Precooling consists of rapid decrease of the produce temperature promptly and immediately after harvest (Thompson, 2003; Raghavan et al., 2004). It reduces respiration rate, postharvest losses and bacterial growth resulting in a longer storage life of the crop. The selection among different precooling methods is based on several parameters such as cooling rate, the physiology of the commodity, capital costs and energy effectiveness of the cooler (Golob et al., 2002). Precooling process is
accomplished using several techniques including forced-air, water, liquid ice, and vacuum cooling.

Forced-air cooling uses air as cooling medium. Cold air is pulled at different flow rates ranging from 0.5 to 3 L of air s\(^{-1}\)·kg\(^{-1}\) of produce (Fraser, 1991) through the commodity packed in a container resulting in a faster removal of heat than room cooling (Edeogu et al., 1997). This intimate contact between the airflow and the commodity removes the heat around the produce by convection (Fraser, 1991). The cooling time is relatively high and a wide range of produce is suitable to be cooled by this method (Kader, 2002).

Hydrocooling involves the application of cold water quickly and uniformly over the surface of a warm produce (ASHRAE, 1998d). Water is a better heat-transfer medium than air; therefore, hydrocoolers cool the produce much faster than forced-air coolers (Thompson et al., 1998). During hydrocooling process, the commodity does not lose moisture (Kader, 2002). Using spray or immersed water flow pattern, this precooling method is well suited for sweet corn and other water resistant crops like apple, peach, and carrot (Kader, 2002). Sanitation of water with chlorine is critical to avoid the contamination of decay micro-organisms that might occur while cooling the produce (Kays, 1997).

Vacuum cooling is the most rapid method to precool horticultural commodities. It consists of placing the warm produce into an air tight chamber and lowering the pressure inside the chamber to the point where water boils at the desired cooling temperature (ASHRAE, 1998d). The saturation pressure for water at 0°C is 0.610 kPa which corresponds to 4.6 mmHg (ASHRAE, 1998d). Water at the surface of the produce evaporates and removes quickly the field heat of the produce and condenses on an evaporative coil (Kader, 2002). Vacuum cooling causes a large mass loss in the produce. This method is best recommended for perishable crops with high surface area to mass ratios such as leafy vegetables.

Currently available precooling technologies are not as efficient to cool down sweet corn. Therefore, the installation and application of an expensive cooling system is not justifiable by most Canadian corn producers due to the relatively short harvesting season compared to Florida or California. Most of the Canadian sweet corn is transported
warm resulting in poor quality and affecting the producer reputation. Hence, this study was undertaken to determine the best technology for precooling of sweet corn and to prolong its storage life while maintaining high marketable quality.
II. GENERAL OBJECTIVES

The overall objective was to study a commercially efficient technology for precooling of Canadian sweet corn, one of the most difficult horticultural crops to precool. The specific objectives are:

1. To compare different methods for precooling sweet corn.
2. To establish the length of storage for all the precooling methods considering the quality attributes of the produce.
3. To determine the optimal conditions for the best precooling method.
4. To make recommendations for appropriate cooling method of sweet corn useful in the postharvest industry.
III. LITERATURE REVIEW

3.1 Overview of the Canadian Horticultural Industry

The global food industry can reach a value of $3.3 trillion and agro-industry is expected to be worth $15 trillion by 2028 (Golob et al., 2002). In Canada, the agriculture sector ranks among the second biggest natural resource-based industry. Thus, the agriculture has been contributing largely to the economy of this country; it attained about 8.4% of the Gross Domestic Product (GDP) in 2001 (Agriculture & Agri-Food Canada, 2002/2003a). In addition, the agriculture sector in Quebec represented 1.05% of the Interior Crude Products (ICP) and generated more than $2.2 billion in 2002 (OAQ, 2004).

The horticulture sector in Canada is becoming more vital and is considered as a major source of income for many citizens. In 2002, it represented $5.0 billion or 15.4% of all agricultural Farm Cash Receipts (FCR) (Agriculture & Agri-Food Canada, 2002/2003a). This sector which includes potatoes, vegetables, fruits, berries, floriculture, nursery, Christmas trees, sod, honey and maple products (Table 3.1) is second to cattle and before grains. Roughly 80% of the horticulture production is concentrated in the provinces of Ontario, Quebec and British Columbia (Figure 3.1).

Advances in new technologies such as standardized Universal Product Code (UPC) and Price Look Up (PLU), Efficient Consumer Response (ECR) and Efficient Foodservice Response (EFR) have lead to a more efficient distribution and flow streaming of fruits and vegetables between producers and consumers (Agriculture & Agri-Food Canada, 2002/2003a).

The challenge to supply high quality horticultural crops and perishable produce to the national and international markets has been the major reason to develop and optimize new techniques used in the Canadian agriculture sector starting from the practices in the field, all the way through the production and processing to marketing sector. In addition, huge investments have been made during last decade in research and development for better understanding and creating new methods to reduce postharvest losses, and ensure high production, quality and safety of agricultural products.
Table 3.1 Domestic horticulture industry in Canada (Agriculture & Agri-Food Canada, 2002/2003a).

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<tbody>
<tr>
<td>Value ($ CAN million)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fruits¹</td>
<td>428.4</td>
<td>485.9</td>
<td>486.6</td>
<td>548.0</td>
<td>517.2</td>
</tr>
<tr>
<td>Vegetables²</td>
<td>923.0</td>
<td>1037.3</td>
<td>1153.3</td>
<td>1273.3</td>
<td>1431.0</td>
</tr>
<tr>
<td>Potatoes</td>
<td>533.1</td>
<td>533.1</td>
<td>612.2</td>
<td>680.0</td>
<td>952.0</td>
</tr>
<tr>
<td>Floriculture / Nursery³</td>
<td>884.0</td>
<td>999.3</td>
<td>1282.4</td>
<td>1659.1</td>
<td>1873.3</td>
</tr>
<tr>
<td>Maple</td>
<td>100.4</td>
<td>121.4</td>
<td>137.5</td>
<td>180.7</td>
<td>162.3</td>
</tr>
<tr>
<td>Honey</td>
<td>58.2</td>
<td>73.7</td>
<td>88.6</td>
<td>69.5</td>
<td>82.3</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>2927.1</strong></td>
<td><strong>3250.7</strong></td>
<td><strong>3760.6</strong></td>
<td><strong>3260.6</strong></td>
<td><strong>5018.0</strong></td>
</tr>
</tbody>
</table>

¹ including fresh and processed (stone and tree fruits, berries)  
² including fresh and processed (and greenhouse)  
³ including Christmas tree and sod

Figure 3.1 Schematic distributions of Canadian horticultural commodities (Agriculture & Agri-Food Canada, 1999/2000).
3.1.1 Canadian vegetable industry profile

According to Statistics Canada, cultivated area of vegetables (excluding potatoes and greenhouse) was estimated as 120,000 hectares in 2001. Half of it was destined for the processing industries while the other half was used for the fresh market. Ontario occupied over half of the cultivated vegetable area in Canada, while Quebec has 33%. Besides, FCR have showed an increase of 2.4% in 2002 and up to 18% from the last five-year average (Agriculture & Agri-Food Canada, 2002/2003b). The production of vegetables in these two provinces has shown a significant increase for the last decade, a growth of 262% in onion, 130% in cucumber, 76% in lettuce, 48% in carrot, and 40% in cabbage.

In 2001, among the vegetables destined for fresh market, sweet corn ranked fifth behind carrots, lettuce, cabbage and dry onions with a farm gate value of $31 million (Table 3.2). Sweet corn declined 6.3% since 1996, although it is still a very common vegetable, with 26.5% (30,000 ha) of all vegetable area (excluding potato and greenhouse). The top four vegetables marketed for processing (Table 3.3), sweet corn, green peas, beans and tomatoes, accounted for over half of all vegetables grown (excluding potatoes).

Improving the production, produce quality and marketing systems remain the major keys to face the word markets and continuous growth. Several investigations were done in this area to introduce new vegetable varieties into Canada.

Table 3.2 Major field grown vegetables destined for fresh market (Statistic Canada, 2001).

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<tr>
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<tbody>
<tr>
<td>Farm Gate Value ($ CAN million)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carrots</td>
<td>59</td>
<td>61</td>
<td>56</td>
<td>41</td>
<td>52</td>
</tr>
<tr>
<td>Lettuce</td>
<td>50</td>
<td>36</td>
<td>38</td>
<td>38</td>
<td>46</td>
</tr>
<tr>
<td>Cabbage</td>
<td>34</td>
<td>39</td>
<td>33</td>
<td>34</td>
<td>42</td>
</tr>
<tr>
<td>Dry onions</td>
<td>41</td>
<td>51</td>
<td>48</td>
<td>45</td>
<td>48</td>
</tr>
<tr>
<td>Sweet corn</td>
<td>34</td>
<td>36</td>
<td>32</td>
<td>27</td>
<td>31</td>
</tr>
<tr>
<td>Broccoli</td>
<td>25</td>
<td>26</td>
<td>24</td>
<td>24</td>
<td>22</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>423</strong></td>
<td><strong>408</strong></td>
<td><strong>408</strong></td>
<td><strong>381</strong></td>
<td><strong>445</strong></td>
</tr>
</tbody>
</table>
Table 3.3 Major field grown vegetables destined for processing (Statistic Canada, 2001).

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Farm Gate Value ($CAN million)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tomatoes</td>
<td>50</td>
<td>59</td>
<td>57</td>
<td>44</td>
<td>50</td>
</tr>
<tr>
<td>Sweet Corn</td>
<td>22</td>
<td>24</td>
<td>21</td>
<td>19</td>
<td>17</td>
</tr>
<tr>
<td>Green Peas</td>
<td>19</td>
<td>23</td>
<td>20</td>
<td>19</td>
<td>20</td>
</tr>
<tr>
<td>Cucumbers</td>
<td>12</td>
<td>13</td>
<td>17</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>Carrots</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Green &amp; Wax Beans</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>TOTAL</td>
<td>127</td>
<td>136</td>
<td>144</td>
<td>148</td>
<td>154</td>
</tr>
</tbody>
</table>

3.2 Postharvest Physiology of Perishable Crops

The postharvest period begins when the commodity item is separated from the medium of growth or its parent plant and ends when the commodity goes into the process of preparation for final consumption (Salunkhe, 1984b). In other words, postharvest engages all actions that take place after production of agricultural commodities, including handling, storage, packaging, transportation, processing and marketing from the producer all the way to the distributor (Golob et al., 2002).

“Postharvest physiology is the division of plant physiology dealing with functional processes in plant material after it has been harvested” (Kays, 1997).

Most vegetables are well-known as highly perishable plant produce (Table 3.4), they are alive and persist to be active metabolically even after harvesting. However, their metabolism is different with that of the mother plant growing in its original environment since the harvested produce undergoes varying degrees of stress. Overall, living plant material is usually subjected to extremely painful behaviour during its postharvest life. An essential characteristic of all living organisms is that they react in a large number of interacting ways to slow down the effects of stresses to which they are exposed to preserve as near as possible a homeostatic condition within the organism (Kays, 1997). Harvest also gets rid of the contribution of mineral nutrients necessary for regular metabolic activity. The harvested produce is then dependent on recycling of these nutrients already present (Kays, 1997).

Careful handling of vegetables after harvest is thus important to maintain their quality in good standing. Besides, freshly cultivated vegetables release significant energy...
in the form of heat which enhances their deterioration during storage, transportation, and marketing resulting in a poor quality and reputation of these plant products (Salunkhe, 1984a).

Table 3.4 Differences between durable and perishable commodities (Golob et al., 2002).

<table>
<thead>
<tr>
<th>Durables</th>
<th>Perishables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suitable for preservation</td>
<td>Not suitable for preservation</td>
</tr>
<tr>
<td>Low moisture content, usually 10-15%</td>
<td>High moisture content, usually 50-90%</td>
</tr>
<tr>
<td>Small unit size, less than 1 g</td>
<td>Large unit size, typically 5 g to 6 kg</td>
</tr>
<tr>
<td>Often symmetrical in shape</td>
<td>Often asymmetrical in shape</td>
</tr>
<tr>
<td>Hard texture</td>
<td>Soft texture</td>
</tr>
<tr>
<td>Stable-inherent storage life of years</td>
<td>Perishable-natural storage life of a few days to months depending on type</td>
</tr>
<tr>
<td>Losses mainly caused by external factors, e.g. mould, insects and rodents</td>
<td>Losses caused by external factors, mainly moulds and bacteria, and internal factors, e.g. respiration, sprouting, ripening, etc.</td>
</tr>
</tbody>
</table>

3.2.1 Postharvest losses

Fruits and vegetables must be transported from the field to the table, to arrive in a good condition at the consumer level (Bakker-Arkema, 1999). Loss is a measure of drop in mass in the amount of food available for consumption. Losses in agriculture increase the cost of production and reduce quantity and quality of the crops. So, these losses should be eliminated to some extent in order to fully satisfy the consumer needs with the same resources and expenditure (Salunkhe, 1984b).

Postharvest losses of fresh fruits and vegetables are of considerable interest due to their extremely high values reaching 5 to 25 percent in developed countries and 20 to 50 percent in developing countries (Kader, 2002). These losses are defined as any change in the quality and quantity of a produce after harvest that prevents its future use or reduces its marketable value (Kays, 1997). Poor handling and storage can easily contribute to a large extent in crop loss. Two main causes of postharvest produce losses may occur: primary and secondary (Salunkhe, 1984b). The primary causes include biological, chemical, mechanical, physical and physiological losses; whereas, secondary causes are
due to respiration, ethylene production, compositional changes, transpiration and growth factors.

3.2.2 Respiration

Physiological modifications in a fruit or vegetable persist even after harvest, and sometimes at an accelerated rate. These changes are mainly due to the respiration process, which includes very complex metabolic pathways (Singh and Chakraverty, 2001).

“Respiration is a process by which stored organic materials such as carbohydrates, proteins, and fats are broken down into simple end products with a release of energy” (Kader, 2002).

In other words, respiration is the conversion or the oxidation of organic matter such as starch, sugar, and organic acids to produce simpler molecules like CO$_2$ and H$_2$O with the release of energy (heat) to maintain cell’s metabolism, tissue and quality of the commodity. The availability of oxygen (O$_2$) is very essential during respiration resulting in an “aerobic respiration process”. However, sometimes when the O$_2$ is unavailable, anaerobic respiration might occur releasing other molecules such as ketons, aldehydes, and alcohols which are toxic to the crop cells (Singh and Chakraverty, 2001). The overall process of aerobic respiration involves the synthesis of adenosine triphosphate (ATP), which is commonly known as energy trapping device, from adenosine diphosphate (ADP) and inorganic phosphate (P$_i$). In addition, glucose coalesces with oxygen to generate carbon dioxide, water and heat (673 kcalories/mol of glucose) (Eq. 3.1) (Kader, 1987).

\[
C_6H_{12}O_6 + 6 O_2 + 38 ADP + 38 P_i \rightarrow 6 CO_2 + 44 H_2O + 38 ATP
\]  

The release of heat can be detrimental for the plant tissue, causing the temperature of the produce to get higher and producing some disagreeable results: degradation of food value; loss of flavour quality attributes, mainly sweetness; speeding up of senescence; and reduced saleable dry mass (Kader, 2002). The amount of heat generated varies with the commodity as shown in Table 3.5.
Table 3.5 Heat of respiration of selected fruits and vegetables (Singh and Chakraverty, 2001).

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Respiratory heat generated per unit mass (mW.kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0°C</td>
</tr>
<tr>
<td>Apples</td>
<td>10-12</td>
</tr>
<tr>
<td>Apricots</td>
<td>15-17</td>
</tr>
<tr>
<td>Blackberries</td>
<td>46-68</td>
</tr>
<tr>
<td>Broccoli</td>
<td>55-63</td>
</tr>
<tr>
<td>Cabbage</td>
<td>12-40</td>
</tr>
<tr>
<td>Celery</td>
<td>21</td>
</tr>
<tr>
<td>Corn, Sweet</td>
<td>125</td>
</tr>
<tr>
<td>Leeks</td>
<td>28-48</td>
</tr>
<tr>
<td>Lettuce, head</td>
<td>27-50</td>
</tr>
<tr>
<td>Onions</td>
<td>7-9</td>
</tr>
<tr>
<td>Oranges</td>
<td>9</td>
</tr>
<tr>
<td>Peaches</td>
<td>11-19</td>
</tr>
<tr>
<td>Potatoes, mature</td>
<td>--</td>
</tr>
<tr>
<td>Strawberries</td>
<td>36-52</td>
</tr>
</tbody>
</table>

The rate of deterioration is proportional to the respiration rate of the produce (Kader, 2002). Horticultural crops are classified based on their respiration rates (Kader, 2002) ranging between very low (<5 mg CO₂·kg⁻¹·hr⁻¹) such as dates, dried fruits and vegetables; and extremely high (>60 mg CO₂·kg⁻¹·hr⁻¹) including sweet corn, asparagus and mushroom. Several factors influence the produce respiration rate such as temperature, commodity and genotype, maturity, climacteric behaviour, and chemical composition of the atmosphere (O₂, CO₂, ethylene, etc.).

The respiration rate is temperature-dependent. For each 10°C reduction in temperature, the respiration rate could decrease by a factor of 2 to 5 (Singh and Chakraverty, 2001). The temperature coefficient (based on Van’t Hoff’s Law) for a 10°C interval is called the “Temperature Quotient of Respiration (Q₁₀)” (Ryall and Lipton, 1979), and can be obtained by determining the respiration rate at two different temperatures through:

$$Q_{10} = \frac{\text{respiration rate at (T + 10)}}{\text{respiration rate at T}}$$  \hspace{1cm} (3.2)

As the temperature of the produce increases, the rate of respiration increases while the Q₁₀ value decreases (Table 3.6).
Table 3.6 Effect of temperature on $Q_{10}$ and deterioration velocity of horticultural crops (Kader, 2002).

<table>
<thead>
<tr>
<th>Temperature ($^\circ$C)</th>
<th>Assumed $Q_{10}$</th>
<th>Relative velocity of deterioration</th>
<th>Relative shelf life</th>
<th>Loss per day (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>--</td>
<td>1.0</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>3.0</td>
<td>3.0</td>
<td>33</td>
<td>3</td>
</tr>
<tr>
<td>20</td>
<td>2.5</td>
<td>7.5</td>
<td>13</td>
<td>8</td>
</tr>
<tr>
<td>30</td>
<td>2.0</td>
<td>15.0</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>40</td>
<td>1.5</td>
<td>22.5</td>
<td>4</td>
<td>25</td>
</tr>
</tbody>
</table>

The nature of the respiration process depends largely on the type of substrate used. When the process of respiration completely oxidises carbohydrates, such as glucose, sucrose, or starch, the amount of CO$_2$ released will be equal to the amount of O$_2$ absorbed. If other substrates are used, or if there is incomplete oxidation, then the amount of O$_2$ consumed and the amount of CO$_2$ produced 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:

$$RQ = \frac{\text{CO}_2 \text{ produced (ml CO}_2 \cdot \text{kg}^{-1} \cdot \text{h}^{-1})}{\text{O}_2 \text{ consumed (ml O}_2 \cdot \text{kg}^{-1} \cdot \text{h}^{-1})}$$

(3.3)

During respiration, the commodity accelerates the use of its internal energy and water reserves causing losses in nutritive values and general appearance. Respiration process is highly affected by relative humidity (RH) (Golob et al., 2002) which is defined as the amount of water vapour in the air as a proportion of the amount of water vapour required to saturate the air at the same temperature. As the temperature falls, the relative humidity of air rises, slowing down respiration rate of the produce (Golob et al., 2002). Thus, controlling the respiration process by maintaining proper storage conditions such as low temperature and high relative humidity has become very essential to enhance the quality of fruits and vegetables at commercial level.
3.2.3 Transpiration

Transpiration is a process by which fresh produce controls its temperature by water evaporation (ASHRAE, 1998a). This process consists of the transport of moisture through the skin of the commodity, the evaporation of this moisture from the commodity surface producing cooling effect, and the convective mass transport of the moisture to the surroundings (Becker and Fricke, 1996). According to Kader (2002), transpiration results in direct losses in mass and appearance that cause wilting and eventually death of the produce, and losses in textural and nutritional quality.

Transpiration rate is influenced by external or environmental factors such as temperature, RH, air movement, and atmospheric pressure (Kader, 2002). Low air humidity encourages the diffusion of water vapour from the produce surface into the surrounding air. The transpiration rate is also dependent on internal factors such as the morphology and the anatomy of the commodity, surface to volume ratio and maturity stage (Kader, 2002).

The transpiration is basically a process with water mass transfer throughout the surface of the produce and it can be determined by the difference in water vapour pressure between the surface of a commodity and the surrounding air (ASHRAE 1998a). It is based on the following equation:

\[
m_t = k_t \left( p_s - p_a \right)
\]

where,

\[
\begin{align*}
    m_t &= \text{Transpiration rate (g·m}^{-2}·\text{s}^{-1}) \\
k_t &= \text{Transpiration coefficient (g·m}^{-2}·\text{Pa}^{-1}·\text{s}^{-1}) \\
p_s &= \text{Water vapour pressure at surface (Pa)} \\
p_a &= \text{Water vapour pressure in the air (Pa)}
\end{align*}
\]

The transpiration process represents an economic loss through the loss of water from the produce which results in a decrease of its saleable mass and quality due to wilting and shrivelling. Consequently, techniques must be considered to control transpiration losses such as maintaining higher relative humidity, controlling air...
circulation, protecting against physical injuries, regulating moisture loss through waxing or other produce surface coatings and wrapping with plastic films.

3.2.4 Ethylene

Ethylene (C$_2$H$_4$), a plant product of natural metabolism, largely affects physiological processes of the plant tissue when released. In fruits, C$_2$H$_4$ is the hormone that regulates many aspects in the life cycle including growth, development, and senescence (Kader, 2002). It is physiologically active in trace amount (less than 0.1 ppm).

Ethylene generation is responsible for ripening of the fruit including changes in the green colour due to loss of chlorophyll, and browning of tissues due to changes in the anthocyanin and phenolic compounds (Singh and Chakraverty, 2001). When fruit starts to ripen, it will generate more ethylene causing senescence to begin in other produces. Usually the ethylene production rate increases after harvesting leading to physiological injuries, or disease occurrence at high temperatures (up to 30$^\circ$C) (Kader, 2002). However, C$_2$H$_4$ effect can be slowed down by lowering the temperature of storage, reducing the O$_2$ (< 8%) and/or increasing the CO$_2$ levels (>2%) surrounding the produce (Kader, 2002).

3.3 Sweet Corn

Corn ranks among the most essential crops in the world agricultural economy. It is recognized as the most efficient converter of the sun’s energy into food. The United States is the largest corn-producing country, followed by China, Brazil, Russia, Mexico, and India (Food Encyclopedia, 1996). Sweet corn has a sweeter taste than other corns since the endosperm contains sugar and starch as well (Salunkhe, 1984c). The precise origin of sweet corn cannot be identified; although, sweet corn was grown by the American Indian and first collected by European settlers in the 1770's. The first variety, Papoon, was brought from the Iroquois Indians in 1779 (Schultheis, 1998). However, modern sugary normal (su) sweet corn cultivars are of relatively recent origin, they were released in the 19$^{th}$ century (Peet, 1995).
In Canada, sweet corn represents a value of 10% of the total grain-corn production (Agriculture & Agri-Food Canada, 2004). It is one of the major field grown vegetable crops in Canada, with a farm gate value of $31 million in 2001 (Statistic Canada, 2001). Annual Canadian sweet corn production ranges between 250,000 to 300,000 metric tonnes (Agriculture & Agri-Food Canada, 2004). It is grown on over 30,000 hectares of land, making it the most extensively planted vegetable in Canada (Agriculture & Agri-Food Canada, 2004). It is cultivated in every province in Canada, with 80% being concentrated in Quebec and Ontario (Munro and Small, 1997). Thus, in 2001, the cultivated surface area of sweet corn in Quebec, mainly in the region of Montérégie, was shown to be roughly at 11 175 ha (OAQ, 2004).

Canada is a major exporter of processed sweet corn for both canned and frozen markets. In 2003, Canada ranked fourth worldwide in exports behind Hungary, Thailand and the United States of America. More than 90% of American frozen sweet corn imports and over 50% of its imported canned corn come from Canada.

3.3.1 Botany and cultivars

Sweet corn or *Zea mays* L. spp. rugosa (or saccharata) belongs to the grass family Gramineae (Poaceae) which represents the majority of food plants in the world. Sweet corn is well-known for its high sugar content in the kernels at the early "dough" stage, and wrinkled, translucent kernels when dry (Magness et al., 1971).

The plant is a single stemmed annual, grown from one seed (monocotyledon); the plant has drooping leaves and bears both male and female flowers (monoecious) (Food Encyclopedia, 1996). Each ear contains numerous silks that stick out from the top of the husk and through which pollination occurs. Corn cobs are classified in yellow, white or bicolor depending on the cultivar.

While sweet corn grows best in a warm weather requiring at least eight hours of direct sunlight daily, it can adapt to a wide range of climates such as in the cooler parts of North America. Cultivars are generally grouped into three main classes: early, medium, and late depending on the time of their edible maturity (Salunkhe, 1984c). Due to many years of research and development of new technologies, recently sweet corn breeders have introduced new genes into the market which are sweeter in taste and much more
resistant to climatic changes and diseases in order to extend their shelf life and eating quality.

Based on the nature of kernel sugar amount and the conversion rate of sugar to starch, sweet corn can also be classified into four basic groups: standard or sugary normal (\textit{su}), sugary enhanced (\textit{se}), supersweet hybrids (\textit{sh2}), and improved supersweet hybrids also known as Sweetie class (Munro and Small, 1997):

1. *Sugary normal (su)* is the most common corn grown for fresh consumption. It stops the conversion of sugar to starch after harvest.

2. *Sugary enhanced (se)* is characterised by a slight increase in sugar level mainly maltose and a slower conversion of sugar to starch after harvest. This corn type has very tender kernels which is highly desirable for consumers but not favourable for mechanical harvesting.

3. *Supersweet or shrunken-2 (sh2)* produces kernels with two to three times the sugar content of the standard corn varieties (\textit{su}) and inhibits the conversion of sugar to starch right after harvest. Texture is relatively crispy than creamy as with the normal and sugary enhanced genes. They have longer shelf life due to their higher capacity of retaining moisture and sweetness inside their kernels. They are mainly destined for canning and freezing.

3.3.2 Harvesting and handling

The most common method of harvesting sweet corn involves pulling the ears by hand. Sweet corn is then transported by a truck to a packing house where it is graded and packed (Ryall and Lipton, 1979). Beside this method, more sophisticated ways using high-tech mechanical harvesters have been introduced to the market which cut the stalks near the ground, remove the ears, and transmit them to a bin attached to the harvester (Ryall and Lipton, 1979).

Sweet corn harvest requires very careful supervision that can avoid some problems during postharvest processes (Boyette et al., 1990). Proper maturity of a corn cob occurs when sugar changes to starch, the hull becomes tougher, and the kernels pass through stages called pre-milk, milk, early dough, and dough. Corn will be ready for harvest at the milk stage, i.e., as soon as the kernels are fully developed and give out a
milky liquid when squeezed (Schultheis, 1998). Other harvest indices can be considered when the silks have just turned brown and dry or approximately 18 to 22 days after the first silks appear (Peet, 1995). Whether harvested by hand or mechanically, sweet corn should be collected early in the morning when its temperature is low in order to reduce cooling loads and to consume energy (Boyette et al., 1990).

Correct postharvest handling of sweet corn is necessary to maintain good quality in today’s market (Herber, 1991). Every effort should be made to cool down sweet corn immediately after harvest to retard its deterioration. However, proper temperature management is very critical to ensure better quality and longer shelf life of this produce.

The technology for production and handling sweet corn for international markets is very particular and varies from those practices required for handling when this vegetable is proposed for home use or distributed through national markets; therefore, handling needs depend upon the market destination (Sargent, 1999).

3.3.3 Cooling and storage

Sweet corn or any other fresh horticultural commodity is a living organism and remains alive even after harvesting (Talbot et al., 1991). The taste and quality of sweet corn depends largely on its sugar content, which rapidly decreases after picking if not maintained at lower temperature (Boyette et al., 1990). Studies on sweet corn have showed that 60% of its sugar can be lost in 24 hours if kept at 30°C; this rate is four times less at 0°C (Herber, 1991). To maintain its best quality, this vegetable must be cooled down to as near 0°C immediately after harvest and keep it refrigerated until it reaches the consumer. The delay between harvest and cooling is of critical importance, since sucrose, the compound primarily responsible for its sweetness, changes dramatically to starch (Salunkhe, 1984c).

Despite the limited storage life of sweet corn (Table 3.7) which is not a chilling-sensitive crop; yet, it can be stored at 0°C and 90-98% RH for maximum of 6 to 8 days with a satisfactory quality (Hardenburg et al., 1986; Sargent et al., 1988). Sweet corn is compatibly stored with vegetables such as carrot, endive, green, lettuce, and spinach. It should not be stored with commodities that produce ethylene, such as muskmelons and tomatoes (Sargent, 1999).
Table 3.7 Classification of fresh commodities based on their relative perishability and potential storage life at optimal temperature and RH (Kader, 2002).

<table>
<thead>
<tr>
<th>Relative perishability</th>
<th>Potential storage life (weeks)</th>
<th>Commodities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very high</td>
<td>&lt;2</td>
<td>Sweet corn, apricot, broccoli, asparagus, strawberry, cantaloupe</td>
</tr>
<tr>
<td>High</td>
<td>2-4</td>
<td>Avocado, banana, mango, cabbage, papaya, head lettuce, artichoke</td>
</tr>
<tr>
<td>Moderate</td>
<td>4-8</td>
<td>Apple, orange, grapefruit, carrot, radish, potato (immature), table beet</td>
</tr>
<tr>
<td>Low</td>
<td>8-16</td>
<td>Lemon, sweet potato, dry onion, garlic, taro, yam</td>
</tr>
<tr>
<td>Very low</td>
<td>&gt;16</td>
<td>Tree nuts, dried fruits and vegetables</td>
</tr>
</tbody>
</table>

3.4 Quality Evaluation of Sweet Corn

Sargent et al. (1988) define quality for fruits and vegetables as those characteristics which consumers relate with. Depending upon the particular end-use, these criteria could include sweetness, tenderness, crispness and freedom from any injuries and disorders.

Quality is an important factor in the production and marketing of horticultural products (Bakker-Arkema, 1999). Producers are looking for good cultivar with high yield and low disease susceptibility. For wholesalers, good handling attributes and long storage life are important quality parameters. Consumers are more and more demanding in terms of food quality and safety, leading the producers towards higher standards in the production of fresh fruits and vegetables. Consumers are looking at several quality parameters such as good external appearance, firmness, and high quality flavour and nutritive value before making the decision to purchase (Kader, 2002).

High quality sweet corn should have uniform size and color, hold fresh husks with sweet, milky and well-developed kernels and be free from any entomological defects or mechanical injuries (Sargent, 1999).

When evaluating the quality, several methods can play an important role, but the only accurate test of quality is the feedback of the consumer (Bakker-Arkema, 1999).
Quantitative and qualitative attributes must be well described in order to determine the best quality conditions and to establish the storage length for sweet corn.

3.4.1 Qualitative attributes

Visual appearance of fruits and vegetables refers to physical characteristics such as shape, form, size, color, and defects (Kader, 2002). The qualitative factors play a dominant role in the selection of the commodity. According to the Canadian Food Inspection Agency (CFIA) (1999):

“Canada No.1 sweet corn must have at least 4 inches of edible kernels and not more than one quarter of the cob may have under-developed or undeveloped kernel. High grade sweet corn must also have a husk with dark green color and moist to light greenish yellow and fairly moist, but not beige, wilted or dried out”.

The appearance of sweet corn is determined by the size and the uniformity in shape of the cob (Figure 3.2). The ear must be free from distortion or underdevelopment.

![Schematic diagram of different corn parts.](image)

**Figure 3.2** Schematic diagram of different corn parts.

Further, the appearance is influenced by the color of the cob and mainly the husk that is covering it. The color of plant tissues are due to the presence of pigments such as chlorophylls (green) and flavonoids (yellow) (Clydesdale and Francis, 1976) which undergo significant modifications during storage.
Besides, many defects influence the appearance quality of the corn cob. They include damages on the external parts such as husks, shank, blades, and external silks and on the internal side like kernels and internal silks. The defects can be morphological due to malformation or underdevelopment of kernels. Pathological and entomological defects including fungi or bacteria and insects respectively cause serious problems inside the kernels (Kader, 2002). Mechanical defects consist of crushing, punctures and abrasion.

Measurement or evaluation of those parameters during storage of the produce sounds like a simple technique. However, it is much more complicated due to large variation between different corn cobs and different cultivars. Qualitative evaluation is usually based on scale charts composed of several rating.

3.4.2 Quantitative attributes

Other important factors for sweet corn are to look deeply inside kernels and see what happens at molecular level. Quantitative attributes including water content, mass loss and total soluble solids (TSS) percent can play a fundamental role in customer choice (Kader, 2002).

Water is the most abundant component in a plant cell. These cells can suck water from outside through the cell wall which gives the desirable crispness, firmness and turgidity for the crop tissue (Martens and Baordseth, 1987). For sweet corn, juiciness and succulence are important quality components to consider during storage (Kader, 2002). The water or moisture content (MC) is expressed by the mass of water in a produce as a proportion of its total mass (Eq. 3.5) (Golob et al., 2002). The determination of water content parameter in sweet corn is very essential to indicate the freshness and turgididity of the produce. Thus, high water content keeps high its juiciness and nutritive value.

\[
MC \text{ (wet basis)} = \frac{\text{mass of water in sample}}{\text{wet sample mass}} \times 100\% \quad (3.5)
\]

Other important quantitative parameter to consider is the mass loss that takes place by evaporating water from the surface of the produce during storage caused by transpiration process as discussed in detail in section 3.2.3. As cited earlier, sweet corn is like all other vegetables, it continues to lose water after harvest. The symptoms of water
or mass loss become undesirable when the produce has lost around 2% of its initial mass (Sargent, 1999). Mass loss is irreversible in sweet corn and may cause husk wilting and shrivelling, and kernel denting (Singh and Chakraverty, 2001); thus, high percent lost can change the overall mass of a commodity and result in economical and financial problems.

The sweetness of sweet corn is due to sucrose and other sugars present in the juice (Harrill, 1994). Total soluble solids in a plant organism are primarily sugars; sucrose, fructose, and glucose. Brix readings are a widespread measure of the concentration of soluble solids in a liquid sample. However, degree Brix or Refractive Index (RI) is a common method to measure the percentage sucrose using a small device known as refractometer. Harrill (1994) has shown in his book several charts known as “Reams’ composite chart” correlating the relation of total soluble solids to quality. Refractive index of crop juices are given for a wide range of horticultural commodities based on four quality scales starting from poor to excellent.

For fresh sweet corn, the kernel carbohydrate composition decreases rapidly after harvest if left under field temperature resulting in unfavourable modification to kernel texture, flavour and consumer satisfaction (Olsen et al., 1990). By lowering the temperature immediately after harvest, the conversion of sugar to starch will gradually slow down. Therefore, sugar retention of the produce during postharvest storage is essential to maintain high quality produce with competitive prices.

3.5 Precooling Concepts and Methods

Fruits and vegetables possess heat after harvest known as field heat. This heat is enclosed inside the produce at harvest and represents thermal energy coming from the environment nearby the mother plant. To maintain maximum storage duration of a produce, it is desirable to remove this field heat as quickly as possible after harvesting (Kays, 1997).

During the period between harvest and consumption, temperature management has been found to be a significant parameter to maintain better quality of perishable horticultural crops. By reducing the temperature of the produce to the lowest possible safe temperature (above freezing), the storage life can be maximised by retaining its saleable quality (Golob et al., 2002). Temperature management after harvest is thus of
critical importance and it can be separated into two processes: (1) the removal of field heat, carrying the produce down to the required storage temperature, and (2) the preservation of that temperature by the continued removal of respiratory heat and heat coming from the storage environment such as heat conducted through the walls and floor (Kays, 1997).

Precooling consists of rapid decrease of the produce’s temperature promptly and immediately after harvest (Thompson, 2003). It permits to increase the shelf life of the produce by slowing down respiration rate, diminishing water losses due to transpiration, inhibiting pathogens (fungi, bacteria) development and retarding the process of senescence and decay (Thompson, 2003; Mohsenin, 1980). Moreover, precooling can avoid mixed load of products of different temperatures, accelerate handling process and decrease cooling load of refrigerated room.

The selection of a precooling method is based on several parameters including the rate of cooling, the nature of the commodity to be cooled, further storage and shipping conditions, and the equipment, labour, and operating costs (Golob et al., 2002; Sargent et al., 1988). An efficient heat removal rate is dependent upon four factors: (1) the duration of cooling, ensuring high cooling rate of the cooler, (2) the temperature of the cooling medium, maintaining constant temperature during the cooling process, (3) the degree of contact of the cooling medium with the produce, providing intimate contact between the medium and the crop surface (Sargent et al., 1988; Sargent, 1990), and (4) the uniformity in the distribution of the cooling medium through the whole mass of produce (Vigneault and Goyette, 2002).

Harvesting should be done in early morning to minimize field heat and the refrigeration load of the produce. Precooling process is widely used for a large number of perishable crops and is accomplished using several techniques including room cooling, forced-air cooling, hydrocooling, ice cooling, and vacuum cooling.

3.5.1 Room cooling

Room cooling is not a true precooling method and known as the simplest and widely used refrigeration technique for fruits and vegetables (Raghavan et al., 2004). It simply involves placing the warm crop in a refrigerated room for several hours or days
It is best designed for products that have low respiration rate and can tolerate slow heat removal with a relatively long storage life after being cooled in the same cold chamber such as potatoes, citrus fruits, apples, and pears (Raghavan et al., 1996; Kader, 2002).

In this type of cooling systems (Figure 3.3), cold air coming from a fan is blown across the ceiling of the room and sweeps the produce containers when returning to the evaporator (Thompson, 2003; Raghavan et al., 2004). For efficient cooling rate, a total air flow of at least 0.005 L·s⁻¹·kg⁻¹ of produce storage capacity is required (Kader, 2002).

The main advantage of room cooling is that the produce can be cooled and stored in the same place resulting in less handling requirements (Kays, 1997). This cooling technique requires low equipment and labour costs; whereas, primarily disadvantages include slow rate of cooling and high moisture loss from the commodity (Kader, 2002).

![Schematic diagram of the air pathway in room cooling (Rennie, 1999).](image)

**Figure 3.3** Schematic diagram of the air pathway in room cooling (Rennie, 1999).

### 3.5.2 Forced-air cooling

Forced-air cooling is a common method used for a wide range of horticultural crops (Kader, 2002). It differs from room cooling in that the cold air is pulled through the individual container rather than around the container resulting in a faster rate of heat...
removal and reducing cooling time to one quarter to one tenth that of room cooling (Kays, 1997).

This method consists of convective heat transfer occurring between the produce and the air (Singh and Chakraverty, 2001). When the cold air touches the commodity, heat is removed out, increasing the temperature of the air and reducing the temperature of the produce. Critical components for forced-air cooling are sufficient refrigeration capacity, air velocity and air distribution uniformity (Castro et al., 2004/2005). According to Fraser (1991), an adequate ventilation system must circulate the air between 0.5 to 3 L·s⁻¹·kg⁻¹ of produce. Greater air flow rates increase the static pressure required, increasing the energy consumption of the fan and shortening the cooling time of the produce (Vigneault and Goyette, 2002). A simple method to measure the air velocity at a point in a flow field is the application of the Pitot tube used in conjunction with a pressure transducer (ASHRAE, 2001). The Pitot tube allows calculating the velocity by measuring the dynamic and static pressures of the air flowing parallel to the tube using the equation 3.6.

\[
v = \sqrt{\frac{2p_w}{\rho}} \quad (3.6)
\]

where,

\(v\) = Velocity of air (m·s\(^{-1}\))

\(p_w\) = Dynamic pressure (Pa)

\(\rho\) = Density of air (kg·m\(^{-3}\))

There are three commonly used forced-air cooling systems: cold wall cooling, serpentine cooling, and forced-air tunnel cooling (Singh and Chakraverty, 2001).

In forced-air tunnel cooling, two rows of palletised containers are placed so that a tunnel (plenum) exists between them (Figure 3.4). A fan is placed at one end of the tunnel creating a negative static pressure in the plenum. Pulling the air through the containers is more effective than pushing the air through (Kader, 2002).
Cold wall system involves the use of a permanent constructed air plenum located inside a cold room and connected to a fan (Figure 3.5). Palletized containers are positioned against the wall and the cold air from the room is pulled through the pallets reducing the temperature of the produce (Kays, 1997). The main advantage of this cooling method is that the container starts to cool down individually right after it is positioned without waiting for other container to complete an air tunnel (Kader, 2002).
The third type of forced-air cooling is known as the serpentine cooling system (Figure 3.6). It is typically used for produce that are packed in bins using a bottom vent inside the container (Singh and Chakraverty, 2001). Modification of the cold wall system is required so that the forklift openings at the base of the pallet are used as air supply and return plenum (Kader, 2002). By blocking the back of those openings, the cold air circulates vertically through the produce in each bin creating a pressure difference between plenums (Kader, 2002). The return air plenum openings are closed from the room side and kept open at the cold wall part (Kays, 1997). The air is then directed through the produce in a serpentine behaviour (Singh and Chakraverty, 2001). The cooling rate of this method is generally slower than tunnel-type coolers; however, serpentine cooling requires no space between rows of bins, desirable for applying large volume of produce at the same time (Kader, 2002).

**Figure 3.6** Schematic diagram of a serpentine cooling system (Rennie, 1999).
3.5.3 Hydrocooling

As its name reveals, this cooling method requires water as a medium for cooling of fruits and vegetables. Studies have shown that cold water can be an effective way for quick cooling of a wide range of horticultural commodities (Kader, 2002) and this is due to much higher surface heat transfer coefficient of water than air (ASHRAE, 1998d). Hydrocooling can thus be very quick and come out in no loss of mass of the crop during the precooling process (Thompson, 2003). Adequate hydrocooling involves intimate contact between the produce surface and cold water for rapid heat removal (Golob et al., 2002). The cooling water must be kept as cold as possible avoiding chilling damages to the plant tissue (Kays, 1997). It is best maintained at 0°C for non chilling-sensitive products; however it should be higher for chill-sensitive commodities (Kader, 2002).

Cooling with water is best applied for many stem and leafy vegetables and some fruits such as peaches, melons and cantaloupes. Additionally, it can be utilized successfully for sweet corn, celery, radishes, and carrots; whereas, hydrocooling is not recommended for citrus, grapes, and berry fruits (ASHRAE, 1998d). The produce cooled by water must have a high resistance to wetting, low vulnerability to physical wounds caused by water on their surface and low susceptibility to damages by chemicals (chlorine) used to sanitize the water from any spoiled organisms that might occur while cooling the produce (Kays, 1997).

The basic principle of this cooling method is that the cold water coming from the evaporator coils gets into direct contact with the surface of the warm produce reducing its temperature to that of the water. Hydrocoolers are separated in two different techniques: (1) showering or spraying the water down through the produce, and (2) submerging the commodity into cold water (Kays, 1997).

With a shower-type hydrocooler, cold water is pumped to a perforated pan situated above the produce container as shown in Figure 3.7. The water circulates through the mass of commodity which can be packaged in a box or bin or left on a conveyor belt (Kader, 2002). The outgoing warm water circulates through the evaporator coils located under the conveyor, being cooled down again and pumped into the overhead perforated pan.
The immersion hydrocooler type consists of a complete immersion of the warm commodity into the cold water. In this system, the produce moves through a cold water bath by a conveyor and lifted up out of the water at the end by an inclined conveyor (Figure 3.8). It is best applied for those products with higher density than water to prevent floating. 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).

Figure 3.7 Schematic diagram of a shower-type hydrocooler (Rennie, 1999).

Figure 3.8 Schematic diagram of an immersed water cooler.
In hydrocooling, adequate water flow around or over the produce surface must be considered. For produce in bins or boxes, water flows of 13.6 to 17.0 L·s⁻¹·m⁻² of surface area are generally suggested. On other hand, produce packed in shallow layers necessitate flows of 4.75 to 6.80 L·s⁻¹·m⁻² (Kader, 2002). In most cases, water is cooled by mechanical refrigeration, but ice could also be used.

One of the main limitations of this method is that water treatment is obligatory in order to prevent decay organisms present on fruits and vegetables from proliferating and causing serious damages to the precooled crop (Sargent et al., 1988). Chlorination is thus very essential to clean up cooling medium; hence it is achieved by adding 100 to 150 ppm chlorine or other sanitizing chemicals including sodium or calcium hypochlorite (Singh and Chakraverty, 2001). Hydrocooling requires additional maintenance such as cleaning the perforated pan at a regular basis to avoid plugging of holes from plant debris and the bottom water reservoir to eliminate debris accumulation. Placing the cooled produce immediately in a cold room before re-warming takes place is also mandatory (Kader, 2002). Finally, packaging material must be tolerant to wetting, easy to handle and designed for adequate water circulation (Vigneault et al., 2004a).

3.5.4 Ice cooling

Since ancient times, ice has been used to cool down the crops after harvest and to maintain the temperature low during shipping (Golob et al., 2002). It is simply adding crushed ice inside the produce container. The ice takes out the heat from the commodity, causing it to melt while ensuring high relative humidity surrounding the produce (Sargent et al., 1988). This method is suitable for produce that can tolerate the contact with ice and water (0°C) (e.g. broccoli, green onion, some root and stem vegetables) and not recommended for chill-sensitive crops (Kays, 1997). Liquid ice or slurry of ice (ice and water) can enhance produce cooling by filling all of the void volume of the container. Ice cooling is considered as a fairly quick and simple method since it can be done directly in the field and within few minutes (Kader, 2002). There are two different types of ice cooling: top icing and package icing.

Top icing involves the application of finely crushed ice over the produce packed in a container before closing it. Although this method is comparatively cheap, the cooling
rate of the commodity is fairly slow since the heat removal will be maximised only for the commodity forming the top layer in the container.

Besides, package icing consists of reasonably homogenous distribution of ice inside the container and between the produce (Golob et al., 2002). The cooling medium can be made of a mixture of crushed or flaked ice and water. Package icing requires specific container design and material (Vigneault and Goyette, 2001). Its cooling rate is considered faster and more uniform compared to top icing, hence it is best applied to cantaloupe, carrot with leaves and broccoli.

Primary limitation of cooling with ice is that mass is added (up to 35-40%) to the container causing some problems for handling and shipping (Kays, 1997). Packaging material must withstand the wet conditions and should contain enough holes to drain out remaining water (Kader, 2002).

3.5.5 Vacuum cooling

Vacuum cooling is known as a very rapid and uniform method for cooling fruits and vegetables; since, produce can be cooled down within 20 to 30 minutes. It consists of rapid evaporation of water from the produce at very low atmospheric pressure using the latent heat of vaporization rather than conduction (Thompson, 2003). Basic components are a strong vacuum chamber, a powerful vacuum device, and an efficient condenser. Cooling under vacuum is more efficient for high surface to mass ratio commodities such as leafy vegetables (e.g. lettuce, cabbage) and in some cases sweet corn, celery and mushrooms (Golob et al., 2002).

The principle behind this type of cooling is based on that the pressure inside the vacuum chamber (Figure 3.9) is dropped down to saturation point equivalent to the lowest required temperature of the water (ASHRAE, 1998d). By reducing the pressure, the boiling point of water will be reduced so that the water from the surface of the substance can boil at 0°C, which corresponds to an ambient absolute pressure of 4.6 mmHg (Kays, 1997). As water boils, field heat is quickly removed from the produce and water vapour condenses on refrigerated coils situated on the outlet from the vacuum chamber to the pump (Kader, 2002). Barger (1961) has found that since vacuum cooling involves the evaporation of water content, every 5 or 6°C reduction in temperature results
in a mass loss of 1% of the produce’s mass. In some cases, a shower of water is practised prior to cooling in order to reduce produce water loss and to increase the uniformity of the cooling process. These coolers are well known as “hydrovac” coolers. Most operators do not reduce the pressure below the freezing temperature of water (0°C) to avoid freezing injuries of the produce (ASHRAE, 1998d).

**Figure 3.9** Schematic diagram of a vacuum cooler (Rennie, 1999).

Heat removed \((Q)\) from the produce is determined (Eq. 3.7) by the mass of water vaporized \((m_v)\) and its latent heat of vaporization \((L)\) (ASHRAE, 1998d).

\[
m_v = \frac{Q}{L}
\]  

(3.7)

where,

\[m_v\] = Water vaporised (kg water·kg\(^{-1}\) produce)  
\[Q\] = Heat produced (kJ·kg\(^{-1}\) produce)  
\[L\] = Latent heat of vaporisation of water (kJ·kg\(^{-1}\) water)  

The total moisture generated during the vacuum cooling process is directly related to the specific heat of the produce and the temperature reduction achieved (Table 3.8).
Table 3.8 Specific heat of some vacuum precooled vegetables (ASHRAE, 1998a).

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Specific Heat, kJ·kg⁻¹·K⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artichoke</td>
<td>3.64</td>
</tr>
<tr>
<td>Asparagus</td>
<td>3.94</td>
</tr>
<tr>
<td>Broccoli</td>
<td>3.85</td>
</tr>
<tr>
<td>Brussels sprout</td>
<td>3.68</td>
</tr>
<tr>
<td>Cabbage</td>
<td>3.94</td>
</tr>
<tr>
<td>Cauliflower</td>
<td>3.89</td>
</tr>
<tr>
<td>Celery</td>
<td>3.98</td>
</tr>
<tr>
<td>Endive</td>
<td>3.94</td>
</tr>
<tr>
<td>Leek</td>
<td>3.98</td>
</tr>
<tr>
<td>Lettuce, iceberg</td>
<td>4.02</td>
</tr>
<tr>
<td>Mushroom</td>
<td>3.89</td>
</tr>
<tr>
<td>Parsley</td>
<td>3.62</td>
</tr>
<tr>
<td>Peppers, sweet, green</td>
<td>3.94</td>
</tr>
<tr>
<td>Snap Bean</td>
<td>3.94</td>
</tr>
<tr>
<td>Spinach</td>
<td>3.94</td>
</tr>
<tr>
<td>Sweet Corn</td>
<td>3.32</td>
</tr>
</tbody>
</table>

Vacuum cooling is considered as the most rapid compared to other cooling methods. However, it requires very expensive equipments and highly skilled operators. It should be used for large volume industries or shared between growers.

3.6 Precooling performance evaluation

The effect of temperature on the behaviour of freshly harvested fruits and vegetables is a question of plant physiology, but a good knowledge of engineering features remains fundamental for an efficient precooling process (Guillou, 1958).

3.6.1 Heat transfer concepts

Heat flows from a warmer substance to a cooler substance. Therefore, to remove heat, it must either be absorbed or transferred to a cooler substance (Kays, 1997). In the case of fruits and vegetables, precooling is a heat transfer process which requires the removal of field heat, or the sensible heat (heat required to be removed to bring down the produce temperature existed at harvest to the level maintained at storage), to achieve maximum storage life of the commodities. Usually, heat can be transferred from one
body to its surroundings by three different modes: convection, conduction, and radiation (Mohsenin, 1980).

According to Newton’s and Fourier’s laws of cooling, heat transfer between an horticultural produce and its environment is classified into three conditions based on the dimensionless Biot number (Mohsenin, 1980):

\[ B_i = \frac{h r}{k} \]  \quad (3.8)

where,

- \( B_i \) = Biot number
- \( h \) = Convection heat transfer coefficient (J·m\(^{-2}\)·oC\(^{-1}\)·s\(^{-1}\))
- \( r \) = Characteristic dimension (m)
- \( k \) = Thermal conductivity (J·m\(^{-1}\)·oC\(^{-1}\)·s\(^{-1}\))

When the Biot number is less than 0.1, the lumped-parameter approach will be used (ASHRAE, 1998b; Singh and Heldman, 2001). In this case, the internal resistance to heat transfer is extremely small compared to the external resistance and the thermal conductivity inside the produce is large enough to liberate easily the heat through it. Therefore, the temperature is considered to be uniform throughout the interior of the produce (Mohsenin, 1980). According to the same author, Newton’s law of cooling may be applied to determine cooling parameters and it is described as a temperature ratio as:

\[
\frac{T_p - T_a}{T_i - T_a} = e^{-\left(\frac{hA}{\rho c_p V}\right)t} \quad (3.9)
\]

where,

- \( T_p \) = Produce temperature (°C)
- \( T_a \) = Cooling medium temperature (°C)
- \( T_i \) = Initial produce temperature (°C)
\[ A = \text{Produce surface area (m}^2\text{)} \]
\[ \rho = \text{Produce density (kg·m}^{-3}\text{)} \]
\[ c_P = \text{Produce specific heat (J·kg}^{-1}·\text{°C}^{-1}\text{)} \]
\[ V = \text{Produce volume (m}^3\text{)} \]
\[ t = \text{Time (s)} \]

When \( \text{Bi} > 40 \), the internal resistance to heat transfer is greater than the external resistance and the temperature of the object surface and the cooling medium become equal (Mohsenin, 1980; ASHRAE, 1998b) which means that there is a temperature gradient from the surface to the centre of the cooling object (in case of fruits and vegetables). In this situation, Fourier’s law of cooling is available for different geometric shapes and it can be expressed by equation 3.10. In this case, the heat transfer phenomena is independent from “\( h \)”. 

\[
\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{q_g}{k} = \frac{\rho c_P}{k} \frac{\partial T}{\partial \theta} 
\]

(3.10)

where,
\[ x, y, z = \text{Cartesian co-ordinates (m)} \]
\[ q_g = \text{Heat generation rate (J·s}^{-1}·\text{m}^3\text{)} \]
\[ \theta = \text{Time (s)} \]

For \( 0.1 < \text{Bi} < 40 \), both the internal and external resistance to heat transfer should be considered (ASHRAE, 1998b). In this case, the temperature ratio is a function of the Biot number and the Fourier number (Fo) (Singh and Heldman, 2001):

\[
Fo = \frac{k \theta}{\rho c_P S_O} 
\]

(3.11)

Temperature-time charts were developed for the three geometric shapes such as sphere, infinite cylinder, and infinite slab. These charts known as Heisler charts are based on the temperature ratio, Fourier’s number, and the Biot number (Singh and Heldman,
Moreover, cooling parameters for finite cylinder can be determined by a combination of an infinite slab and an infinite cylinder (Singh and Heldman, 2001).

3.6.2 Cooling rate and cooling time

The actual rate of temperature reduction varies widely with the cooling method and its conditions (Kays, 1997). Therefore, cooling rate depends on several factors including the difference in temperature between the crop and the cooling medium, the flow rate of cooling medium (water, air, vacuum), thermal properties and physical dimensions of the commodity (Dinçer, 1997).

Newton’s law of cooling can be used to determine cooling rate of a vegetable commodity. For this reason, some of the parameters can be calculated such as cooling coefficient (CC) which is expressed as (Mohsenin, 1980):

\[ CC = \frac{hA}{\rho c_p V} \]  

Cooling coefficient is an indication of the cooling ability of the produce during cooling process; it indicates the modification in the commodity temperature per unit of time (Dinçer, 1997). Graphically, CC is the slope of the plot between the logarithm of the temperature ratio versus time (Guillou, 1958). Some other methods for calculating the cooling coefficient can be found in the literature (Gariépy et al., 1987; Goyette et al., 1996).

One important parameter to measure for evaluating the precooling performance is the length of time a produce can take to achieve commercially acceptable cooling process. This time is well referred to as half-cooling time (HCT). According to Mohsenin (1980), half-cooling time is “the time at which the average temperature difference between the commodity and its surrounding becomes one-half of the initial temperature difference”. It can be determined by the equation 3.13:

\[ HCT = \frac{\ln(0.5)}{CC} \]  

35
As cooling starts, the initial temperature drop is rapid, although during subsequent cooling times or half-cooling periods, this rate slows down (Figure 3.10). HCT is independent of the initial produce temperature and remains constant during the cooling process (Kays, 1997).

![Diagram of cooling process](image)

**Figure 3.10** Various HCT required to cool down the warm horticultural commodity.

To achieve commercial cooling of fruits and vegetables, three half-cooling times or seven-eighth cooling should be attained (Singh and Chakraverty, 2001). It can be determined through:

\[
\text{Temperature}_{7/8\text{cooling}} = T_i - \frac{7}{8} (T_i - T_a)
\]

(3.14)

where,

- \(T_i\) = Initial produce temperature (°C)
- \(T_a\) = Cooling medium temperature (°C)
In addition, instantaneous cooling rate \( CR_{\text{ins}} \) can be calculated at any given time by the following equation (Singh and Chakraverty, 2001):

\[
CR_{\text{ins}} = \frac{2.08 \left( T_{\text{ins}} - T_a \right)}{T_{7/8}}
\]

(3.15)

where,

\( T_a \) = Cooling medium temperature (°C)

\( T_{\text{ins}} \) = Instantaneous produce temperature (°C)

\( T_{7/8} \) = Seven-eighth cooling time (s)

3.6.3 Mass-average temperature

Throughout precooling of fruits and vegetables, a precise knowledge of temperature distribution and behaviour inside the produce remains fundamental to determine the time of the cooling process. One useful measurement of the temperature is by inserting thermocouples at the geometric centre or the warmest point of the commodity. However, this technique provides information about one location inside the produce but not the overall temperature; thus, it can not be as accurate and representative since the temperature at all positions is not uniform. Therefore, some parts of the produce reach the desirable temperature before others.

“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, 1998d).

During the initial cooling period of fruits and vegetables, a relatively large temperature gradient occurs since the temperature profile is non-linear (Mohsenin, 1980). As the precooling progresses, this gradient diminishes to a certain limit resulting in an approximate uniform distribution of temperature at any point of the produce. For this reason, Smith and Bennett (1965) have developed a method to obtain meaningful and easy representation of the overall produce temperature. Known as mass-average
temperature during the transient cooling of horticultural commodities, this method indicates a single value from the temperature distribution that would become the uniform produce temperature under adiabatic conditions. This approach is useful to standardise temperature measurements and to use a temperature that is more representative of the product temperature.

3.6.4 Refrigeration load

Cooling load calculations can be used to determine the required capacity of refrigeration components. These calculations are also used to calculate total energy consumption of the horticultural industry (Bakker-Arkema, 1999). The refrigeration capacity necessary for precooling is larger than that needed for maintaining temperature in storage (ASHRAE, 1998d). In case of precooling, the field heat must be removed out from the crop while dropping down its temperature to the desirable level. However, during storage it is required to maintain constant the produce’s temperature. From an economical point of view, it is always fundamental to provide adequate amount of refrigeration for efficient precooling (ASHRAE, 1998d). The refrigeration system must remove all the heat inputs including heat conducted through facility’s walls, floor, and ceiling; heat produced by the commodity (for example: field and respiration heat); sensible and latent heat coming from air infiltration; heat from personnel and equipments such as fans, lights and pumps (Bakker-Arkema, 1999).

Field heat represents the largest load for precooling. The field heat load \( Q_f \) (Eq. 3.16) is a function of the mass of product to be cooled, the specific heat, and the temperature reduction.

\[
Q_f = mc_p \left( T_i - T_{ma} \right)
\]

where,

\[
Q_f = \text{Field heat load (kJ)}
\]

\[
M = \text{Mass of produce (kg)}
\]

\[
c_p = \text{Produce specific heat (kJ·kg}^{-1}·\text{°C}^{-1})
\]
\[ T_i = \text{Initial produce temperature (°C)} \]

\[ T_{ma} = \text{Mass-average temperature of produce (°C)} \]

\[ T_i - T_{ma} = \text{Temperature reduction (°C)} \]

Refrigeration load calculation is achieved to establish the appropriate size of the equipment required to supply the cooling, to effectively activate the system, and to estimate operating costs (ASHRAE, 1998c). Two main load calculation approaches are widely considered:

“(1) peak load calculation where all load sources are added together to determine the total load. In this method, the equipment is selected on the basis that all of the maximum load will occur at the same time to ensure that the design temperature will never be exceeded (ASHRAE, 1998c); (2) hour-by-hour calculation where the different sort of operation of refrigerated facilities must be accounted. However, the equipment may have insufficient capacity to handle changes in diversity from normal operation and product temperature may rise” (ASHRAE, 1998c).
IV. FORCED-AIR COOLING SYSTEM FOR ZEA MAYS

4.1 Introduction

Sweet corn or Zea mays L. spp. saccharata is recognized as an important horticultural crop in North America. After harvest, its metabolism continues to use its energy to maintain its essential living function. Due to its high perishability, an adequate control of the corn cob temperature remains essential to extend its quality life. Thus, sweet corn must be precooled, or cooled down quickly and immediately after harvesting, and maintained at low temperature to protect its quality and marketability (Boyette et al., 1990).

Precooling may be accomplished using several techniques including forced-air, water, liquid ice and vacuum (Kader, 2002). All these methods are widely used and the selection of the most appropriate one is based on several parameters including the rate of cooling, the nature of the commodity and the container, further storage and shipping conditions, and the capital and labour costs (Kader, 2002; Sargent et al., 1988). For example: vacuum cooling is best suited for leafy vegetables with high surface-to-mass ratio; and hydrocooling and liquid icing can not be used with high moisture sensitive container (Vigneault and Goyette, 2002) and produce (Kader, 2002).

Studies have shown that forced-air precooling can be adapted to a wide range of horticultural crops such as berries, citrus and cut flowers. Commercial forced-air is the most important precooling technology during horticultural crop postharvest process in North America (Kader, 2002). During forced-air cooling process, cold air is pulled through individual produce container rather than around container unit resulting in a faster heat removal and reducing cooling times to one quarter to one tenth that of room cooling (Kader, 2002; Edeogu et al., 1997). Forced-air precooling method is achieved by creating an air static pressure gradient and suctioning cold air through produce container resulting in heat removal from the commodity (Vigneault and Goyette, 2002; Talbot et al., 1992). Critical components for forced-air cooling are the refrigeration capacity and the air velocity. According to Fraser (1991), an adequate ventilation system must circulate at 0.5 to 3 L of air s\(^{-1}\)·kg\(^{-1}\) of produce. Greater air flow rate requires higher static pressure, increasing the total energy consumption (Castro et al., 2005).
The main disadvantages of this precooling method are excessive dehydration or, sometime, produce freezing injuries in case of poor precooler temperature control and heterogeneous air distribution or poor precooling management (Dinçer, 1997). If corn not transported immediately after precooled, forced-air cooling process should be followed by storage in a 0°C and 95% relative humidity room to maintain its good quality (Sargent, 1990). Several studies were done to optimize the performance of forced-air cooling for fruits and vegetables. Vigneault and Goyette (2002) have developed a new version of reusable plastic container for handling horticultural crops. Their results showed that the relative surface area of the openings directly affects the air circulation through the commodity but this effect becomes negligible when increasing the opening area over 25% of the container walls (Vigneault and Goyette, 2002). Other related research studies demonstrated different effect when comparing vertical and horizontal air flow directions (Edeogu et al., 1997).

4.2 Objective

The overall research objective was to assess the performance of a forced-air cooler system for sweet corn. This can be accomplished by:
- determining the effect of airflow rates and cob orientations on the half cooling time of the produce;
- evaluating the effect of these parameters on quality of sweet corn stored at 1°C for 7 and 21 days;
- assessing and comparing the quality of three precooled sweet corn cultivars after 7 and 21 days of storage at 1°C.

4.3 Materials and Methods

4.3.1 Plant material

Locally produced mature sweet corn (Zea mays L. spp. saccharata) was manually harvested during sunny warm summer days. The corn was maintained under a shed and then transported to the Research Centre within one hour following harvest. The harvest
was performed at two consecutive days in mid July, mid August and mid September. The sweet corn cultivars were chosen based on their availability at each period which resulted in using early, mid-late and late maturity sweet corn (Table 4.1). The initial produce temperature before precooling was generally near 24°C.

Table 4.1 General characteristics of the sweet corn cultivars used for the forced-air precooling study.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Date of Harvesting</th>
<th>Maturity period</th>
<th>Diameter Size (mm)</th>
<th>Sweetness</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet</td>
<td>Mid July</td>
<td>Early</td>
<td>44 to 51</td>
<td>High</td>
<td>Bicolor</td>
</tr>
<tr>
<td>Sensor</td>
<td>Mid August</td>
<td>Medium</td>
<td>53 to 58</td>
<td>Very high</td>
<td>Bicolor</td>
</tr>
<tr>
<td>Promise</td>
<td>Mid September</td>
<td>Late</td>
<td>48 to 54</td>
<td>High</td>
<td>Bicolor</td>
</tr>
</tbody>
</table>

During each day of the test, ears were gathered together. Eight experimental units were prepared by randomly picking up sixteen ears, for which mass and diameter were measured before any treatment. One corn cob was added to each experimental unit and used to follow the temperature profile of the produce during the precooling process. Two type-T thermocouples were positioned one between the corn leaves and the kernels, and one between the kernels and the core of the ear. Two experimental units ready for precooling process were put at the same time in a standard plastic container (Vigneault and Goyette, 2002).

4.3.2 Experimental set-up

The experimental set-up is presented in Figure (4.1). Two 406 mm square plywood boxes, 15 mm thick wall and 482 mm in height, were built to contain 34 ears of sweet corn each. On both sides of air pathway, the walls of the boxes were built from uniformly perforated aluminium plates with 3 mm diameter openings covering 51% of their surface. After filling, each box was attached to a different ventilation system used to circulate the desired air flow rates. The air-tightness was ensured using sealant tape.
Each ventilation system used a direct drive radial blade fan powered by a 0.75 kW variable speed electric motor controlled by a computer. The static and total air pressures were measured according to the standard method (ASHRAE, 2001) using a home made calibrated Pitot system described by Castro et al. (2004). An electronic pressure transducer (Dwyer, 607 series) was used to measure the difference in the total and static pressure resulting in the air velocity dynamic pressure. The transducer was connected to a data acquisition system (Agilent Technology Packard, Loveland, Colorado, USA) driven by a portable computer as described by Vigneault and Castro (2005). The same data acquisition system was also recording the air and corn temperature profiles at every 30 s during the precooling process. The Data logger software (Benchlink, Agilent Technologies, Loveland, Colorado, USA) was used to visualize the obtained data. The half cooling time (HCT) was calculated from the temperature data using a dedicated Excel Macro™ (Goyette et al., 1996).

Figure 4.1  Experimental set-up used to measure the effects of air flow rates on the cooling time; a) parallel and b) perpendicular orientations of the sweet corn cobs.
4.3.3 Experimental procedure

For each experimental set-up, different combinations of two air flow rates 1 and 3 L·s⁻¹·kg⁻¹ of produce and two produce orientations, parallel and perpendicular to the air flow, were tested. The corn ears were placed in their respective plywood boxes and cooled down until the temperature of the warmest cob reached the seven-eighth of the difference between the initial temperature of the corn and the air temperature inside the room (Goyette et al., 1996). The corn ears were then removed from both systems at the same time. Each test was repeated at two consecutive days at each of the three different periods during the summer.

Two other experimental units were placed inside a corrugated carton box to simulate room cooling and set as control. Four temperature data loggers, Hobos (Onset, T-type, H 12), were used to measure the temperature of two corn samples with the thermal sensor placed in the produce at the same locations as of the forced-air cooling process. A 5 min-interval was used to record the temperature measurements. The box was then put in a cold room at 1°C and 90-95% RH for generating the room cooling process.

4.3.4 Storage and quality evaluation

After cooling, all the corn cobs were placed in the same 1°C and 90-95% RH conditioned room for 7 and 21 days of storage. The plastic boxes containing the corn cobs were covered with perforated plastic bags to ensure high humidity and to avoid desiccation.

The mass loss of the corn cobs was measured immediately after harvest; after precooling, and after each storage period. The mass losses during the cooling process and the storage period were calculated as the percent difference between initial and final mass of the produce divided by the initial mass.

The moisture content and the total soluble solids percentage (TSS) of the corn were also measured. From each experimental unit, 150 g of whole kernels were taken out, mixed together and then separated into six sub-samples of 25 g each. Three sub-samples were dried using a lab-scale oven (Isotemp® Premium Ovens, Fisher Scientific, 700 series) for 72 hours at 60°C, and then put in a vacuum desiccator cabin for one hour.
before measuring their mass using a 0.001 g precision scale. Moisture content (MC) was obtained from mass difference before and after corn drying process according to the standard method (Anon., 1982).

Three other sub-samples were dipped into liquid nitrogen and kept in a freezer chamber at -20°C for TSS analysis. TSS was measured using a handheld refractometer (Fisher Scientific, Ottawa, Canada). Each sub-sample was blended for 1 min and centrifuged for 15 min at 3500 rpm. Few drops of the centrifuge liquid were used for this measurement.

Visual quality was evaluated for individual cobs before any cooling and on days 7 and 21 using a nine point hedonic scale for the subsequent parameters as described by Brecht et al. (1990): husk color, husk drying, silk appearance, kernel appearance and presence of defects. A quality index (QI) (Table 4.2) summarising all these parameters was determined and the total score for each parameter was calculated according to the method described by Rodov et al. (2000).

Finally, an analysis of variance (ANOVA) followed by Duncan’s test for comparison of the means was conducted using XLSTAT – Pro 7 software (Addinsoft, Paris, France).

Table 4.2 Full description of quality index scales of sweet corn (Vigneault et al., 2004b).

<table>
<thead>
<tr>
<th>Quality Index</th>
<th>Quality</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Excellent</td>
<td>Husks of freshly harvested, turgid appearance, dark green, slightly moist. Silks light-colored (greenish-yellow) and turgid. Kernels bright and very turgid. Absence of major defects.</td>
</tr>
<tr>
<td>5</td>
<td>Average</td>
<td>Pale green husks, withered or slightly dry. Silks lightly browning, some dried. Kernels dull but not dented. Absence of major defects.</td>
</tr>
<tr>
<td>3</td>
<td>Poor</td>
<td>Husks very pale, some yellowing and perhaps browning, much withered and partly dry. Silks brown, soft and possibly dry. A few dented kernels. Major defects possible.</td>
</tr>
<tr>
<td>1</td>
<td>Unmarketable</td>
<td>Husks yellow, straw-colored or brown. Very withered or dry. Many dented kernels. Major defects present.</td>
</tr>
</tbody>
</table>
4.4 Results and Discussion

4.4.1 Initial quality

The initial quality attributes of corn cobs measured immediately after harvest were used as reference for quality evolution. Despite high quality index was observed for the three cultivars, “Fleet” was significantly lower in quality compared to others. Although the three cultivars were classified as sugary enhanced (se) sweet corn, they were significantly different in their degree of sweetness. TSS level reached up to 27% in “Sensor” cultivar while reaching only 23% and 21% in the case of “Fleet” and “Promise” cultivars respectively. Since the juiciness can play a major role in quality of corn; one could expect better quality conservation from the higher moisture content obtained from the “Fleet” and “Promise” cultivars compared to the “Sensor” one (Table 4.5).

4.4.2 Precooling performance evaluation

4.4.2.1 Air flow rate

The results of the HCT (min) and mass loss (% of initial mass) for the two air flow rates used are reported in Table 4.3. The results showed a decrease of 49.3% in the HCT as the air flow was increased from 1 to 3 L·s⁻¹·kg⁻¹. Further, there was no significant difference in the HCT between the core and kernel position measurement which corresponds to the theoretical assertion claiming the cooling rate at any point in a uniform produce should be the same (Holman, 1986). During the experiment, cooling time was noticed to be reduced with cultivars, “Fleet” and “Promise” compared to “Sensor”. This cooling time reduction is likely due to their smaller diameter size (Table 4.1). Larger diameter took longer time to cool down which agrees with the theory (Goyette et al., 1996).
Table 4.3 Half cooling time (HCT) and mass loss (%) for different forced-air precooling combinations compared to room cooling.

<table>
<thead>
<tr>
<th>Precooling parameters</th>
<th>HCT (min)</th>
<th>Mass loss during cooling (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Corn cob orientation</td>
<td>Air flow rate (L·s⁻¹·kg⁻¹)</td>
</tr>
<tr>
<td>Parallel</td>
<td>1</td>
<td>93.4ᵇᶜ</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>1</td>
<td>92.1ᵇ</td>
</tr>
<tr>
<td>Parallel</td>
<td>3</td>
<td>68.1ᶜ</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>3</td>
<td>47.3ᵈ</td>
</tr>
<tr>
<td>Room Cooling</td>
<td></td>
<td>436.7ᵃ</td>
</tr>
</tbody>
</table>

*Values in the same column with the same letter are not significantly different at α = 0.05.

The average mass loss during forced-air precooling process was 2.68% of the initial mass. Although, the difference of the loss was not significant between the two flow rate results, the higher flow rate showed a tendency of producing mass loss increase; more trial would be necessary to determine if this difference is attributable to experimental error or associated with the flow rate increase.

4.4.2.2 Orientation of corn cobs

Results (Table 4.3) show the effect of cob orientation on HCT and mass loss during the cooling process. The perpendicular orientation showed a reduction in the HCT of sweet corn compared to parallel orientation while using higher air flow rate. This effect may be due to a higher turbulent air movement reducing the immobile film of air at the surface of the produce as the air hits the produce perpendicularly. Furthermore, the perpendicular ears are more exposed to a maximum degree of contact and the cooling is achieved in all locations throughout the entire length of the cob at the same time, resulting in high uniformity of cooling through different parts of the cooled produce. Moreover, under perpendicular orientation, cold air is passed from side to side through smaller area (diameter) compared to other orientation resulting in lower cooling time. In the case of parallel orientation, the surface of contact is minimal and only the end facing the air entering in the container is exposed to the cold air requiring much time to cool.
down the entire ear. However, to demonstrate this theory, a separate research plan would be essential.

The results showed no difference in mass loss during cooling between the two cob orientations but tendency of higher mass loss was noticed for the case of perpendicular orientation.

4.4.2.3 Room cooling

When compared to forced-air, HCT obtained in room cooling (436 min) is by far the highest than all other combinations used (Table 4.3). It reached up to nine times the HCT (47 min) obtained under perpendicular cob orientation at $3 \text{ L} \cdot \text{s}^{-1} \cdot \text{kg}^{-1}$ airflow condition. Regardless of cob orientation using lower flow rate, HCT (92 min) of sweet corn was approximately reduced to one fifth compared to room cooling.

In terms of mass loss during cooling process, no significant difference was found for any of the airflow rate and orientation combinations. However, room cooling process resulted in a much lower mass loss. This lower mass loss obtained after room cooling was likely due to a higher relative humidity maintained in the closed box containing the corn cobs.

4.4.3 Storage duration

The effect of forced-air precooling parameters on the quality attributes of sweet corn stored for 7 and 21 days at $1^\circ\text{C}$ is presented in Table 4.4. Generally, quality of sweet corn is inversely related to the length of storage. For the same storage duration, results have demonstrated that quality factors including TSS, moisture content and quality index were similar among the different combinations tested; whereas, room cooling retained lower mass loss with lower TSS and quality index values. Sweet corn benefited from forced-air and room cooling as it was possible to store this highly perishable commodity for duration up to 21 days at $1^\circ\text{C}$ while maintaining high TSS and moisture content with good market quality.
Table 4.4 Quality attributes of sweet corn for different forced-air precooling combinations compared to room cooling after 7 and 21 days of storage at 1°C.

<table>
<thead>
<tr>
<th>Precooling parameters</th>
<th>Mass loss during storage (%)</th>
<th>TSS (%)</th>
<th>Moisture content (%)</th>
<th>Quality Index</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>7 days</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallel</td>
<td>2.65&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>22.56&lt;sup&gt;a&lt;/sup&gt;</td>
<td>74.02&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.54&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>4.52&lt;sup&gt;b&lt;/sup&gt;</td>
<td>22.22&lt;sup&gt;a&lt;/sup&gt;</td>
<td>73.99&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.16&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Parallel</td>
<td>3.63&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>22.36&lt;sup&gt;a&lt;/sup&gt;</td>
<td>74.20&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.44&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>3.73&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>22.13&lt;sup&gt;a&lt;/sup&gt;</td>
<td>74.16&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.06&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Room Cooling</td>
<td>1.96&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20.90&lt;sup&gt;a&lt;/sup&gt;</td>
<td>74.20&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.04&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>21 days</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallel</td>
<td>3.94&lt;sup&gt;b&lt;/sup&gt;</td>
<td>21.47&lt;sup&gt;a&lt;/sup&gt;</td>
<td>73.93&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.70&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>4.11&lt;sup&gt;b&lt;/sup&gt;</td>
<td>21.75&lt;sup&gt;a&lt;/sup&gt;</td>
<td>73.58&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.14&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Parallel</td>
<td>4.58&lt;sup&gt;b&lt;/sup&gt;</td>
<td>21.66&lt;sup&gt;a&lt;/sup&gt;</td>
<td>73.63&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.94&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>3.46&lt;sup&gt;b&lt;/sup&gt;</td>
<td>21.67&lt;sup&gt;a&lt;/sup&gt;</td>
<td>73.79&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.92&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Room Cooling</td>
<td>2.29&lt;sup&gt;a&lt;/sup&gt;</td>
<td>19.76&lt;sup&gt;a&lt;/sup&gt;</td>
<td>73.26&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.48&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

*Values in the same column with the same letter and storage duration are not significantly different at α = 0.05.

4.4.4 Cultivar effects

Table 4.5 shows the effect of precooling on quality factors of the three sweet corn cultivars after storage. For all three cultivars, mass loss percent has significantly increased over time as expected. However, TSS reduction was different among cultivars. This loss of sweetness was higher after 21 days of storage in case of “Promise” with 14.9% followed by “Fleet” and “Sensor” cultivars with 10.1% and 5.4% respectively. Moisture content maintained was high for all the three cultivars with a tendency to decrease over time. Also, all cultivars significantly reduced their quality index after storage with higher reduction noted for “Promise” cultivar.

Therefore, the cultivar selection can only be limited to their diameter size which affects the cooling time, their supply into the market which is related to the maturity stage, and the preference of the consumers in terms of sweetness and juiciness. For example, the cultivar “Sensor” can be best chosen for its high degree of sweetness; whereas, “Fleet” is good in terms of maintaining its quality over time compared to others.
Table 4.5 Quality attributes for different precooled cultivars of sweet corn after storage at 1°C.

<table>
<thead>
<tr>
<th>Storage duration (days)</th>
<th>Mass loss during storage (%)</th>
<th>TSS (%)</th>
<th>Moisture content (%)</th>
<th>Quality index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fleet</td>
<td></td>
<td>Sensor</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.00&lt;sup&gt;a&lt;/sup&gt;</td>
<td>22.70&lt;sup&gt;a&lt;/sup&gt;</td>
<td>75.70&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.75&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>7</td>
<td>3.97&lt;sup&gt;b&lt;/sup&gt;</td>
<td>21.56&lt;sup&gt;b&lt;/sup&gt;</td>
<td>75.69&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.66&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>21</td>
<td>3.71&lt;sup&gt;b&lt;/sup&gt;</td>
<td>20.41&lt;sup&gt;c&lt;/sup&gt;</td>
<td>74.75&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.52&lt;sup&gt;b&lt;/sup&gt;</td>
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<tr>
<td>0</td>
<td>0.00&lt;sup&gt;a&lt;/sup&gt;</td>
<td>27.10&lt;sup&gt;a&lt;/sup&gt;</td>
<td>68.80&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8.87&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>7</td>
<td>2.93&lt;sup&gt;b&lt;/sup&gt;</td>
<td>25.83&lt;sup&gt;b&lt;/sup&gt;</td>
<td>68.05&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.74&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>21</td>
<td>3.52&lt;sup&gt;b&lt;/sup&gt;</td>
<td>25.62&lt;sup&gt;b&lt;/sup&gt;</td>
<td>68.03&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.62&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
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<td></td>
<td></td>
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</tr>
<tr>
<td>0</td>
<td>0.00&lt;sup&gt;a&lt;/sup&gt;</td>
<td>21.50&lt;sup&gt;a&lt;/sup&gt;</td>
<td>76.50&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8.69&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>7</td>
<td>2.99&lt;sup&gt;b&lt;/sup&gt;</td>
<td>19.21&lt;sup&gt;b&lt;/sup&gt;</td>
<td>76.42&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.74&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>21</td>
<td>3.81&lt;sup&gt;b&lt;/sup&gt;</td>
<td>18.29&lt;sup&gt;c&lt;/sup&gt;</td>
<td>76.12&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.36&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

*Values in the same column with the same letter and sweet corn cultivar are not significantly different at α = 0.05.

4.5 Conclusion

Sweet corn cobs under perpendicular orientation and 3 L of cold air s<sup>-1</sup>·kg<sup>-1</sup> of produce were precooled faster than the parallel orientation and lower air flow rates. Under the best precooling conditions, HCT was reduced by almost 90% to that of room cooling. Precooling parameters had no effect on the quality attributes of sweet corn which still were high after 7 and 21 days of storage at 1°C except for quality index; therefore, the assessment of the performance of the forced-air cooler system can be limited to cooling time and mass loss during the cooling process. On the other hand, the quality of sweet corn cobs was different among cultivars except for moisture content which was steady over time.
4.6 References


Forced-air cooling is only one method to assess the performance of precooling technologies for sweet corn. However, the application of hydrocooling on the same produce is also of extreme importance for the sweet corn industry. The next chapter describes the assessment of the performance of a hydrocooler system by determining the effect of water flow patterns and cob orientations on the half cooling time of the produce and for evaluating the effect of hydrocooling on the quality parameters during storage.
V. EFFECT OF EAR ORIENTATIONS ON HYDROCOOLING PERFORMANCE AND QUALITY OF SWEET CORN

5.1 Introduction

Quality is the most important factor in judging the acceptability of the consumer to purchase food commodities. Since temperature has such a noticeable influence on deterioration, its management is fundamental in preserving good vegetable quality during postharvest processes (Sargent et al., 1988). Studies showed that for each 10 degrees reduction in produce temperature, the rate of respiration will reduce by a factor of 2 to 4 (Golob et al., 2002). Sweet corn (Zea mays L. spp. saccharata) has an extremely high respiration rate (Kader, 2002). Its taste and quality depends upon its sugar content which decreases rapidly after harvest if kept at ambient temperature (Boyette et al., 1990). Therefore, rapid reduction of its temperature to the lowest and safe temperature range maximizes its storage life while maintaining its pre-harvest quality (Golob et al., 2002).

Precooling may be accomplished by several different techniques using cold air, water or ice. Cold water, or hydrocooling process, can be an effective way for quick cooling of a wide range of fruits and vegetables including celery, sweet corn, carrots, apples, peaches, (Kader, 2002), and takes advantages of the fact that surface heat transfer coefficient of produce-to-water is much higher than air (ASHRAE, 1998). Hydrocooling provides faster and more uniform cooling through the produce treated than air (Golob et al., 2002) and comes out in no crop mass loss during the precooling process (Thompson, 2003). Rate of cooling is dependent on the size and shape of the commodity being cooled (Goyette et al., 1996). For rapid heat removal, the cooling water must be maintained at 0°C for non chilling-sensitive produces; however the water temperature must be adjusted to chill-sensitive crops according to the requirement of each produce (DeEll et al., 2000).

The basic principle of this cooling method is that the cold water coming from the evaporator coil gets in direct contact with the surface of the warm produce; the surface temperature of the commodity becomes basically identical to that of the water.
Conductive heat transfer process occurs through the produce, resulting in a produce temperature reduction.

Hydrocoolers can be based on two different patterns of water flow: (1) showering (spray) water down upon the produce, and (2) submerging (immersion) the commodity inside the cold water (Kays, 1997). With a spray-type hydrocooler, cold water is pumped to a perforated-floor reservoir situated above the produce container. The water circulates through the mass of produce which can be packaged in a box or pallet-bin, or left on a conveyor belt (Kader, 2002). The outgoing warmer water must be filtered to remove the plant residues and debris; passed through the refrigeration coils, cooling down again and pumped into the overhead pan.

The other most common hydrocooler principle is by immersion of warm produce into the cold water. In this system, the produce moves through a water bath. This type is best suited for products that do not float (Kader, 2002); it performs well even for lower density produce such as cucumber (DeEll et al., 2000). Water must be pumped at adequate speed to avoid restriction to its movement and to achieve the desirable final temperature with the shortest possible time (Singh et al., 2001).

In general, the produce cooled by water must have a high resistance to wetting, low vulnerability to physical wound caused by water on their surface and low susceptibility to damage by chemicals (chlorine) used to sanitize the water from any spoiled organisms that might occur while cooling the produce (Kays, 1997). Both types of hydrocoolers are not recommended for produce containing even small air space such as sweet pepper or tomato. Hydrocooling creates some negative air pressure inside the produce, forcing water to penetrate into the produce; thus, resulting in drastic increase of contamination potential (Vigneault et al., 2000). Hydrocooling requires additional maintenance such as cleaning the shower pan at a regular basis to avoid plugging of hole. Placing the cooled produce immediately in a cold room before re-warming occurs is also very important (Kader, 2002). Finally, packaging material must be tolerant for wetting and easy to handle (Golob et al., 2002).

The research objectives were to assess the performance of a sweet corn hydrocooler system by determining the effect of water flow patterns and cob orientations on the half cooling time of the produce; by evaluating the effect of those parameters on
quality of sweet corn stored at 1°C for 7 and 21 days; and by assessing and comparing the quality of three precooled sweet corn cultivars.

5.2 Materials and Methods

5.2.1 Produce handling procedures

Locally produced mature sweet corn (Zea mays L. spp. Saccharata) was manually harvested during sunny warm summer days. The corn was maintained under a shed and then transported to the Research Centre within one hour following the harvest. The harvest was performed at two consecutive days in mid July, mid August and mid September. The sweet corn cultivars were chosen based on their availability at each period which resulted in using early, mid-late and late maturity sweet corn (Table 5.1). The initial produce temperature before precooling was generally near 24°C.

Table 5.1 General characteristics of the sweet corn cultivars used for the water precooling study.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Date of Harvesting</th>
<th>Maturity period</th>
<th>Diameter Size (mm)</th>
<th>Sweetness</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet</td>
<td>Mid July</td>
<td>Early</td>
<td>44 to 51</td>
<td>High</td>
<td>Bicolor</td>
</tr>
<tr>
<td>Sensor</td>
<td>Mid August</td>
<td>Medium</td>
<td>53 to 58</td>
<td>Very high</td>
<td>Bicolor</td>
</tr>
<tr>
<td>Promise</td>
<td>Mid September</td>
<td>Late</td>
<td>48 to 54</td>
<td>High</td>
<td>Bicolor</td>
</tr>
</tbody>
</table>

During each day of the test, ears were gathered together. Eight experimental units were prepared by randomly picking up sixteen ears, for which mass and diameter were measured before any treatment. One corn cob was added to each experimental unit and used to follow the temperature profile of the produce during the precooling process. Two type-T thermocouples were positioned one between the corn leaves and the kernels, and one between the kernels and the core of the ear. Two experimental units ready for precooling process were put at the same time in a standard plastic container (Vigneault and Goyette, 2002).
5.2.2 Experimental set-up

Two hydrocooler systems, spray and immersion, were used to conduct the cooling of 34 corn cob batches each. For the immersion type, a 406 mm square plastic box and 457 mm in height was built. Both sides of water pathway were equipped with two uniformly perforated aluminium plates of 51% openings to uniform water distribution (Figure 5.1). The box was covered on all its faces with 50.8 mm thick Styrofoam to ensure adequate insulation. In the case of spray type (Figure 5.2), sweet corn inside a standard plastic container was placed into a 600x500 mm chamber, 550 mm in height, of a lab-scale hydrocooler described by DeEll et al. (2000).

**Figure 5.1** Experimental set-up used to measure the effects of immersed-type water flow on the cooling time; a) parallel and b) perpendicular orientations of the sweet corn cobs.
5.2.3 Experimental procedure

For each hydrocooler system, two produce orientations were tested. Sweet corn ears were positioned in parallel and perpendicular direction to the water flow direction. The cooling process lasted until the cooling of the produce reached the seven-eighth cooling time. The corn was then removed from both orientation systems.

Two other experimental units were placed inside a corrugated carton box to simulate room cooling. Four temperature data loggers, Hobos (Onset, T-type, H 12), were used to measure the temperature of two corn samples by locating the thermal sensor at
the same position in the corn ear then the corn used for the hydrocooling process. A 5 min-interval was used to record the temperature measurements. The box was then put in a cold room at 1°C and 90-95% RH for generating the room cooling process data.

5.2.4 Quality evaluation

After cooling, all the corn cobs were placed in the same 1°C and 90-95% RH conditioned room for 7 and 21 days of storage. The plastic boxes containing the corn cobs were covered with perforated plastic bags to ensure high humidity and to avoid desiccation.

The mass loss was obtained by measuring the mass of the corn cobs immediately after harvest; after precooling, and after each storage period. The mass losses at any point during the cooling process and the storage period were calculated as the percent difference between the initial mass and the mass of the produce at a given point divided by the initial mass.

The moisture content and the total soluble solids percentage (TSS) of the corn were also measured. From each experimental unit, 150 g of whole kernels were taken out, mixed together and then separated into six sub-samples of 25 g each. Three sub-samples were dried using a lab-scale oven (Isotemp® Premium Ovens, Fisher Scientific, 700 series) for 72 hours at 60°C, and then put in a vacuum desiccator cabin for one hour before measuring their mass using a 0.001 g precision scale. Moisture content (MC) was obtained from the mass difference of before and after corn drying process according to the standard method (Anon., 1982).

Three other sub-samples were dipped into liquid nitrogen and kept in a freezer chamber at -20°C for TSS analysis. TSS was measured using a handheld refractometer (Fisher Scientific, Ottawa, Canada). Each sub-sample was blended for 1 min and centrifuged for 15 min at 3500 rpm. Few drops of the centrifuge liquid were used for this measurement.

Visual quality was evaluated for individual cobs before any cooling and on days 7 and 21 using a nine point hedonic scale for the subsequent parameters as described by Brecht et al. (1990): husk color, husk drying, silk appearance, kernel appearance and presence of defects. A quality index (QI) (Table 5.2) summarising all these parameters
was determined and the total score for each parameter was calculated according to the method described by Rodov et al. (2000).

Finally, an analysis of variance (ANOVA) followed by Duncan’s test for comparison of the means was conducted using XLSTAT – Pro 7 software (Addinsoft, Paris, France).

**Table 5.2** Full description of quality index scales of sweet corn (Vigneault et al., 2004b).

<table>
<thead>
<tr>
<th>Quality Index</th>
<th>Quality</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Excellent</td>
<td>Husks of freshly harvested, turgid appearance, dark green, slightly moist. Silks light-colored (greenish-yellow) and turgid. Kernels bright and very turgid. Absence of major defects.</td>
</tr>
<tr>
<td>5</td>
<td>Average</td>
<td>Pale green husks, withered or slightly dry. Silks lightly browning, some dried. Kernels dull but not dented. Absence of major defects.</td>
</tr>
<tr>
<td>3</td>
<td>Poor</td>
<td>Husks very pale, some yellowing and perhaps browning, much withered and partly dry. Silks brown, soft and possibly dry. A few dented kernels. Major defects possible.</td>
</tr>
<tr>
<td>1</td>
<td>Unmarketable</td>
<td>Husks yellow, straw-colored or brown. Very withered or dry. Many dented kernels. Major defects present.</td>
</tr>
</tbody>
</table>

### 5.3 Results and Discussion

#### 5.3.1 Initial quality

The initial quality attributes of corn cobs measured immediately after harvest were used as reference for quality evolution. Despite high quality index was observed for the three cultivars, “Fleet” was significantly lower in quality in comparison to others. Although the three cultivars were classified as sugary enhanced (se) sweet corn, they were significantly different in their degree of sweetness. TSS level reached up to 27% in “Sensor” cultivar while reaching only 23% and 21% in the case of “Fleet” and “Promise” cultivars respectively. Since the juiciness can play a major role in quality of corn; one could expect better quality conservation from the higher moisture content obtained from the “Fleet” and “Promise” cultivars compared to the “Sensor” one (Table 5.5).
5.3.2 Precooling performance evaluation

5.3.2.1 Water flow pattern

The results of the HCT (min) and mass gain (% of initial mass) for the two water flow patterns used are presented in Table 5.3. The results showed a decrease in the HCT as the produce was completely immersed into cold water within the same combinations of cob orientation. HCT was reduced by 42.3% compared to spray water flow. This reduction may be due to the higher degree of contact between the produce surface and cold water when using immersed corn ear system. Moreover, there was no significant difference in the HCT between the core and kernel position measurement which corresponds to the theoretical assertion claiming the cooling rate at any point in a uniform produce should be the same (Holman, 1986). During the experiment, it was noticed that the cooling time was reduced with cultivars Fleet and Promise compared to Sensor. This cooling time reduction is likely due to their smaller diameter (Table 5.1). Larger diameter took longer time to cool down which agrees with the theory (Goyette et al., 1996).

Table 5.3 Half cooling time (HCT) and mass gain (%) for different hydrocooling combinations compared to room cooling.

<table>
<thead>
<tr>
<th>Precooling parameters</th>
<th>HCT (min)</th>
<th>Mass gain during cooling (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Core</td>
<td>Kernel</td>
</tr>
<tr>
<td>Corn cob orientation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water flow pattern</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallel spray</td>
<td>27.9(^b)</td>
<td>27.4(^b)</td>
</tr>
<tr>
<td>Parallel immersed</td>
<td>26.9(^b)</td>
<td>26.6(^b)</td>
</tr>
<tr>
<td>Perpendicular spray</td>
<td>19.2(^c)</td>
<td>18.6(^c)</td>
</tr>
<tr>
<td>Perpendicular immersed</td>
<td>16.1(^c)</td>
<td>15.8(^c)</td>
</tr>
<tr>
<td>Room Cooling</td>
<td>436.7(^a)</td>
<td>434.6(^a)</td>
</tr>
</tbody>
</table>

*Values in the same column with the same letter are not significantly different at \( \alpha = 0.05 \).

The mass loss was completely eliminated and water was even added to the produce during the hydrocooling process. The average mass gain was 6.53% of the initial mass during cooling process. Further, the difference in percent gain was significant; an immersed type hydrocooler resulted in a large increase in mass gain. The percent mass
gain in spray type hyrdocooler was lower, hence this gain in mass might be due to the distance parameter between sprinklers and produce followed by the gravity outflow.

5.3.2.2 Orientation of corn cobs

Results (Table 5.3) showed the effect of cob orientation on HCT and mass gain during the precooling process. For both systems, spray and immersed, the perpendicular orientation produced a smaller HCT of sweet corn cobs compared to parallel orientation. This effect may be due to a higher turbulent water movement reducing the immobile film of water at the surface of the produce as the water hits the produce perpendicularly (Singh and Heldman, 1984). Additionally, the perpendicularly oriented ears could be more exposed to water flow (attaining a maximum degree of contact), resulting in faster cooling effect in all locations throughout the entire length of the cob. High uniformity of cooling through different parts of the produce is the result. For parallel orientation, some cold water was circulating from side to side through small open channel created by adjacent corn cobs bypassing direct contact between them and resulting in less efficient cooling rate. Further, with parallel orientation, the direct surface of contact was minimal and only one end of the ears was exposed perpendicularly to the cold water requiring much time to cool down.

The results also showed a difference in mass gain between the two cob orientations. The highest value (9.5%) was obtained under perpendicular cob orientation. The cold water was circulated perpendicularly to the corn cob surface, increasing the impact force to migrate water particles into the first husk of the ear when hitting its surface compared to parallel water circulation mode.

5.3.2.3 Room cooling

When compared to water, HCT obtained in room cooling (435.5 min) is by far higher than all other combinations used (Table 5.3). Regardless of the water flow pattern, during parallel (27.4 min) and perpendicular (17.4 min) cob orientation precooling process, HCT of sweet corn was approximately reduced by 93.8% and 96% respectively compared to room cooling.
5.3.3 Storage duration

The effect of hydrocooling parameters on quality attributes of sweet corn is presented in Table 5.4. For the same storage duration, results have demonstrated that quality attributes including TSS, moisture content and quality index were similar among the different precooling combinations tested; whereas, room cooling showed a mass loss and a significantly lower quality index. Therefore, hydrocooling parameters had no effect on the quality attributes of corn cobs which still maintained high during storage except for quality index after 21 days due to the fact that bacterial growth occurred when hydrocooling was used. Pink colonies of bacteria over the entire corn cob and unpleasant smell appeared. Therefore, with hydrocooling, sanitation of water is mandatory, especially if it is reused. Water should be taken from a clean source and disinfected by adding chlorine to the extent that the free chlorine level is 100 to 150 ppm (Sargent et al., 1988). The same authors recommended to frequently draining out the water of the hydrocooler and the system sanitised regularly.

Table 5.4 Quality attributes of sweet corn for different hydrocooling combinations compared to room cooling after 7 and 21 days of storage at 1°C.

<table>
<thead>
<tr>
<th>Precooling parameters</th>
<th>Mass gain during storage (%)</th>
<th>TSS (%)</th>
<th>Moisture content (%)</th>
<th>Quality Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn cob orientation</td>
<td>Water flow pattern</td>
<td>7 days</td>
<td>21 days</td>
<td></td>
</tr>
<tr>
<td>Parallel</td>
<td>Spray</td>
<td>5.41&lt;sup&gt;a&lt;/sup&gt;</td>
<td>21.21&lt;sup&gt;a&lt;/sup&gt;</td>
<td>76.45&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Parallel</td>
<td>Immersed</td>
<td>5.65&lt;sup&gt;a&lt;/sup&gt;</td>
<td>21.77&lt;sup&gt;a&lt;/sup&gt;</td>
<td>76.27&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>Spray</td>
<td>3.95&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20.98&lt;sup&gt;a&lt;/sup&gt;</td>
<td>75.41&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>Immersed</td>
<td>6.25&lt;sup&gt;a&lt;/sup&gt;</td>
<td>21.32&lt;sup&gt;a&lt;/sup&gt;</td>
<td>76.17&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Room Cooling</td>
<td></td>
<td>-1.96&lt;sup&gt;b&lt;/sup&gt;</td>
<td>20.90&lt;sup&gt;a&lt;/sup&gt;</td>
<td>74.20&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>21 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallel</td>
<td>Spray</td>
<td>4.07&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20.41&lt;sup&gt;a&lt;/sup&gt;</td>
<td>74.30&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Parallel</td>
<td>Immersed</td>
<td>5.36&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>20.56&lt;sup&gt;a&lt;/sup&gt;</td>
<td>74.11&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>Spray</td>
<td>3.79&lt;sup&gt;b&lt;/sup&gt;</td>
<td>20.67&lt;sup&gt;a&lt;/sup&gt;</td>
<td>74.76&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Perpendicular</td>
<td>Immersed</td>
<td>5.68&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20.39&lt;sup&gt;a&lt;/sup&gt;</td>
<td>74.92&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Room Cooling</td>
<td></td>
<td>-2.29&lt;sup&gt;c&lt;/sup&gt;</td>
<td>19.76&lt;sup&gt;a&lt;/sup&gt;</td>
<td>73.26&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>Values in the same column with the same letter and storage duration are not significantly different at α = 0.05.
5.3.4 Cultivar effects

Table 5.5 showed the effect of precooling on quality factors of the three sweet corn cultivars after storage. All the three cultivars had gained mass during storage probably due to high humidity atmosphere inside the storage room which causes condensation on the surface of the produce. This gain percent had tendency to reduce over time. However, TSS reduction was different among cultivars. This loss of sweetness was higher after 21 days of storage in the case of “Promise” with 19.7% followed by “Fleet” and “Sensor” cultivars with 16% and 8.7% respectively. Moisture content did increase significantly with time compared to initial value for all the three cultivars. Further, the cultivar “Fleet” had maintained its quality index high after 21 days of storage while this index was maintained high only for 7 days and was significantly reduced after 21 days for both “Sensor” and “Promise” cultivars.

Table 5.5 Quality attributes for different precooled cultivars of sweet corn after storage at 1°C.

<table>
<thead>
<tr>
<th>Storage duration (days)</th>
<th>Mass gain during storage (%)</th>
<th>TSS (%)</th>
<th>Moisture content (%)</th>
<th>Quality index</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fleet</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.00^b</td>
<td>22.70^a</td>
<td>75.70^b</td>
<td>7.75^a</td>
</tr>
<tr>
<td>7</td>
<td>4.96^a</td>
<td>20.25^b</td>
<td>77.97^a</td>
<td>7.73^a</td>
</tr>
<tr>
<td>21</td>
<td>3.80^a</td>
<td>19.07^c</td>
<td>75.84^b</td>
<td>7.38^a</td>
</tr>
<tr>
<td><strong>Sensor</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.00^b</td>
<td>27.10^a</td>
<td>68.80^a</td>
<td>8.87^a</td>
</tr>
<tr>
<td>7</td>
<td>4.61^a</td>
<td>25.38^b</td>
<td>70.35^a</td>
<td>7.84^a</td>
</tr>
<tr>
<td>21</td>
<td>3.37^a</td>
<td>24.74^c</td>
<td>69.07^b</td>
<td>6.25^b</td>
</tr>
<tr>
<td><strong>Promise</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.00^b</td>
<td>21.50^a</td>
<td>76.50^c</td>
<td>8.69^a</td>
</tr>
<tr>
<td>7</td>
<td>4.14^a</td>
<td>18.08^b</td>
<td>78.78^a</td>
<td>8.23^a</td>
</tr>
<tr>
<td>21</td>
<td>3.28^a</td>
<td>17.26^c</td>
<td>77.91^b</td>
<td>6.74^b</td>
</tr>
</tbody>
</table>

*Values in the same column with the same letter and sweet corn cultivar are not significantly different at α = 0.05.

The selection among cultivars can be limited to their diameter size which affects the cooling time, their supply into the market which is related to the maturity stage, and the preference of the consumers in terms of sweetness and juiciness. For example, the cultivar “Sensor” can be best chosen for its high degree of sweetness; whereas, its moisture content was lower compared to others.
5.4 Conclusion

Performance of a hydrocooling system for sweet corn depends to a much greater extent upon operating practices such as orientation of corn cobs and type of water flow than upon system effectiveness. HCT was reduced by 42.3% when the corn cob was immersed into 1°C water and perpendicularly oriented to the direction of water flow compared to parallel and spray-type water flow. Under the same conditions, HCT has been reduced by 96% compared to room cooling; hence, sweet corn can be cooled down with an HCT of 16 min. All water precooling combinations didn’t affect the quality parameters of corn cobs during storage. However, hygienic procedures are always required; cleanliness of water should be done on a regular basis by adding chlorine followed by draining out of water for each use of the system. The cultivar “Fleet” has maintained best quality factors after 21 days at 1°C.
5.5 References


After studying the performance of forced-air and hydrocooling techniques for sweet corn, the following chapter evaluates the performance of vacuum cooling and compares all precooling methods based on half cooling time and quality of sweet corn over time.
VI. PERFORMANCE OF PRECOOLING TECHNOLOGIES

6.1 Introduction

Both quantitative and qualitative postharvest losses in fresh fruits and vegetables are of considerable interest due to their extremely high economical values reaching 5 to 25% of the production in developed countries and 20 to 50% in developing countries (Kader, 2002) which represents billion of dollars per year around the world. Improving technology in postharvest can reduce these losses to a great extent.

Sweet corn is an very important fresh vegetable in North America. It is highly perishable and has an extremely high respiration rate (Kader, 2002) which generates a large quantity of heat after harvest resulting in a rapid degradation of the quality (Boyette et al., 1990). Thus, proper temperature management is very critical to ensure maintaining quality and longer shelf life of the produce. Studies on sweet corn showed that 60% of its sugar can be lost in 24 hours at 30°C; even at 10°C, this rate of sugar loss is four times that at 0°C (Herber, 1991). Sweet corn can be stored at 0°C and 90-98% RH for maximum of 6 to 8 days still retaining a satisfactory quality (Sargent et al., 1988). Precooling is well recommended to maintain the maximum storage duration of sweet corn by removing field heat as quickly as possible after harvest. This process could be achieved by three main techniques including forced-air, water, and vacuum cooling.

Forced-air cooling uses air as a cooling medium. Cold air could be pulled at different flow rates ranging from 0.5 to 3 L of air s⁻¹·kg⁻¹ of produce (Fraser, 1991) through the commodity packed in containers resulting in faster removal of heat than room cooling (Edeogu et al., 1997). The close contact between the flowing air and the commodity removes the heat around the produce by convection (Fraser, 1991), which is much faster than conduction through the container walls and natural convection. The cooling rate is relatively high and a wide range of produce is suitable for this method.

Hydrocooling involves the application of cold water quickly and uniformly distributed over the surface of a warm produce (ASHRAE, 1998). Water is a better heat-transfer medium than air; therefore, hydrocoolers cool produce faster than forced-air coolers (Thompson et al., 1998). Hydrocooling provides uniform cooling through the produce (Golob et al., 2002) and the commodity does not lose moisture during the
process (Sargent et al., 1990). This precooling method is well suited for sweet corn and other water resistant crops like apple, peach, carrot, etc. (Kader, 2002). Sanitation of water with chlorine is critical to avoid contamination by decay micro-organisms that might occur while cooling the produce (Kays, 1997).

Vacuum cooling is the most rapid precooling method. It consists of placing the warm produce into an air tight chamber and lowering the inside chamber pressure to the point that water boils at the desired cooling temperature (ASHRAE, 1998). The saturation pressure for water at 0°C is 0.610 kPa or 4.6 mmHg (ASHRAE, 1998). Water at the surface of the produce evaporates and removes quickly the field heat of the produce and condenses on an evaporative coil (Kader, 2002). Vacuum cooling causes a mass loss in the produce which corresponds to 1% mass loss for each 6 degrees reduction in temperature (Thompson et al., 1998). To reduce mass loss and avoid chilling injury that might occur during non uniform temperature decrease, some coolers are equipped with water spray systems (hydrovac) that are activated before cooling process (Thompson et al., 1998; ASHRAE, 1998). This method is best suited to cool produce with high surface area to mass ratio such as leafy vegetables. Other commodities like sweet corn, green beans and mushrooms can also be precooled by this method (Kader, 2002).

Capital costs differ considerably among different precooling systems (Kader, 2002). Vacuum coolers require the highest investment cost including equipments and skilled operators followed by forced-air coolers and hydrocoolers (Kader, 2002; Thompson et al., 1998). According to Kader (2002), energy use can be based on the term energy coefficient (EC) defined by Equation 6.1. Vacuum cooling provides higher EC than hydro followed by forced-air cooling.

\[
EC = \frac{\text{Energy removed (kWh)}}{\text{Electrical energy used (kWh)}} \tag{6.1}
\]

Studies were done on forced-air and hydrocooling of sweet corn (Chapter IV; V) using different combinations of air flow rates (1 and 3 L·s⁻¹·kg⁻¹) and water flow patterns (immersed and spray) under two corn cob orientations (parallel and perpendicular). The best results for forced-air precooling were obtained with 3 L of cold air·s⁻¹·kg⁻¹ of produce.
under perpendicular cob orientation. In the case of hydrocooling, best results were achieved with immersion water type flow under perpendicular cob orientation.

6.2 Objective

The objectives of this research were:
- To assess the performance of a vacuum cooler system for sweet corn by measuring the produce half cooling time; and, to evaluate the quality of three sweet corn cultivars after 7 and 21 days of storage at 1°C.
- To compare the performance of the best conditions obtained in Chapters IV and V for forced-air and hydrocooling of sweet corn with vacuum and room cooling by evaluating the effect of precooling on half cooling time and quality of sweet corn over time.

6.3 Materials and Methods

6.3.1 Sweet corn preparation

Fresh mature sweet corn (Zea mays L. spp. Saccharata) was manually harvested from a local producer during sunny warm summer days. The corn was maintained in a shed and then transported in a truck to the Research Centre within approximately one hour following the harvest. The harvest was performed on two consecutive days in mid July, mid August and mid September. The sweet corn cultivars were chosen based on their availability at each period which resulted in using early, mid-late and late maturity sweet corn (Table 6.1). The initial produce temperature before precooling was generally near ambient (24°C).
### Table 6.1 General characteristics of the sweet corn cultivars used for the study.

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>Date of Harvesting</th>
<th>Maturity period</th>
<th>Diameter Size (mm)</th>
<th>Sweetness</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet</td>
<td>Mid July</td>
<td>Early</td>
<td>44 to 51</td>
<td>High</td>
<td>Bicolor</td>
</tr>
<tr>
<td>Sensor</td>
<td>Mid August</td>
<td>Medium</td>
<td>53 to 58</td>
<td>Very high</td>
<td>Bicolor</td>
</tr>
<tr>
<td>Promise</td>
<td>Mid September</td>
<td>Late</td>
<td>48 to 54</td>
<td>High</td>
<td>Bicolor</td>
</tr>
</tbody>
</table>

During each day of the test, ears were gathered together. Experimental units were prepared by randomly picking up sixteen ears, for which mass and diameter were measured before any treatment. One corn cob was added in each experimental unit and used to follow the temperature profile of the produce during the precooling process. Two type-T thermocouples were positioned one between the corn leaves and the kernels, and one between the kernels and the core of the ear. Two experimental units ready for precooling process were put at the same time in a standard plastic container (Vigneault and Goyette, 2002).

#### 6.3.2 Experimental set-up

The experiment consisted of three methods of cooling for sweet corn: forced-air, hydro and vacuum. A detailed description of the experimental set-ups used during forced-air and hydrocooling are provided in Chapters IV and V. The vacuum cooling experiment was performed using a lab-scale vacuum cooler fabricated by Amesse Réfrigération Inc. (Beauharnois, Quebec, Canada) for the Postharvest Engineering Laboratory of Agriculture and Agri-Food Canada. This precooling system was equipped with a hermetic chamber, a vacuum pump, a two-stage indirect cooling system and instrumentation. The hermetic chamber was designed to support an absolute zero pressure, or a negative relative pressure of 101.3 kPa (760 mm Hg), and was of cross section of 820 x 520 mm and of 1400 mm in height. The vacuum pump was designed to reduce the hermetic chamber pressure to 800 Pa within 360 s. The two-stage indirect cooling system consisted on an air-Freon mechanical refrigeration cooling down the
100 L of glycol used as thermal mass to meet the maximum refrigeration peak load. A glycol pump was used to circulate the glycol from an insulated reservoir to a heat exchanger located inside the hermetic chamber and required to condensate any water vapour. The vacuum cooler was instrumented with four thermocouples, a pressure sensor, and a micro valve controlled by computer (Rennie et al., 2001) to maintain a constant pressure at 644.7 Pa which corresponds to the water evaporation temperature of 1°C. The produce temperature and pressure profiles were measured at every 30 s during the precooling process using a data acquisition system (Agilent Technology Packard, Loveland, Colorado, USA) connected to a portable computer. The Data logger software (Benchlink, Agilent Technologies, Loveland, Colorado, USA) was used to visualize the obtained data. The half cooling time (HCT) was calculated from the temperature data using a dedicated Excel Macro™ built and described by Goyette et al. (1996).

6.3.3 Experimental procedure

For each cooler system, tests were repeated during two consecutive days at each of the three harvesting periods. In the case of vacuum cooling, two experimental units of sweet corn were placed at the same time inside the vacuum chamber and the system was turned on. The inside absolute pressure was reduced and maintained constant at 644.7 Pa during the cooling process. The temperature of the produce was reduced to reach the seven-eighth of the difference between the initial temperature of the corn and the water evaporation temperature corresponding to the inside room pressure (Rennie et al., 2000). The corn was then removed from the cooler.

Two other experimental units were placed inside a closed corrugated carton box for room cooling at 1°C and 90-95% RH. After the cooling period, all corn cobs were placed in the same conditioned room for 7 and 21 days of storage. The plastic boxes containing the corn cobs were covered with perforated plastic bags to ensure high humidity and to avoid desiccation of the commodity.

Experimental procedures for forced-air and hydrocooling are described in detail in Chapters IV and V, and the results were used here for comparison purposes.
6.3.4 Quality measurement

The mass of the corn cobs was measured immediately after harvest; after precooking, and after each storage period. The mass loss after the cooling process and the storage period were calculated as the percent difference between the initial and the final mass of the produce at the measurement point divided by the initial mass. The moisture content and the total soluble solids percentage (TSS) of the corn were also measured (Chapters IV; V).

Visual quality was evaluated for individual cobs before any cooling and on days 7 and 21 using a nine point hedonic scale for the subsequent parameters (Brecht et al., 1990): husk color, husk drying, silk appearance, kernel appearance and presence of defects. The quality index (QI) scale (Table 6.2) summarising all these parameters was determined and the total score for each parameter was calculated according to the method presented by Rodov et al. (2000). An analysis of variance (ANOVA) followed by Duncan’s test for comparison of the means was conducted using XLSTAT – Pro 7 software (Addinsoft, Paris, France).

Table 6.2 Full description of quality index scales of sweet corn (Vigneault et al., 2004b).

<table>
<thead>
<tr>
<th>Quality Index</th>
<th>Quality</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Excellent</td>
<td>Husks of freshly harvested, turgid appearance, dark green, slightly moist. Silks light-colored (greenish-yellow) and turgid. Kernels bright and very turgid. Absence of major defects.</td>
</tr>
<tr>
<td>5</td>
<td>Average</td>
<td>Pale green husks, withered or slightly dry. Silks lightly browning, some dried. Kernels dull but not dented. Absence of major defects.</td>
</tr>
<tr>
<td>3</td>
<td>Poor</td>
<td>Husks very pale, some yellowing and perhaps browning, much withered and partly dry. Silks brown, soft and possibly dry. A few dented kernels. Major defects possible.</td>
</tr>
<tr>
<td>1</td>
<td>Unmarketable</td>
<td>Husks yellow, straw-colored or brown. Very withered or dry. Many dented kernels. Major defects present.</td>
</tr>
</tbody>
</table>
6.4 Results and Discussion

6.4.1 Starting quality

The initial quality attributes of corn cobs measured immediately after harvest were used as reference for quality evolution. Despite high quality index was observed for the three cultivars, “Fleet” was significantly lower in quality compared to others. Although the three cultivars were classified as sugary enhanced (se) sweet corn, they were significantly different in their degree of sweetness. TSS level reached up to 27% for “Sensor” cultivar while reaching only 23% and 21% in the case of “Fleet” and “Promise” cultivars respectively. Since the juiciness can play a major role in quality of corn; one could expect better quality conservation from the higher moisture content obtained from the “Fleet” and “Promise” cultivars compared to the “Sensor” one (Table 6.5).

6.4.2 Precooling performance measurement

6.4.2.1 Cooling time

HCT of sweet corn obtained in room cooling (436 min) is by far higher to that of vacuum (Table 6.3). It was reduced by 97% under vacuum cooling condition. Further, there was no significant difference in the HCT between core and kernel position measurement which corresponds to the theoretical assertion claiming the cooling rate at any point in a uniform produce should be the same (Holman, 1986).

The results of HCT for different cooling techniques are also presented in Table 6.3. Among the three precooling methods, higher half cooling time was observed using forced-air system followed by water which was three times less. Vacuum cooling provided an HCT of 12 min, resulting in four times less than the time taken in forced-air coolers. Room cooling took tremendously much longer time (HCT = 436 min) compared to other methods to cool down the same amount of sweet corn. For all precooling methods, cooling time was reduced during the experiment with cultivars “Fleet” and “Promise” compared to “Sensor”. This difference is likely due to their smaller diameter.
Larger diameter cobs took longer time to cool down which agrees with the theory (Goyette et al., 1996).

**Table 6.3** Half cooling time (HCT) and mass loss (%) for this four cooling methods tested.

<table>
<thead>
<tr>
<th>Cooling method</th>
<th>HCT (min) Core</th>
<th>HCT (min) Kernel</th>
<th>Mass change during cooling (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td>12.4\textsuperscript{c}</td>
<td>11.9\textsuperscript{c}</td>
<td>-4.12\textsuperscript{c}</td>
</tr>
<tr>
<td>Hydro</td>
<td>16.1\textsuperscript{c}</td>
<td>15.8\textsuperscript{c}</td>
<td>9.48\textsuperscript{a}</td>
</tr>
<tr>
<td>Forced-air</td>
<td>47.3\textsuperscript{b}</td>
<td>47.1\textsuperscript{b}</td>
<td>-2.96\textsuperscript{bc}</td>
</tr>
<tr>
<td>Room</td>
<td>436.7\textsuperscript{a}</td>
<td>434.6\textsuperscript{a}</td>
<td>-0.38\textsuperscript{b}</td>
</tr>
</tbody>
</table>

*Values in the same column with the same letter are not significantly different at $\alpha = 0.05$.

In terms of mass loss, higher percent (4%) was obtained during vacuum precooling. Contrary to vacuum cooling mass loss effect, mass loss was avoided and water was even added to the produce (+9.5%) during hydrocooling process (Table 6.3). The lowest next percent loss for sweet corn was obtained after 20 hours of room cooling, likely due to higher facility to maintain high relative humidity with still air movement inside the box.

6.4.3 Quality preservation

The effect of different cooling methods on quality attributes of sweet corn stored for 7 and 21 days at 1°C is presented in Table 6.4. Quality of sweet corn is inversely related to the length of storage. For the same storage duration, results have showed that quality factors including TSS and moisture content were similar among the different combinations tested; whereas, room cooling retained lower mass loss with lower TSS and quality index values. On the other hand, higher quality was obtained with hydrocooling technique after 7 and 21 days of storage. Sweet corn benefited from all cooling methods as it was possible to store this highly perishable commodity for duration up to 21 days at 1°C while maintaining high TSS and moisture content with good market quality.
Table 6.4 Quality attributes of cooled sweet corn cobs after 7 and 21 days of storage at 1°C.

<table>
<thead>
<tr>
<th>Cooling Method</th>
<th>Mass change during storage (%)</th>
<th>TSS (%)</th>
<th>Moisture content (%)</th>
<th>Quality Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vacuum</td>
<td>-5.01&lt;sup&gt;c&lt;/sup&gt;</td>
<td>22.18&lt;sup&gt;a&lt;/sup&gt;</td>
<td>74.60&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.04&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Hydro</td>
<td>6.25&lt;sup&gt;a&lt;/sup&gt;</td>
<td>21.32&lt;sup&gt;a&lt;/sup&gt;</td>
<td>76.17&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.99&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Forced-air</td>
<td>-3.73&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>22.13&lt;sup&gt;a&lt;/sup&gt;</td>
<td>74.16&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.06&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Room</td>
<td>-1.96&lt;sup&gt;b&lt;/sup&gt;</td>
<td>20.90&lt;sup&gt;a&lt;/sup&gt;</td>
<td>74.20&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.04&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>21 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vacuum</td>
<td>-5.54&lt;sup&gt;c&lt;/sup&gt;</td>
<td>21.83&lt;sup&gt;a&lt;/sup&gt;</td>
<td>74.11&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.83&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Hydro</td>
<td>5.68&lt;sup&gt;a&lt;/sup&gt;</td>
<td>20.39&lt;sup&gt;a&lt;/sup&gt;</td>
<td>74.92&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.71&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Forced-air</td>
<td>-3.46&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>21.67&lt;sup&gt;a&lt;/sup&gt;</td>
<td>73.79&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.92&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Room</td>
<td>-2.29&lt;sup&gt;b&lt;/sup&gt;</td>
<td>19.76&lt;sup&gt;a&lt;/sup&gt;</td>
<td>73.26&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.48&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>*Values in the same column with the same letter and storage duration are not significantly different at α = 0.05.</sup>

6.4.4 Cultivar effects

Table 6.5 showed the effect of vacuum precooling on the quality factors of the three sweet corn cultivars after storage. For all the three cultivars, mass loss percent has significantly increased over time as expected. However, TSS reduction was different among cultivars. This loss of sweetness was higher after 21 days of storage in the case of “Promise” with 11.7% followed by “Fleet” and “Sensor” cultivars with 8% and 5.4% respectively. Moisture content was maintained similar to the initial value for all the three cultivars with a tendency to decrease over time. Furthermore, quality index was significantly reduced after 7 and 21 days except for the cultivar “Fleet” which maintained high quality index over time.
Table 6.5 Quality attributes for different vacuum precooled cultivars of sweet corn after storage at 1°C.

<table>
<thead>
<tr>
<th>Storage duration (days)</th>
<th>Mass loss during storage (%)</th>
<th>TSS (%)</th>
<th>Moisture content (%)</th>
<th>Quality index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fleet</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.00&lt;sup&gt;a&lt;/sup&gt;</td>
<td>22.70&lt;sup&gt;a&lt;/sup&gt;</td>
<td>75.70&lt;sup&gt;a&lt;/sup&gt;</td>
<td>7.75&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>7</td>
<td>4.36&lt;sup&gt;b&lt;/sup&gt;</td>
<td>21.08&lt;sup&gt;b&lt;/sup&gt;</td>
<td>75.67&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.56&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>21</td>
<td>4.74&lt;sup&gt;c&lt;/sup&gt;</td>
<td>20.88&lt;sup&gt;b&lt;/sup&gt;</td>
<td>75.08&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.50&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Sensor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.00&lt;sup&gt;a&lt;/sup&gt;</td>
<td>27.10&lt;sup&gt;a&lt;/sup&gt;</td>
<td>68.80&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8.87&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>7</td>
<td>5.63&lt;sup&gt;b&lt;/sup&gt;</td>
<td>26.05&lt;sup&gt;b&lt;/sup&gt;</td>
<td>68.34&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.18&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>21</td>
<td>6.08&lt;sup&gt;b&lt;/sup&gt;</td>
<td>25.63&lt;sup&gt;c&lt;/sup&gt;</td>
<td>68.09&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4.94&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Promise</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.00&lt;sup&gt;a&lt;/sup&gt;</td>
<td>21.50&lt;sup&gt;a&lt;/sup&gt;</td>
<td>76.50&lt;sup&gt;a&lt;/sup&gt;</td>
<td>8.69&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>7</td>
<td>5.06&lt;sup&gt;b&lt;/sup&gt;</td>
<td>19.41&lt;sup&gt;b&lt;/sup&gt;</td>
<td>76.40&lt;sup&gt;a&lt;/sup&gt;</td>
<td>6.68&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>21</td>
<td>5.79&lt;sup&gt;c&lt;/sup&gt;</td>
<td>18.98&lt;sup&gt;c&lt;/sup&gt;</td>
<td>76.21&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.75&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>*Values in the same column with the same letter and sweet corn cultivar are not significantly different at α = 0.05.</sup>

Similar effect was observed with other precooling methods for the cultivar “Fleet” which maintained best quality attributes for duration up to 21 days in storage (Chapters IV; V). However, for all the three cultivars, higher percent reduction in TSS content between 0 and 21 day interval was observed with hydrocooling (Fleet = 16%, Sensor = 8.7%, Promise = 19.7%) compared to vacuum (Fleet = 8%, Sensor = 5.4%, Promise = 11.7%) and forced-air cooling (Fleet = 10%, Sensor = 5.4%, Promise = 14.9%). This effect is likely due to the diffusion of water inside the kernels of corn cob resulting in the dilution of the soluble solids causing a higher reduction in the degree of sweetness of the kernel.

For all the precooling techniques, the selection between sweet corn cultivars can be limited to their diameter which affects the cooling time, their supply into the market which is related to the maturity stage, and the preference of the consumers in terms of sweetness and juiciness. For example, the cultivar “Fleet” can be best chosen for its high quality after storage; whereas, the cultivar “Sensor” has shown the lowest percent loss of sweetness over time.
6.5 Conclusion

Vacuum cooling was the most rapid cooling technique for sweet corn; whereas, it caused significant mass loss to the produce followed by forced-air precooling method. All compared cooling techniques were very similar in terms of the effect on the quality of sweet corn cobs even after 21 days at 1°C and 90-95% RH. The tendency of reduction in the produce quality attributes for room cooling exists; while the hydrocooled produce retained the highest marketable quality. Best hygienic procedures are required in water cooling to avoid microbial contamination; cleanliness of water should be done at a regular basis by adding chlorine followed by draining out of water at each use of the system. Forced-air cooling was also a good method to cool down sweet corn by taking into consideration its reduced cooling rate. The three cultivars of sweet corn gave different results during storage after precooling; the cultivar “Fleet” preserved its superior quality compared to the other two cultivars used in the study.
6.6 References


VII. GENERAL SUMMARY AND CONCLUSIONS

Precooling process was beneficial for sweet corn from two different points of view. The first is to reduce the half cooling time of the produce inside the cooler, and the second is to maintain the storage life of sweet corn for duration up to 21 days at 1°C.

For forced-air cooling, the results showed a decrease of 49.3% in the HCT as the air flow rate was increased from 1 to 3 L·s⁻¹·kg⁻¹ under perpendicular cob orientation. This reduction was about 42.3% when the produce was completely immersed into cold water and perpendicularly oriented to the direction of water flow compared to parallel and spray type hydrocooler. However, under the same conditions, HCT was reduced by 90% and 96% with forced-air and hydrocooling respectively when compared to room cooling. This effect may be due to a higher turbulent medium (air or water) movement reducing the immobile film thickness of the medium at the surface of the produce as it hits the produce perpendicularly. The perpendicular ears are exposed to a maximum degree of contact with the fluid, and the cooling is achieved in all locations throughout the entire length of the cob at the same time. Vacuum was the most rapid precooling method providing a HCT of 12 min, resulting in four times less than the time taken in forced-air coolers. Room cooling took much longer time to cool the produce compared to other methods. For all cooling methods, there was no significant difference in the HCT between the core and kernel. This observation agrees with the theoretical assertion claiming the cooling rate at any point in a uniform produce should be the same (Holman, 1986).

In terms of mass loss, vacuum cooling caused higher percent loss (4%) followed by forced-air. During hydrocooling, water was added to the produce (+9.5%). The lowest percent mass loss for sweet corn was obtained after 20 hours of room cooling, likely due to higher facility to maintain high relative humidity associated with still air around the produce.

Different combinations used for forced-air and hydrocooling produced similar results in terms of quality attributes of sweet corn for the same storage period; hence, these combinations had no effect on the quality of the produce over time. For room cooling, the quality of sweet corn cobs was reduced for duration up to 21 days at 1°C and
90-95% RH; while, hydrocooled produce retained its best marketable quality. Sanitation practices are required in water cooling to avoid microbial contamination and to ensure cleanliness of water at a regular basis.

The use of three cultivars of sweet corn was important so that their quality factors could be evaluated after precooling. The cultivar “Fleet” maintained its superior quality among the three cultivars used. The cultivar selection can be limited to their size which affects the cooling time, their availability during a season, and the preference of the consumer in terms of sweetness and juiciness.

Finally, the performance of existing systems can be improved if the operators make modifications recommended in this study. Additional studies are required to provide more thorough advice to the packing-house precooling operators.
REFERENCES


