Rapid cooling of porous and moisture foods by using vacuum cooling technology

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Vacuum cooling is a rapid evaporative cooling method for porous and moisture foods to meet the special cooling requirements. Vacuum cooling has been used as an effective method for pre-cooling certain type of horticultural products such as vegetables and fruits to prolong their storage life by reducing post-harvest thermal deterioration. Vacuum cooling has also been successfully applied to the processing procedures for some foods such as liquid and baked foods to improve the processing efficiency by shortening the cooling time. Recent research has highlighted the feasibility of vacuum cooling for cooked meats, fishery products and ready meals, for which rapid cooling is beneficial to controlling growth of micro-organisms and preserving quality of the products. © 2002 Elsevier Science Ltd. All rights reserved.

Introduction
Vacuum cooling, like vapour-compression refrigeration, is based on liquid evaporation to produce a cooling effect. The difference between vacuum cooling and conventional refrigeration methods is that for the vacuum cooling the cooling effect is achieved by evaporating some water from a product directly, rather than by blowing cold air or other cold medium over the product (Mellor, 1980). Speed and efficiency are two features of vacuum cooling, which are unsurpassed by any conventional cooling method, especially when cooling boxed or palletised products. Cooling time, in the order of 30 min ensures that tight delivery schedules and strict cooling requirements for the safety and quality of foods can be met (Malpas, 1972).

Any product which has free water and whose structure will not be damaged by the removal of such water can be vacuum cooled. The speed and effectiveness of vacuum cooling are mainly related to the ratio between its evaporation surface area and the mass of foods (Noble, 1985). Vacuum cooling has been satisfactorily used to remove field heat of horticultural products in the United States since the 1950s (Thompson & Rumsey, 1984), and proven to be an effective method for pre-cooling certain types of fresh vegetables such as lettuce and mushroom (Anon., 1981). It can significantly reduce postharvest deterioration of vegetables, thus prolonging their storage life. For the same reason, vacuum cooling is also a very effective method for the pre-cooling of floricultural products to prolong the vase life of flowers (Brosnan & Sun, 2001; Gao, Sun, Guo, & Xu, 1996; Sun & Brosnan, 1999). However, if there is a low ratio between the surface area and the mass, or an effective barrier to water loss from the produce surface, vacuum cooling may be very slow. Produces such as tomatoes, apples and pepper, which have a relatively thick wax cuticle, are not suitable for vacuum cooling (Longmore, 1973).

Vacuum cooling has been successfully applied to the processing procedures for some foods, such as liquid foods and baked foods, to reduce the cooling time for improvement of the efficiency of the processes and reduction of the distribution time to markets (Anon., 1978; Shen, 1983).

Recently, vacuum cooling has been investigated as an effective cooling method for cooked meats as typical conventional cooling methods cannot achieve a rapid cooling for cooked meats (Burfoot, Self, Hudson, Wilkins, & James, 1990).
Vacuum cooling principle and equipment

Vacuum cooling principle

Liquid evaporation is the most popular cooling sink in the refrigeration industry. Whenever any portion of a liquid evaporates to become its vapour state, an amount of heat equal to the latent heat of evaporation must be absorbed by the evaporated portion either from the liquid body or from the surroundings, resulting in reduction of the temperature of the liquid body or surroundings (Dossat, 1991). Water boils at 100°C if it is subjected to the atmospheric pressure (1 atm). However, reduction in the imposed pressure on water lowers the boiling temperature of water, that is, water can also boil at as a low temperature as 0°C if the imposed pressure is reduced to 611 Pa. The imposed pressure on water determines the minimum temperature, which can cause water to boil to produce a cooling effect (Perry, Green, & Maloney, 1984).

If porous and moisture foods are subjected to vacuum pressure, part of water within the foods can boil out to achieve the cooling effect for the food bodies at a temperature as low as the saturation temperature of water related to the vacuum pressure. Generally, most of foods have two main compositions: water and solid texture. Therefore, the refrigerant used in a vacuum cooler is not pure water but one of the food compositions. The temperature decrease caused by per unit of percentage weight loss is determined by

\[
\eta_T = \frac{\Delta T}{\Delta m_w/m_p} = \frac{h_{fg}}{c}
\]

As shown in eqn (1), the specific heat of foods determines the temperature decrease per unit of the percentage weight loss. Table 1 gives the specific heat, and the calculated temperature decrease caused per unit of the percentage weight loss for pure water and some typical foods (McDonald & Sun, in press-a; Sweat, 1994).

A typical vacuum cooler

Since porous and moisture foods can be cooled directly by boiling part of the moisture in the foods at a low temperature under vacuum pressure, a vacuum cooler is really a system to maintain the required vacuum pressure. A typical vacuum cooler is illustrated in Fig. 1, which consists of two basic components: a vacuum chamber and a vacuum pumping system (Longmore, 1974; Sun & Wang, 2001). The vacuum cooling process occurs in two fairly distinct stages: (a) the removal of most of the air in the chamber to the flash point, or the saturation pressure at an initial temperature of foods, with relatively little cooling, and (b) the continuous drop of the pressure in the vacuum chamber to final pressure with main cooling phase of the products.

The vacuum chamber, which is normally horizontal with cylindrical or rectangular construction, is used to keep the foods. During the cooling process, the door of the chamber is hermetically sealed and any leakage of

### Table 1. Moisture, specific heat and temperature decrease per unit of percentage weight loss for pure water and some typical foods

<table>
<thead>
<tr>
<th>Moisture (%)</th>
<th>c (kJ/kg °C)</th>
<th>(\eta_T) (°C/1% weight loss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>100</td>
<td>4.2</td>
</tr>
<tr>
<td>Leafy vegetables</td>
<td>90</td>
<td>3.9</td>
</tr>
<tr>
<td>Cooked meats</td>
<td>74</td>
<td>3.5</td>
</tr>
<tr>
<td>Baked foods</td>
<td>35</td>
<td>2.6</td>
</tr>
</tbody>
</table>

McDonald and Sun (in press-a); Sweat (1994).
air into the vacuum cooler increases the load of the vacuum pumping system (Malpas, 1972).

The pumping system may have two elements, which are a vacuum pump and a vapour-condenser. The vacuum pump is usually designed to reduce the pressure in the vacuum chamber from the atmospheric pressure to the saturation pressure at the initial temperature of foods such as vegetables and fruits for 3–10 min (Longmore, 1973). The rotary oil-sealed vacuum pump is widely chosen for a vacuum cooler. The required pumping speed (m³/h) can be determined by (Andrew, 1963):

\[
S = \frac{V_t}{t/3600} \ln \frac{P_0}{P_{tp}}
\]

(2)

The vapour-condenser in effect acts as a vacuum pump to remove the vapour in the vacuum chamber by condensing the vapour back into water and then drain the water out. However, it should be noted that the cooling effect for foods comes from the water evaporation in foods, and application of a vapour-condenser in a vacuum cooler is only for practical and economical removal of a large amount of vapour generated. The necessity of a vapour-condenser in a vacuum cooler can be confirmed by the following example.

The total evaporated water (weight loss of food) during vacuum cooling of a food product can be calculated by (Rennie, Raghavan, Vigneault, & Gariepy, 1999)

\[
\Delta m_w = \frac{c m_p \Delta T}{h_{fg}}
\]

(3)

If the vapour is assumed to be an ideal gas, the volume of the vapour expanded by the evaporated water is given by (Finn, 1993)

\[
V = \frac{\Delta m_w}{M_w} \frac{RT_{x,vc}}{P_{vc}}
\]

(4)

If a vacuum cooler is used to cool 1000 kg vegetables from the temperature of 25 to 5°C, the evaporated water calculated by eqn (3) should be about 31 kg. Therefore, the total volume of steam calculated by eqn (4) is above 4300 m³ at the temperature of 25°C and pressure of 1 kPa. If the cooling time is 30 min, including 5 min to evacuate the pressure in the chamber to the flash point, and the system is air tight, the pumping speed should be around 10,300 m³/h. In practice, it is difficult for a vacuum pump or even for a group of vacuum pumps in parallel to achieve this load. Furthermore, the capital cost of the vacuum pump increases significantly with the increase in its displacement.

Advantages and disadvantages of vacuum cooling

The major advantage of vacuum cooling is the fast cooling rate, compared with conventional cooling methods. For example, experimental results of cooling vegetables show that average cooling rate achieved by vacuum cooling is 0.5°C/min, which is 60 times that of slow air cooling. For the slow air cooling, the heat generated by respiration may result in the vegetables still being above cold-store temperature 24 h after loading (Longmore, 1973).

A uniform and rapid cooling can be achieved for an individual food body and a package of foods by vacuum cooling if the porosity is uniformly distributed within the food body and package. For example, for vacuum

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Fig. 1. A typical vacuum cooler.
cooling of packaged moisture foods, no matter where the individual food body may be located in a package or bulk container, a uniform temperature distribution can be achieved as a result of the cooling effect directly comes from water evaporation in local pores. However, for the cold store cooling, the cooling rates for individual food body may vary between 0.05 and 3 °C/h depending on the type of container and location of the product in a stack or pallet load. If the air blast cooling at a temperature below freezing point of water is used, the outer surfaces of the product will be damaged due to freezing whilst the inside is still cooled inadequately (Longmore, 1971).

Vacuum cooling has the lowest energy cost per unit of cooled product compared with air cooling and hydrocooling (Chen, 1986). This is because there is no need to move the cooling medium through the system and the vacuum minimizes heat transfer from the environment. For vacuum cooling of one ton of lettuce, the energy consumption is about 0.56 kWh to reduce 1 °C, compared with 3.7 kWh to reduce 1 °C for hydrocooling. If the driving energy is electrical energy, for pre-cooling vegetables and fruits, the COE (ratio of heat removed from the product over driving energy) of the vacuum cooling unit is 2.65, compared with 0.52 for forced air cooling systems and 1.20 for hydro-coolers. However, the COE varies between different coolers of the same type. There are two main factors affecting the COE, which are the type of product to be cooled and the load of product within the cooling chamber (Chen, 1986).

Furthermore, vacuum cooler is very sanitary because air goes into the container only when the container is opened to release the vacuum. Almost any type of package is suitable for vacuum cooling provided that the package containing the product is porous or has breathing holes or spaces. The precise temperature control can also be achieved during the vacuum cooling process. The temperature of the products can be brought within 1–3 °C by controlling the absolute pressure (Longmore, 1973).

Vacuum cooling also has its disadvantages. For example, vacuum cooling can not replace established freezing techniques (Longmore, 1971). Furthermore, weight loss occurs during vacuum cooling. The weight loss of vegetables is about 3–4% of the weight before vacuum cooling but similar losses may be experienced in cold store cooling.

However, the weight loss of vacuum cooled foods may be reduced by adding a suitable amount of water to the cooled foods. For this purpose, a special water sprayer is installed in a vacuum cooler (Thompson, 1996). Alternatively, a pre-selected volume of water is added to the product packaged in the moisture-impermeable plastic bags and the free ends of the bag are tucked in, providing a loose closure. The package is then palletised and inserted into a vacuum cooler (Muse & Stanish, 1996). The foods can also be pre-wetted to absorb an amount of water before vacuum cooling (Sun, 1999a).

**Traditional applications**

**Vacuum cooling of vegetables and fruits**

**Vacuum cooling of lettuce**

Lettuce is most suited to vacuum pre-cooling. Today vacuum cooling is the standard commercial process used for lettuce not only in US, but also in many European countries (Haas & Gur, 1987). Before vacuum cooling, iceberg lettuce is normally wrapped in PVC stretch film, packed in cartons and stacked on pallets (Haas & Gur, 1987). A field test showed that for cooling four pallets of 700 kg lettuce each and 2800 kg totally by a commercial vacuum cooler, the best result could be obtained by using a nominal pumping of 1660 m³/h during the first 10 min and afterwards by using a nominal pumping of 1250 m³/h to continue the cooling process. In this case, after vacuum cooling for 32 min, the low and uniform final temperatures were reached. The final temperature of the lettuce leaves was 0.3–1.1 °C and 1.6–2.3 °C for the butts, which is also the recommended final temperature for unwrapped lettuce.

Weight loss, wilting, physiological disorders, bacterial decay and overall visual quality were measured for the lettuce heads: (1) vacuum cooled heads and then packed in closed polypropylene (PP) film, (2) individual vacuum cooled head in perforated PP film, (3) naked vacuum-cooled heads, (4) naked heads, (5) individual head wrapped in perforated PP film, and (6) individual head in sealed PP bags (Artes & Martinez, 1994). The lettuce heads, which were vacuum cooled for 20 min, sealed by PP film, and followed by 1 week of storage at 2 °C show the best results with an extension of shelf-life for 2.5 days of display at 12 °C.

The storage conditions recommended for lettuce are 0–5 °C, 1–5% O₂ and 0–2% CO₂. However, it is difficult to obtain simultaneously low O₂ and CO₂ concentrations and more research is needed to find an available commercial film that can provide a considerable reduced level of O₂ (near 5%) and a level of CO₂ not higher than 2%. Vacuum cooling can affect the gas composition within sealed bags. Only perforated films can, however, be used if the lettuce is wrapped before vacuum cooling. Cooling performance also depends on the types of film. The more stretchy or pliable film provides the least cooling. A tighter wrap decreases ventilation space between the lettuce and the film, and excessive film wrapping blocks the evacuation of water vapour (Cheyney, Kasmire, & Morris, 1979).

**Vacuum cooling of mushrooms**

As mushrooms have approximately 90% water and the porous structure of the mushroom sporophore...
allows water to escape very readily, they would therefore appear to be suitable for vacuum cooling (Noble, 1985). Experiments were carried out to compare the effects of vacuum cooling on browning and hyphal structure of mushrooms with those of conventional cooling. The first sample was cooled by vacuum cooling and then put into a cold store maintained at 5°C and 86–88% RH (relative humidity), the second sample was put into the cold store directly, and the third sample was held at the ambient environment with the temperature of 18°C and 76–78% RH (Frost, Burton, & Atkey, 1989). Results showed that there were no differences in quality and hyphal structure between the vacuum cooled mushrooms and the conventionally cooled ones, both of which were subsequently stored at 5°C. However, vacuum cooled mushrooms were significantly better than conventionally cooled mushrooms in colour if they were stored at 18°C for a period. There is no apparent damage or change in hyphal structure of the vacuum cooled cap tissue, compared with that of the conventionally cooled one. Browning of the mushroom cap, which is the main criterion of quality, can be measured as loss of whiteness using a reflectometer. There was no significant difference in reflectance between vacuum cooled and conventionally cooled mushrooms when the mushrooms were kept at 5°C continuously for 102 h. It should be noted that the vacuum cooled mushrooms were much less brown than those conventionally cooled when the cool chain was broken and the mushrooms cooled by two cooling methods were transferred to 18°C after 102 h.

The measured weight loss of vacuum cooled mushrooms from 21 to 1°C was 3.6% of weight before cooling, which was almost twice as high as the value of 2% for air blast cooling. However, the experimental results also showed that the total weight loss of the vacuum cooled mushrooms was almost as small as that of the air blast cooled mushrooms after cooling treatment followed by storage for 5 days at 1°C. Therefore, the weight loss of the vacuum cooled mushrooms was lower than that of the air blast cooled mushrooms during the storage period (Sun, 1999a). The mushrooms can absorb as much as 6% of their weight in water if they are wetted for 5 min. Therefore, wetting mushrooms before cooling is an effective method to reduce the weight loss during vacuum cooling (Sun, 1999a).

Experiments were also carried out to evaluate the effects of different packages on the weight loss and quality of mushrooms (Barnard, 1974). However, it should be noted that only packages with perforations could be used to wrap mushrooms before vacuum cooling. The weight loss of mushrooms was evaluated at given time intervals during cooling and storage periods. The results showed that, the greater the exposed surface area of mushrooms, the greater the weight loss. In all cases, the wrapped and then vacuum cooled open mushrooms had better quality than those vacuum cooled and then wrapped. Both treatments were superior to non-vacuum cooled but wrapped ones. The overall weight loss of vacuum cooled and wrapped mushrooms over a seven-day cold storage was less than 4.5%. However, after seven days, the weight loss of the cooled mushrooms stored in chip baskets was as high as 10.3%.

Vacuum cooling of other vegetables

Conventional cooling such as cold storage, air blast and water immersion cannot provide a rapid cooling treatment for broccoli because the poor thermal conductivity of broccoli controls the heat transfer rate (Hackert, Morey, & Thompson, 1987). However, vacuum cooling is also an effective rapid cooling method for broccoli (Sun, 1999b, 2000). As shown in Fig. 2, it takes only 9 min for an experimental vacuum cooler to reduce the core temperature of broccoli from 20 to 2.5°C, compared with 65 min for an air blast cooler.

Vacuum cooling of non-leafy vegetables, i.e. eggplant, cucumber and carrot is also reported (Hayakawa, Kawano, Iwamoto, & Onodera, 1983). However, vacuum cooling rate for non-leafy vegetables is much lower than that for leafy vegetables such as lettuce. The vacuum cooling rate of cucumber is the lowest among these three mentioned non-leafy vegetables. The reported weight loss of vacuum-cooled eggplant and carrot is 2.80 and 3.45%, respectively, for each 10°C temperature reduction. Although it is possible to reduce the weight losses to a certain extent by pre-wetting, it is difficult to keep such conditions in operation for non-leafy vegetables (Hayakawa et al., 1983).

Fruits such as strawberries can also be vacuum cooled to minimize deterioration process during storage and...
Vacuum cooling of baked products

The integration of vacuum cooling system into a part of baked bread lines has been a recent process advance. This technique is known as modulated vacuum cooling, for the rapid cooling of bakery products from the oven (Bradshaw, 1976). In this case, vacuum cooling takes place immediately after bread and similar products are removed from the oven and before packaging in order to avoid vapour condensation in the wrapping, particularly in plastics bags. Bread rolls, crusty breads, biscotti, bread cakes and baked biscuits have all been proven to be suitable vacuum-cooled baked products.

There are two main types of modulated vacuum-cooling systems used by the bakery industry, which are the rack cooler and in-line cooler (Everington, 1993). The rack cooler is essentially a batch-cooling system. The racks are used to load the baked products and then pushed into the vacuum chamber. The in-line cooler operates on the same principle with the exception that the conveyor runs through the vacuum chamber.

The precise control over cooling rates coupled with increased product stability is the main product benefit. The distribution of the humidity through the vacuum-cooled loaf is more even, which is a vital control factor in extending the shelf life of the baked products. Furthermore, the product is cooled in a sterile vacuum environment. Any spores entering the vacuum chamber during the loading cycle are carried away from the product surface by the flow of air and vapour during the cooling cycle and the air is readmitted via a micro-biological filter system at the end of cooling cycle. The shape and texture of vacuum-cooled products are also superior to the air-cooled product. The total time required for the complete baking cycle with vacuum cooling is also reduced by 2 h over conventional cooling methods. The shortened cooling time gives important production advantages: the manufacturing process becomes more effective as waiting time for the cooled product is removed. Baking can be continued to the end of the working shift, thus leading to greater plant utilisation. The deliveries of the product can leave the bakery up to 2 h earlier than before (Anon., 1978; Bradshaw, 1976).

Vacuum cooling of bakery products typically takes place in a temperature range between 98 and 30°C and the temperature drop is about 68°C. Therefore, the weight loss is about 6.8% depending on the specific heat of the products. If the product is cooled in air and the weight loss would be between 3 and 5% depending on air velocity, humidity and temperature. The penalty in weight loss is small and this difference can be compensated for by the lower weight loss of vacuum cooled strawberries than that of conventionally cooled ones during subsequent distribution.

Vacuum cooling of some fluid foods

Many liquid foods, such as soups, beer, milk and sauces are produced by heating and cooling the ingredients in a closed batch vessel. These products have two common characteristics: containing high moisture and evaporating part of it easily. Vacuum cooling can thus be chosen as a rapid cooling method for these products. However, the main attention should be paid to the correct size and integration of the process equipment to ensure an adequate and reasonable cooling rate. It was reported that vacuum cooling was used to cool a blueberry fruit product in the preparation of yoghurts, which is a concentrated sugar solution with a refractometric dry matter. Experiment results show that it only took about 5 min to cool 500-l batches of blueberry fruit product with a mean refractometric dry matter of 61%, from 90 to 50°C. Vacuum cooling can thus reduce the processing time of liquid foods significantly (Houska et al., 1996).

In the distilling industry, the gelatinised liquid and mash used in the continuous production of potable alcohol are usually vacuum cooled (Shen, 1983). In the confection industry, an aerated gum confection is produced by preparing a plastic semi-solid candy mass, mixing the mass with a gum base and other desirable flavouring and colouring additives to form a homogeneous batch material, forming into discrete pieces and subjecting the pieces to vacuum cooling to expand the pieces into an aerated gum confection (Elias, 1985). Vacuum cooling is also introduced in the butter production line to evaporate hot high-fat cream for rapid and uniform crystallisation of high and medium melting triglycerides and for destabilisation of the fat emulsion. In operation under factory conditions it produces high quality butter similar to conventional butter but with considerable saving in costs (Kuzmin, Strakhov, & Gisim, 1974).

Advanced applications

Vacuum cooling of cooked meats

Current cooling status

Meats in their natural states are particularly susceptible to spoilage under normal conditions due to their intrinsic nature. A variety of preservation techniques have been developed to supply meat products with a...
High quality and safety to the consumers. The cooking process is widely used to ensure destruction of vegetative stages of any pathogenic micro-organisms. However, there is always the possibility that some micro-organisms that produce spores will not be killed during the cooking process. At the temperature range from about 7 to 60°C, these surviving organisms can readily multiply (Anon., 1989, 1991). Therefore, the temperature of the cooked meats should be rapidly reduced through the dangerous temperature region to prevent multiplication. Furthermore, rapid reduction in temperature of cooked meats aids in the retention of nutrients (Evans, Russell, & James, 1996). Improper storage and/or inadequate cooling practices in retail food operations have been cited as the cause for food poisoning for 97% of *Clostridium perfringens* and 34% of *Clostridium botulinum* outbreaks (Bean & Griffin, 1990).

The outbreaks clearly stress the importance of cooling foods quickly after cooking. Therefore, guidelines for the cooling process of cooked meats have been issued and recommended by governments of some countries in Europe. In Ireland, it is recommended that joints of meat should be chilled from 74 to 10°C within 2.5 h after removal from the cooking process (Anon., 1991). Other countries in Europe also have similar guidelines (Anon., 1989).

In the cooked meat industry, cooling is usually accomplished by using the conventional methods of slow air, air blast and water immersion cooling. During the conventional cooling, the heat is removed from the core of the joint to the surface by conduction and then released to the cooling medium such as air or water mainly by convection. The surface heat transfer can be easily enhanced by increasing the velocity of the cooling medium. A high heat transfer coefficient of surface convection can cause the surface temperature to approach the temperature of the cooling medium after a very short cooling period. However, the temperature of the core cannot be reduced so quickly because the heat transfer from the core to the surface is by conduction. Cooked meat joints are inherently slow to cool by the conventional cooling methods because they have poor thermal conductivity and large dimensions, which put a limit on the cooling rate. Thus, rapid cooling cannot be achieved for large cooked meat joints by using the conventional cooling methods (Sun & Wang, 2000). If these methods are used, in order to meet the government guidelines on the cooling requirements, the shortest dimension of the meat should not exceed a certain value. However, many cooked meat processors and caterers still produce large meat joints (up to 8 kg) for economic reasons (Burfoot *et al.*, 1990).

**Cooling rate**

For cooling large commercial cooked meat joints from the initial temperature of about 70–74°C to below 10°C by vacuum cooling and conventional cooling such as slow air, air blast and water immersion cooling, the experimental cooling rates are given in Fig. 3. The cooling rates are based on the decrease of maximum temperature with cooling time. The maximum temperature during conventional cooling processes is located in the core of a meat body. However, it should be noted that the maximum temperature of cooked meats during vacuum cooling is not always the core temperature since

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**Table 2. Weight loss of cooked meat joints during vacuum cooling and conventional cooling**

<table>
<thead>
<tr>
<th>Cooling method</th>
<th>Temperature (°C)</th>
<th>Velocity (m/s)</th>
<th>Relative humidity (%)</th>
<th>Initial weight (g)</th>
<th>Brine injection level (%)</th>
<th>Initial T&lt;sub&gt;aver&lt;/sub&gt; (°C)</th>
<th>Final T&lt;sub&gt;aver&lt;/sub&gt; (°C)</th>
<th>Weight loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC</td>
<td>2.9</td>
<td>0.30</td>
<td>65</td>
<td>4779</td>
<td>120</td>
<td>70.6</td>
<td>6.0</td>
<td>5.94</td>
</tr>
<tr>
<td>ABC</td>
<td>5.0</td>
<td>1.78</td>
<td>92</td>
<td>5415</td>
<td>120</td>
<td>71.1</td>
<td>7.9</td>
<td>6.61</td>
</tr>
<tr>
<td>WIC</td>
<td>1.8</td>
<td>0.007</td>
<td>-</td>
<td>5799</td>
<td>120</td>
<td>69.6</td>
<td>5.4</td>
<td>1.22</td>
</tr>
<tr>
<td>VC</td>
<td>Pumping time to 6.5 mbar: 12 min</td>
<td>5048</td>
<td>120</td>
<td>72.4</td>
<td>8.0</td>
<td>10.00</td>
<td>3.1</td>
<td>11.95</td>
</tr>
</tbody>
</table>

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*vc*: SAC, slow air cooling; ABC, air blast cooling; WIC, water immersion cooling; VC, vacuum cooling.

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**Fig. 3.** Maximum temperature histories of cooked meat joints during vacuum cooling and conventional cooling.
the local temperature is mainly determined by the water evaporation in the local region. It can be seen from Fig. 3 that the maximum temperature of the cooked meat using vacuum cooling decreases much more quickly than those using the other three cooling methods. By quantitative comparison, it took less than 1.5 h for the vacuum cooling to cool a cooked ham of 5–7 kg weight from the core temperature of about 70–74 to 10°C, compared with about 10 h for the slow air cooling and more than 7 h for the air blast cooling and the water immersion cooling. Therefore, only vacuum cooling can meet the cooling requirements of the cooking–chilling guidelines (from around 74 to 10°C in 2.5 h) (Sun & Wang, 2000; Wang & Sun, 2001). It can also be seen from Fig. 3 that the total cooling time for vacuum cooling of cooked meat joints varies with the samples and mainly depends on the porosity, pore size and pore distribution within the samples (McDonald & Sun, in press-b). The preparation of cooked meats, particularly whether samples were vacuum tumbled, minced or whole muscle, packaged in casing or netting, and brine injection level have significant effects on the development of the porosity (McDonald & Sun, 2001).

**Weight loss**

The weight loss of a big block of cooked meat during vacuum cooling is obviously higher than that of the conventional cooling methods. Table 2 lists the typical weight losses of cooked meat joints during vacuum cooling and conventional cooling (Wang & Sun, 2001). As shown in Table 2, the weight loss for vacuum cooling of cooked meats from the initial average temperature of 72–75°C to the final average temperature of 3–8°C is about 10–12% of the weight before vacuum cooling depending on the properties of samples, initial and final temperatures. Therefore, 1% of weight loss can cause a 6–6.5°C temperature drop in average. For slow air and air blast cooling, it can be seen from Table 2 that the weight losses are also as high as 6–7% of the weight before cooling. However, it should be noted that the big weight loss during slow air and air blast cooling cannot shorten the total cooling time significantly.

The economic loss caused by the moisture loss during vacuum cooling can be compensated by adjusting the brine injection level, which is a necessary treatment for preparing cooked meats. It was reported that total yield in vacuum cooled samples at the injection level to as high as 135% of green weight was comparable to water immersion cooled samples at the injection level of 120% of green weight. Percentage weight losses were similar for all vacuum cooled samples with different injection levels (McDonald, Sun, & Kenny, 2001). The weight loss of cooked meat for pie fillings during vacuum cooling can be compensated for by adjusting the gravy composition by increasing its water content (Everington, 1993). Especially as in the case of meat cooling, weight loss is less likely to occur after the addition of water if the surface to volume ratio is large, enabling the thin mass to be cooled by heat conduction with the evaporation taking place at the surface. Furthermore, meat cubes of 25 × 25 mm or thinly sliced meat can be cooled from 100 to 10°C in 25 min and the weight loss is less than 3% of the weight before cooling. If the meat is steam cooked in trays by injecting steam into the vessel to the required temperature and then vacuum cooled, the accumulation of steam condensed in the trays during cooking process can offset most of the evaporation loss in cooling back down to 10°C (Everington, 1993).

**Quality analysis**

Vacuum cooled samples can significantly lower bacterial counts of *psychrophiles* and *mesophiles* after storage for several days. This may be explained by the cold shocking of the micro-organisms due to the rapid decrease in temperature during vacuum cooling and the lower water activity in comparison to the other samples (McDonald, Sun, & Kenny, 2000). Experimental results show that after 7 days storage, the mean mesophilic counts of vacuum cooled samples were 3.6 × 10⁴ per g in comparison to high value of 9.8 × 10² per g for water immersion cooled samples. Psychrophilic counts were 6.0 × 10⁴ per g in vacuum cooled samples and 8.0 × 10⁵ per g in water immersion cooled samples. The presence of *Salmonella*, *Staphylococcus aureus*, *Clostridium perfringens* and *Escherichia coli* was not detected in any samples (McDonald et al., 2000).

Sensory analysis indicates that vacuum cooling had a significant adverse effect on the binding cohesion of cooked beef. However, sensory analysis also shows that vacuum cooling had no significant effect on the tenderness, juiciness, overall flavour and overall acceptability of the cooked beef (Desmond, Kenny, Ward, & Sun, 2000; McDonald et al., 2000). Although the instrumental analysis showed that vacuum-cooled samples had a tougher texture, the sensory panellists did not find the texture of the vacuum cooled samples significantly different to that of conventional cooled samples (Desmond et al., 2000; McDonald et al., 2000). It was also reported that the pressure change rate during vacuum cooling did not affect the tenderness of cooked chicken breast as judged by sensory panellists (Self, Nute, Burfoot, & Moncrieff, 1990). High moisture losses during vacuum cooling were anticipated as causing a reduction in juiciness but the panellists did not make any difference between the vacuum cooled samples and the conventional cooled samples. The colour of the vacuum-cooled samples was even preferred by the panellists. Some panellists also commented on the intense or concentrated beef flavour of vacuum cooled samples. Therefore, vacuum cooling had the highest colour scores and did not affect the overall flavour and overall acceptability significantly (McDonald et al., 2000).
Sensory analysis also indicates that cooked beef after water-immersion-cooling treatment was more tender, juicy and had better binding cohesion than other samples. The air-blast-cooled samples had the highest attributes of overall flavour and the least acceptable overall colour. The slow air-cooled samples had the lowest score of overall flavour. However, sensory analysis shows that there is no significant difference for the overall acceptability after different cooling treatments and all samples were found to be between moderately and very acceptable. The instrumental analysis confirmed that water immersion cooled samples were the most tender, and no significant differences of tenderness were found between the air-blast-cooled and slow air-cooled samples (McDonald et al., 2000).

**Mathematical simulation**

Mathematical modelling is very useful for understanding and optimizing the vacuum cooling process (Hu & Sun, in press-a). Vacuum cooling process of large cooked meat joints was modelled by the finite element numerical method. The model includes two sub-models for analysing the vacuum-cooling system, and heat and mass transfer through cooked meats under vacuum pressure, respectively (Wang & Sun, in press-a, in press-b).

The first sub-model is for the vacuum cooling system based on mass balances of air and vapour in the vacuum chamber, which mainly includes four components to describe the flow rates of evaporated vapour, ingress air, air release and vapour release, respectively. The ingress of air into the vacuum chamber was assumed as the flow of an adiabatic compressible gas through a nozzle. The ingress area of a given system was determined by experiments (Wang & Sun, in press-a).

The second sub-model is for the heat and mass transfer through cooked meats under vacuum pressure, mainly including two components: describing mass transfer with inner vapour generation and heat transfer with inner heat generation (Wang & Sun, in press-b).

For simplicity, the geometries of cooked meat joints were mainly divided into two groups: ellipsoid (including sphere, cylinder, infinite cylinder) and brick (including cube and infinite slab) (Wang & Sun, in press-c, in press-d, in press-e). The variations in physical properties and the shrinkage of the cooked meat during vacuum cooling process were covered in this model. The model was solved by the finite element method (Wang & Sun, in press-a, in press-b, in press-c, in press-d, in press-e). The model and software can also be used to analyse vacuum cooling of other foods with some modifications.

The simulation results showed that for vacuum cooling a block of cooked meat with the weight of 5.3 kg from the core temperature of around 74°C to below 10°C, the maximum deviation between the predicted and experimental core temperatures was within 2.5°C. The deviation between the predicted and experimental total weight losses was 7.5% (Wang & Sun, in press-a, in press-b). The simulation also indicated that it took less than 2 h for vacuum cooling to reduce the maximum temperature of cooked meat joints to 10°C, compared with more than 6 h for air blast cooling (Hu & Sun, 2000, 2001a, 2001b, in press-b).

Vacuum cooling of fishery products

Vacuum cooling may be introduced into the fishery industry. During processing tuna, the tuna are caught at sea and frozen in brine immediately. They are then transported to canning plants, where they are thawed and then steam cooked to 65°C. After cooking, the tuna are cooled to between 35 and 40°C by vacuum cooling, which typically results in a 3-4% weight loss (Everington, 1993). Vacuum cooling can also be used to cool small fish such as whiting or crustacean such as shrimp by using waste stack gases to power the equipment (Carver, 1975).

Vacuum cooling of ready meals

A vacuum-cooling system can be integrated with the cooking operations of many ready meals manufacturers. It can maintain high quality of heat-sensitive products and provide an efficient method of cooling high particulate sauces and slurries. Since the same unit can be used for both cooking and cooling without the delay due to the transferring process of product between vessels, the processing time can be decreased and the throughput is thus increased. However, development of these systems needs careful consideration of safety. High vacuum can pull cooked product into the vacuum-pumping system or onto the roof of the processing vessel. In this case, the extensive cleaning operations will be required to remove the product from the equipment and prevent microbial proliferation. On the other hand, low vacuum will increase cooling time (James, Burfoot, & Bailey, 1987).

**Conclusions**

Vacuum cooling is a rapid cooling technology for porous and moisture foods. The heat of food body is released by evaporating an amount of water within the foods under vacuum pressure directly. The size and shape of food body have no significant effect on the cooling rate of vacuum cooling, which is different from traditional cooling such as slow air, air-blast and water-immersion cooling.

Weight loss inherently occurs during vacuum cooling since the cooling effect comes from water evaporation. However, weight loss of vacuum-cooled foods can be reduced or compensated by adding a suitable amount of water before vacuum cooling.

Vacuum cooling has been widely used to rapidly remove the field heat from certain horticultural and floricultural products to extend their shelf life. Vacuum cooling is also successfully used to the process procedures of some liquid foods and baked foods to improve...
the cooling efficiency of processing machines and reduce the cooling time. A rapid cooling is important for safety and quality of cooked meats to minimise the growth of surviving organisms. However, only vacuum cooling can meet the cooling requirement of cooked meats in cooking–chilling guidelines issued by the governments of many European countries. Furthermore, vacuum cooling has also found applications in rapid cooling of fishery products and ready meals.

Application of vacuum cooling is attractive to the food industry. Vacuum cooling can provide an effective and efficient cooling technique for a variety of food products. It is thus envisaged that there will be more widespread use of the technology in the food processing industry in the future.

References


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