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Vacuum cooling for the fruit and vegetable industry

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Abstract

Purpose of review: This review focuses on the state-of-the-art of vacuum cooling in the fruit and vegetable industry, with the objective of highlighting areas that require further research.

Findings: Recently, there has been renewed research interest into vacuum cooling. Research on the vacuum cooling process for fruits and vegetables can be divided into three subcategories: optimisation of vacuum cooling, product quality and mathematical modelling of the process. There has been some research into the optimisation of the vacuum cooling process to minimise mass loss as well as to determine the peak refrigeration loads. Although the bulk of the research papers focus on the effects of vacuum cooling on product quality, several unanswered questions remain. Additionally, only recently have articles on mathematical modelling of the vacuum cooling process emerged.

Directions for future research: Each of the three subcategories mentioned above requires further research. The industry would benefit from articles on improved engineering, detailing the optimal design of each of the components of a vacuum cooler; which may help to reduce capital costs and increase energy efficiency. There are also several areas of product quality that need further exploration. One of these is the effect of the vacuum on plant tissue, and how this affects the keeping quality of the product.

Keywords: vacuum cooling; precooling; fruits; vegetables; postharvest; refrigeration

Abbreviations

EC	Energy Coefficient
TRPML	Temperature Reduction Per Percent Mass Loss

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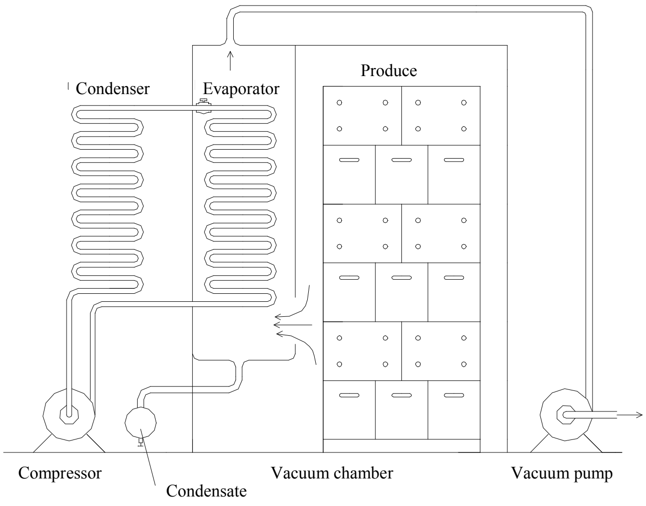
Introduction

Proper temperature management is essential for maintaining high quality fresh fruits and vegetables. The greatest amount of deterioration occurs at high ambient temperatures, a scenario that exists just after harvest [1]. The benefits of precooling, the rapid cooling of fruits and vegetables immediately after harvest and prior to cold storage, are well documented [2, 3**]. The two main advantages of precooling are the rapid cooling of the product, which helps to prolong its storage life compared with non-precooled produce, and reduction in the required refrigeration capacity of the storage room. Precooling is a vital part of maintaining an effective cold chain.

Vacuum cooling is a specific method of precooling fruits and vegetables. The first commercial use of vacuum cooling was in Salinas, California, in 1948, specifically for the cooling of iceberg lettuce [3**]. Vacuum cooling has been extended to other products, including other varieties of lettuce, spinach, cauliflower, bok choy, bean sprouts, mushrooms, celery, artichokes, green onions, cabbage and other leafy

Figure 1. Schematic of a typical vacuum cooler.



vegetables. It is best suited for products with high surface area to mass ratios, as it is an evaporative cooling method.

A schematic of a typical vacuum cooler is shown in Figure 1. It consists of an air-tight retort where the product is loaded, usually in pallets, and the product can be pre-packaged, as long as the packaging allows for vapour removal. The doors are sealed and a vacuum pump evacuates the air from the chamber. As the ambient pressure inside the chamber decreases, it approaches the saturated vapour pressure of the liquid water in the product (flash point), resulting in sudden surface water vaporisation. The evaporation results in localised cooling of the plant tissue due to the energy requirement of the phase change. Lowering the retort temperature to an absolute pressure of 0.61 kPa would result in an equilibrium product temperature of approximately 0°C. However, the evaporation of product water results in a large volume of vapour that is too large to be removed by most vacuum pumps; rather, this vapour is condensed using a refrigeration system. The turn-around time for one load of product depends on several factors, including the capacity of the vacuum pump, the rate of cooling (product dependent), and the volume of the retort. The rate of cooling is generally 2–3 times faster than forced-air cooling [4], resulting in a turn-around time for some produce, such as lettuce, of as little as 25–30 min. Figure 2 shows a plot of the retort pressure, theoretical product temperature, and the saturation temperature for a typical vacuum cooling operation for lettuce.

Equipment and vacuum cooler design

Vacuum cooling systems can be designed using one of four types of vacuum evacuation systems: steam ejector, centrifugal, rotary or reciprocating [5*]. For the fruit and vegetable industry, rotary vacuum pumps are generally used, in single or double stage [6*]. The pressure-volume relationship in the vacuum retort can be approximated using the ideal gas law. This relationship is broken into two phases, one prior to the flash point and one after the flash point [5*].

$$Pv = 8{,}697 \text{ Nm/kg} \qquad \text{...(1)}$$

$$Pv^{1.056} = 16{,}985 \text{ Nm/kg} \qquad \text{...(2)}$$

where P (Pa) is the retort pressure and v (m^3/kg) is the specific volume. Haas and Gur [6*] defined the pumping speed, S (m^3/h), of a vacuum pump as:

$$S = \frac{V}{t/60} \ln \frac{P_1}{P_2} \qquad \text{... (3)}$$

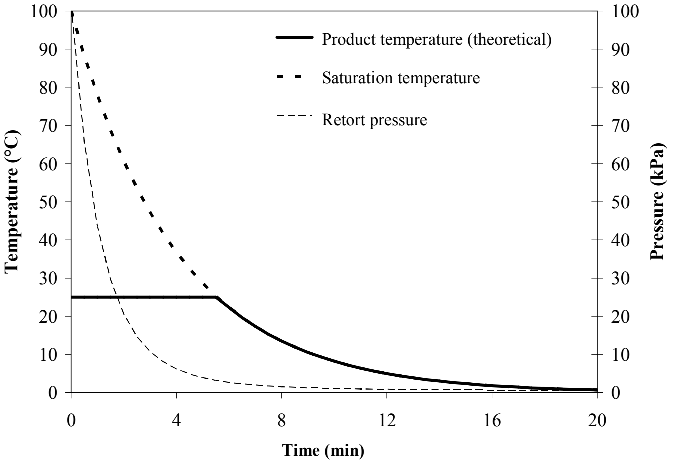
where V is the retort volume (m^3), t is the time (min) to reach the flash point, and P_1 and P_2 are the initial pressure (Pa) and the pressure at the flashpoint (Pa), respectively.

The total product refrigeration load expected from a vacuum cooler, Q (kJ) can be estimated as:

$$Q = mc_p \Delta T \qquad \text{... (4)}$$

where m (kg) is the mass of the product, c_p (kJ/kg°C) is the specific heat, and ΔT (°C) is the temperature change. There are other sources of heat that need to be removed, such as the cooling of the retort itself. However, the cooling of the retort can be kept to a minimum if the condensation of water vapour on the retort walls is prevented. In this case, the refrigeration load from the retort can be kept to about 2 or 3% of the product load [7]. Furthermore, product respiration results in a refrigeration load that is approximately 3% of the total product load for lettuce [7]. This would vary depending on the product.

Figure 2. Theoretical product temperature, retort pressure and saturation temperature versus time for a typical vacuum cooler.



The evaporator coils are placed in the evacuation passage, along the ceiling or the along the sides of the retort wall [6*]. There is little information in the literature dealing with the optimum placement, size, and operating conditions for the refrigeration system. Hass and Gur [7] note that the evaporator coils are best constructed with unfinned copper tubes to obtain uniform air vapour flow.

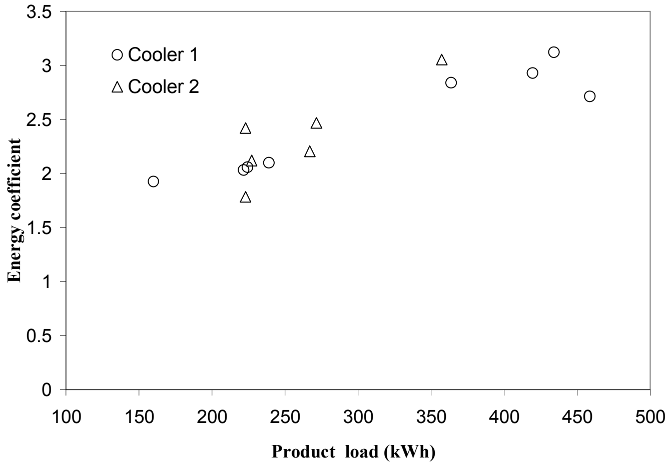
Optimisation of vacuum cooling

Thompson *et al.* [8*] suggested that the energy efficiency of vacuum coolers could be increased by shutting off compressors when not needed, reducing the idling time of the compressors, shutting off some of the vacuum capacity once the flash point is reached (for vacuum coolers with multiple vacuum pumps), and increasing the quantity of lettuce being cooled per cycle. The authors measured the energy consumption from two different industrial-scale vacuum coolers and found that one of the coolers had lower energy consumption per carton of lettuce compared with the other cooler; however, they also noted that comparing cooler efficiency was misleading because the carton weights and initial temperatures can change significantly between loads, and the cooler with the lower energy per carton was cooling lettuce with a much lower initial temperature. Therefore, the authors defined the following energy coefficient (EC):

$$EC = \frac{Q}{E} \qquad ...(5)$$

where Q (kWh) is the sensible heat removed from the product and E is the total electrical energy (kWh) consumed during the operation of the cooler. Using this criterion, it was determined that the vacuum cooler with the higher energy per carton was actually a more efficient cooler. However, this measure of energy efficiency is not independent of the initial temperature of the product or the total mass of the product load. For example, the operation of the vacuum pump will consume approximately the same amount of energy per cooling cycle regardless of the initial temperature of the product. From the data presented by Thompson *et al.* [8*], Figure 3 has been constructed showing a plot of the energy efficiencies, as calculated by equation 5, versus the amount of heat removed (kWh) from the product. Based on this plot, it is difficult to determine which cooler is more efficient. However, it clearly illustrates that the energy efficiency increases with increasing product load. Equation 5 remains a good comparison for cooler efficiency when the coolers are loaded under comparable situations, such as full capacity and the same initial product temperatures. An improved method is needed to adequately describe the efficiency of vacuum coolers.

Figure 3. Energy coefficient versus product load from the data of Thompson *et al.* [8*].



The peak refrigeration load for lettuce in a vacuum cooler, based on the mass of the product, the size of the retort, and the pump speed, was determined theoretically and experimentally by Rennie *et al.* [9]. The authors simulated various vacuum pump speeds by controlling a leak valve so that the pressure would decrease following a given function. The product refrigeration load was related to the rate of temperature reduction of the lettuce. The theoretical and experimental results were in good agreement, except at the largest vacuum pump size, where there was a slight deviation. The experimental results showed a slower temperature drop at this speed compared with theoretical data. This was attributed to a lag in the heat and mass transfer, which was not taken into account in the theoretical model.

The weight loss caused by vacuum cooling limits the use of this precooling method to products that are wilting sensitive. Rennie *et al.* [10] presented a simple method to estimate the mass loss, and compared it with experimental data for lettuce; the results showed that a change in the pressure reduction rate had no effect on the mass loss, temperature reduction per percent mass loss (TRPML), or the temperature difference between various locations.

HydroVac (Western Precooling Systems, Fremont, California, USA) is a design that incorporates water spraying just prior to the flash cooling to minimise moisture loss from the product. It is useful for several products including lettuce, celery and sweet corn. There is very little literature on the reduction of weight loss due to water spraying. Pre-wetting the product has been shown to increase the product's weight in some cases, although water may be left on the surface [11]. Bronson and Sun [12] attempted several treatments on cut white lilies to reduce weight loss. Their results showed that spraying flowers prior to cooling could eliminate the weight loss if enough water was applied.

Effect of vacuum cooling on produce quality

Vacuum cooling has one immediate effect, a reduction in moisture content, that could compromise the quality of the product. Moisture loss is approximately 1% per 5–6°C of cooling [2, 6*, 10, 11]. This loss is distributed throughout the product and wilting is often not detectable if the loss is below 5% [13], although lower levels have caused noticeable wilting in some leafy vegetables [3**].

Several research studies indicate that the beneficial effects of vacuum cooling on lettuce quality do not appear until late into the storage period. Aharoni and Ben–Yehosua [14] found that the beneficial effects of vacuum cooling on the prevention of bacterial decay were not apparent until after 3 weeks of cold storage. Similarly, Martinez and Artés [15] found that after 2 weeks of cold storage at 2°C, there was no difference in the quality of vacuum cooled and non-vacuum cooled iceberg lettuce. The quality determination was based on the severity of pink rib, russet spotting, brown stain, heart-leaf injury and bacterial soft rot. However, after an additional 2.5 days of storage at 12°C, to mimic a marketing period, vacuum cooled lettuce showed less severity of pink rib and heart-leaf injury compared with non-vacuum cooled lettuce.

No immediate effects of vacuum cooling on the quality of mung bean sprouts were found by DeEll *et al.* [16]. After 4 days of storage, vacuum-cooled mung bean sprouts had greater freshness and better hypocotyl colour than room-cooled mung bean sprouts. However, after an additional 3 days of storage, the differences between room-cooled and vacuum-cooled sprouts were not significant. This is near the maximum possible storage for maintaining saleable quality mung bean sprouts. A shelf life of 7–9 days was reported by Hardenburg *et al.* [13], whereas Lipton *et al.* [17] reported a shelf life that ranged between 2.5 and 8.5 days, depending on the storage temperature. It is likely that in the experiments by DeEll *et al.* [16], that the sprouts had deteriorated to a point where it would be unlikely to detect any differences.

Türk and Çelik [18] studied the effect of packaging on the quality of two head lettuce cultivars (Yedikule and Lital) after vacuum cooling and storage. Porous polyethylene bags were used to package the lettuce prior to precooling. The packaged lettuce had less weight loss after precooling compared with non-precooled lettuce. Furthermore, precooled lettuce had lower water loss at the end of the storage period compared with lettuce that was not precooled. Discolouration was noted in both types of lettuce after storage, along with significant increase in acidity during the storage period. Vacuum cooling was shown to have a positive effect on pH and acidity.

The effect of vacuum cooling and several types of packaging, including perforated and non-perforated polypropylene bags, on the quality of 'Salinas' lettuce after 2 weeks of storage was determined by Artés and Martinez [19]. The results showed no significant differences in the weight loss or wilting of vacuum cooled and non-vacuum cooled lettuce after the 2 week storage period. However, the mass loss was measured for only the storage period, with the initial mass taken after vacuum cooling. Furthermore, it is unclear what the temperature of the non-vacuum cooled lettuce was when the initial weight was taken, making it difficult to compare these data with the results from Türk and Çelik [18]. Artés and Martinez [19] found that the incidence and severity of pink rib, after 2 weeks of storage at 2°C and 2.5 days at 12°C, was highest in vacuum cooled lettuce wrapped in perforated polypropylene. They could not find an explanation for this observation. They also found that vacuum-cooled lettuce were more susceptible to heart-leaf injury than non-vacuum lettuce.

Rennie *et al.* [20] studied the effects of the pressure reduction rate on the subsequent storage quality of iceberg lettuce. The hypothesis of this study was that a slower rate of water evaporation, obtained by reducing the pressure reduction rate, could lead to less tissue damage. Three levels of pressure reduction rate were used. Using chlorophyll fluorescence and visual inspection as quality indicators, no significant effects of different rates pressure reduction rates on the storage quality were noted. However, the chlorophyll fluorescence measurements indicated that vacuum cooling may stress the plant tissue, but the tissue does recover during the subsequent storage.

The effect of different pressure reduction rates on the cooling of cut lily flowers was investigated by Bronson and Sun [21]. They found no effect on the quality of the flowers in subsequent storage; however, they found that the evacuation rate affected the mass loss and the TRPML. The mass loss was higher for quicker cooling, and hence the TRPML was lower for faster pressure reduction rates. This is in contrast to Rennie *et al.* [20] who found that TRMPL to be independent of the pressure reduction rate, however Rennie *et al.* [20] used a smaller range of pressure reduction rates. Bronson and Sun [21] noted that their results were similar to those of McDonald and Sun [22], which showed TRPML dependency on the evacuation rate.

He *et al.* [23] used a setup similar to Rennie *et al.* [10, 20] to study the effects of the pressure reduction rate on the quality and the ultrastructure of iceberg lettuce. They used a similar method to control the pressure reduction rate as Rennie *et al.* [10, 20]. Vacuum cooling was shown to have a positive effect on the firmness of the lettuce after 2 weeks of storage compared with lettuce that were not vacuum cooled. The lowest pressure reduction rate was shown to result in a slightly smaller mass loss compared with the two higher rates. Vacuum cooling was shown to have a positive effect on ascorbic acid retention, with the moderate pressure reduction rate having the highest retention after 2 weeks of storage. Measurements of catalase activity showed an increase in all treatments, including the control, except those cooled at the highest pressure reduction rate. He *et al.* [23] also used light microscopy and transmission electron microscopy to determine the effect of vacuum cooling on the quality of lettuce. Light microscopy showed that the morphology of lettuce tissue remained intact. However, transmission electron microscopy revealed that compared with the control, vacuum cooling resulted in variation of the ultrastructure including plasmolysis, irregular membrane structure, and discontinuity of plasmalemma and tonoplast [23]. The greatest variation was found with the lowest pressure reduction rate. After 2 weeks of storage, the lettuce cooled at the moderate pressure reduction rate showed intact organelles, whereas those vacuum cooled at the lowest and highest pressure reduction rates had damaged organelles.

Mathematical modelling

There has been very little research on the mathematical modelling of vacuum cooling of fruits and vegetables, although there are several papers available for meat products [24, 25]. He and Li [26] simulated the cooling of spherical foods in a vacuum cooler. They used a spherical coordinate system and assumed that the heat transfer was only in the radial direction. They also assumed that internal cooling was proportional to the rate of mass reduction and that this occurred throughout the product. To determine the rate of mass loss, the mass transfer coefficient was determined based on the experimental results of Haas and Gur [6*]. For verification of the results, simulations with similar vacuum parameters as Haas and Gur [6*], such as effective deflating speed of the pump (evacuation rate), were compared with the experimental results. However, the initial temperature distribution was higher in the simulations. The simulations resulted in a quicker cooling time compared with the experimental results.

An interesting result from the simulations, although not discussed by the authors, was an increase in the product mass just as the flash cooling started. The experimental results of Haas and Gur [6*] and Rennie *et al.* [10] both show a slight increase in the surface temperature of the product as flash cooling commences. This phenomenon was hypothesised, by Rennie *et al.* [10], as the condensation of water vapour that has started to migrate from the inner portions of the product to the surface, where the vapour encounters a surface temperature below the saturation temperature of that vapour. The vapour condenses on this surface, slightly increasing the surface temperature. Though the simulations of He and Li [26] do not predict this change in temperature, the results indicate an increase in mass, which could be due to condensation.

The numerical results of He and Li [26] predict a mass loss in the product of roughly 1%. In contrast, Barger [11, 27] states that there is roughly a 1% decrease in product mass for every 6°C of cooling. Experiments by Rennie *et al.* [10] showed a temperature decrease of about 5.5°C for every 1% mass loss.

Sun *et al.* [28] developed an effective heat flux model for vacuum cooling. This model combined the effects of conduction and inner vapour evaporation into a single parameter, the effective thermal conductivity, thus decreasing the number of differential equations needed for the model. They performed experimental trials for comparison with the numerical model, with very good agreement between the two. It is unclear how quickly their experimental setup decreased the pressure, and if it was modelled in the simulation. The results of their work, both numerical and experimental, show immediate cooling of the product, which suggests that the pressure reduction rate was extremely high or that the presented results are only from the point of flash cooling onwards.

Conclusion

Review of the vacuum cooling literature indicates that there is a need for future research in three main areas. With increasing concerns of energy consumption, there needs to be further research into the use of vacuum coolers as a potential precooling method for a greater range of products. It is one of the most energy efficient methods currently available, but this could still be improved upon. Investigation of optimal design could help reduce the capital costs of vacuum coolers, one of the major drawbacks of this precooling method.

There are several aspects of the product quality that needs further exploration. The literature indicates some discrepancies in the results from fairly similar experiments. These inconsistencies need to be clarified. There is also the effect of vacuum on plant tissue that needs further investigation, both for optimisation of the vacuum cooling process and storage, as well as for the general understanding of the functioning of plant tissues under vacuum.

The final area that will likely develop more attention is the mathematical modelling of the vacuum process. One of the biggest challenges in this area will be to develop methods to integrate the complex physical and thermal characteristics of fruits and vegetables into the mathematical models, especially for leafy products such as lettuce.

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