Evaluation of the temperature variation in the vacuum chamber during vacuum cooling of lettuce

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Abstract
Pre-cooling is used to lower the temperature of the harvested agricultural products while vacuum cooling is known as a rapid evaporative cooling technique for any porous product which has free water. The vacuum cooling of lettuce was described in this paper, it is carried out to investigate the variations of temperature in the vacuum chamber, moisture content and evaporation rate. The experimental results show that the chamber temperature has some fluctuations during vacuum cooling, the variation of temperature in the vacuum chamber includes four different phases: (1) the reduction of the initial chamber temperature from 18 °C to 10 °C; (2) the increment of the chamber temperature from 10 °C to the maximum temperature, 19 °C; (3) the reduction of the chamber temperature from the maximum, 19 °C to the minimum, 6 °C; (4) the increment of the chamber temperature from the minimum temperature, 6 °C, to the final chamber temperature, 13 °C. it can be also found that the average moisture content of lettuce decreases from 71% to 60.69%. In during vacuum cooling, there are two periods: an accelerating period and a falling period. The transition from the accelerating evaporation rate period to the falling evaporation rate period occurs after about 5 minute.

Keywords: vacuum cooling; lettuce; temperature; moisture content

Introduction

Vegetables and flowers are living dynamic systems even after detachment from the parent plant. As living biological entities, they respire and transpire (Brosnan and Sun, 2001). The process of pre-cooling is the removal of field heat which arrest the deteriorative and senescence processes so as to maintain a high level of quality that ensures customer satisfaction (Brosnan and Sun, 2001 & Sun and Brosnan, 1999 & Mc Donald and Sun, 2000). Vacuum cooling mainly depends on latent heat of Evaporation to remove the sensible heat of cooled products. It can be considered a rapid and evaporative cooling method. Generally, vacuum cooling can be applied to any porous product which has free water (Mc Donald and Sun, 2001 & Wang and Sun, 2000 & Dustal and Petera, 2004 & Tao et al, 2006 & Jackman et al, 2007 & Houska et al, 1996). The effect of vacuum cooling on extending the shelf-life of produce has been shown by (Burton et al, 1987 & Martinez and Artes, 1999). The function of the vacuum pumps and vapor condenser is to provide the vacuum in the chamber [4]. There are two main requirements for using the vacuum cooling: (a) the product should have a large surface area for mass transfer, (b) product water loss should not represent an economic or sensory problem due to weight reduction and possible changes in structure or appearance (Martinez and Artes, 1999). The basic principles of the vacuum cooling process are described as follows (Everington, 1993): 1. At atmospheric pressure (1013 mbar), the boiling temperature of water is 100 °C. This boiling point changes as a function of saturation pressure therefore at 23.37 mbar the water boiling temperature will be 20 °C and at 6.09 mbar, it will be 0 °C. 2. To change from the liquid to vapor state, the latent heat of vaporization must be provided by the surrounding medium, so that the sensible heat of the product is reduced. 3. The water vapor given off by the product must be removed. During vacuum cooling, loss of moisture and development of porosity have the most significant effects on the thermo physical properties of the cooled products. Cheng and sun compared the mass loss of cooked meat product for the different cooling methods such as vacuum cooling, air blast cooling, slow air cooling, and water immersion cooling. They also compared the cooling rate, the weight loss, and the quality of large cooked ham joints. They indicated that despite the highest cooling loss, vacuum cooling significantly increases the cooling rate, and it is the only method that can meet the chilling requirements (Haas and Gur, 1993 & Cheng and Sun, 2008).

The experiments are conducted to investigate the variation of temperature in the vacuum chamber and discuss the variations of moisture content and evaporation rate during vacuum cooling of lettuce. In addition, the variation mechanism of temperature in the vacuum chamber is also investigated in this paper.

Material and methods

Theoretical approach

In this section, a simple theoretical analysis of vacuum cooling process based on thermodynamic principles is presented. This analysis is limited to the mass loss based on temperature drop observed during vacuum cooling process. The weight of samples and Moisture content of lettuce before and after vacuum cooling were measured. Moisture content of lettuce during vacuum cooling can be calculated indirectly by Equation (1).

$$Wn = \frac{m0w0 - \Delta\tau \sum_{\tau=0.5}^{n} m\tau}{m0 - \Delta\tau \sum_{\tau=0.5}^{n} m\tau} \times 100\% \quad (1)$$

where m0 and W0 are the initial mass and moisture content of lettuce respectively, 0.5≤ n ≤ N. Evaporation rate of lettuce during vacuum cooling can be expressed by:

$$m\tau + \Delta\tau = \frac{m\tau - m\tau + \Delta\tau}{\Delta\tau} \quad (2)$$

where time interval $\Delta\tau$ = 0.5 min, 0 ≤ τ ≤ N, N is total vacuum cooling time of lettuce, mτ and mτ+Δτ are the mass of lettuce at the time of τ and τ + Δτ respectively.

Plant material

lettuce were bought on day of experiment and was transported to the Shahid Chamran University of Iran. The temperature of the cabbage during this time was near room temperature (20 °C). Samples vacuum cooled 2 h later.

Vacuum cooling system, measurements and data collection

Testes were performed using a laboratory-scale vacuum cooler (Agricultural Machinery and Mechanization Engineering Department of Iran), equipped with a piston vacuum pump. The vacuum volume was approximately 0.335 m3. The experimental apparatus is presented in **Figure 1**.

Variation of surface and center temperature of the lettuce is determined with two calibrated sensors (±1 accuracy). The sensors are inserted into the samples; one sensor placed in center of lettuce and second under the first leaves of lettuce. Relative humidity (±1% rh) and temperature of vacuum chamber have been measured with the same probe and data are recorded. Also Pressure has been measured from the pipe between the vacuum pumps and vacuum chamber (see Figure 1). The weights of the foods before and after the cooling process are determined with an electronic balance (with accuracy of ±0.01 gr).

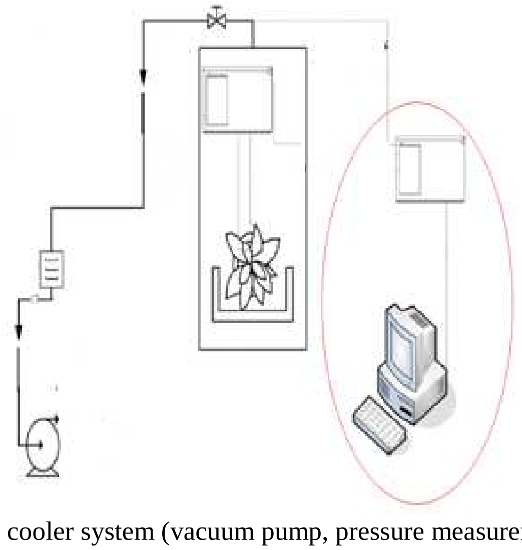

Figure 1. Schematic of the vacuum cooler system (vacuum pump, pressure measurement, Temperature measurement, Humidity measurement, vacuum control valve, vacuum chamber)

Result and Discussion

During vacuum cooling, the variation of temperature in the vacuum chamber is shown in **Figure 2**. The initial temperature in the vacuum chamber is 18 °C. It is evidently found from **Figure 2** that the temperature in the vacuum chamber has some fluctuations during vacuum cooling. The maximum and the minimum temperatures are 19 °C and 6 °C, respectively. The variation of chamber temperature can be divided as four different phases: A–B, B–C, C–D, D–E–F, as is shown in **Figure 2**. The cooling curve of lettuce is given in **Figure 3**. It can be seen from **Figure 3** that the initial core and surface temperatures of lettuce are 26 °C and 23 °C. Compared with the variation of temperature in the vacuum chamber, the average temperature of lettuce decreases from 24.5 °C to 5.1 °C, which has no sharp variation during vacuum cooling. The cooling rate of lettuce is high at the beginning. However, after 10 min, cooling rate of lettuce becomes low. The variation mechanism of temperature in the vacuum chamber during vacuum cooling can be expressed as follows: First, the total pressure in the vacuum chamber is the sum of the partial pressure of air and water vapor. During vacuum cooling, the air is evacuated by vacuum pump. The total pressure in the vacuum chamber is reduced from the atmosphere to the defined vacuum pressure. It is well known that at any fixed pressure there exists a temperature at which water boils. The saturation pressure P_{sat} is related to the local temperature and determined by (Sheng et al, 2001):

$$Psat = \frac{2}{15} \times 10^3 \exp\left(18.5916 - \frac{3991.11}{T-39.13}\right) \quad (3)$$

Air evacuated by vacuum pump is assumed to be a process of adiabatic expansion. The expression can be obtained by (Sheng et al, 2001):

$$T_{vc,t} = \left(\frac{P_t}{P_0}\right)^{\frac{k-1}{k}} T_{vc,0} \quad (4)$$

where k is the ratio of specific heat at constant pressure and constant volume. For air, the ratio of specific heat at constant pressure and constant volume is 1.4. When the air in the vacuum chamber is evacuated by vacuum pump, Pt < P0. Therefore, it can be concluded from Equation (4):

$$T_{vc,t} < T_{vc,0} \quad (5)$$

It can be seen that from **Figure 2**. The temperature in the vacuum chamber decreases from 18 °C to 10 °C, the time is only 34 s in A–B phase. During A–B phase, the pump time is less than the flash point ($t \leq t_{fp}$). when the time reaches the flash point, water vapor evaporates from the lettuce into the vacuum chamber. Because the initial temperature of lettuce is above 20 °C, the water vapor evaporated from lettuce is at the local temperature of lettuce, which can increase the temperature in the vacuum chamber from 10 °C to the maximum temperature, 19 °C. The variation of temperature in the vacuum chamber is shown in B–C in **Figure 2**.

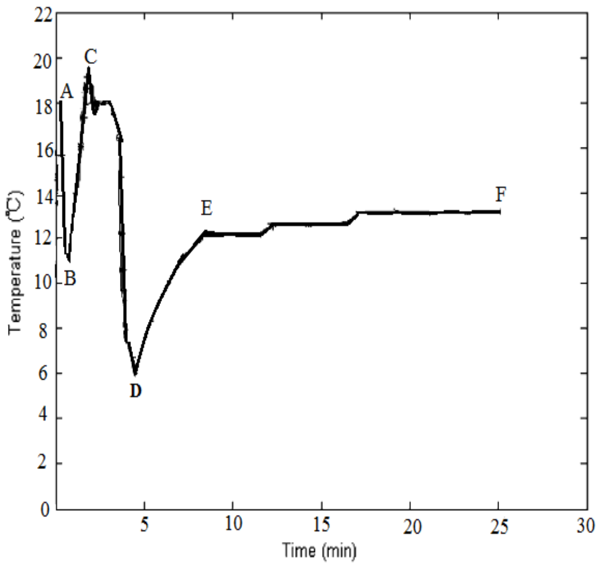

Figure 2. The temperature history in the vaccum chamber during vaccum cooling.

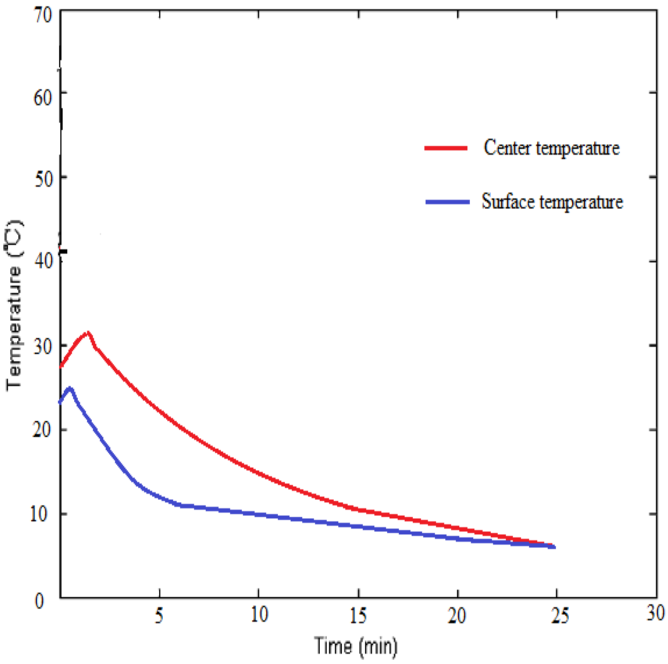

Figure 3. Variation of center and surface temperature of lettuce during vacuum cooling.

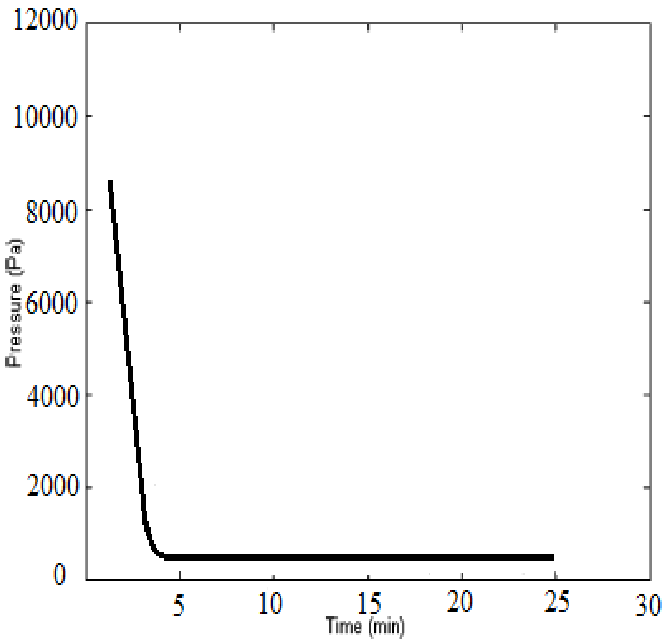

Figure 4. Variation of pressure of vacuum chamber

Then, With the reductions of the temperature of lettuce and the vacuum pressure in the vacuum chamber, the temperature in the vacuum chamber decreased from the maximum temperature, 19 °C, to the minimum temperature, 6 °C. During C–D phase in **Figure 2**, the vacuum pressure in the vacuum chamber, which was dropped from 8500 Pa to 600 Pa rapidly, reaches the defined pressure, as can be shown in **Figure 4**. In order to avoid freezing within lettuce, the bleeding valve is switched on to adjust the leakage rate of air into the chamber for maintaining the defined vacuum pressure, which could prevent the vacuum pressure decreasing continuously.

The vacuum pressure in the vacuum chamber is shown in **Figure 4**. It can be found that when the vacuum pressure reaches the defined pressure, the vacuum pressure in the vacuum chamber is kept at the defined vacuum pressure.

However, the temperatures of lettuce decrease continuously, which is shown in **Figure 3**. With starting machine and the reduction of pressure in the vacuum chamber, the time at the beginning of boiling is usually called the flash point. For example, the time getting to flash point was after the 5-6 minute of Beginning of the experiment, because the center and surface temperature had not varied. After some minute of beginning cooling, temperature decreased but often the center and surface temperature decrease non-uniformly Due to the temperature gradient in the lettuce.
When the bleeding valve is switched on, some air at a room temperature entering into the vacuum chamber can increase the temperature in the vacuum chamber. During this phase, the temperature in the vacuum chamber varies from the minimum temperature, 6 °C, to 13 °C, the variation of temperature in the vacuum chamber is shown form D–E–F in **Figure 2**. The final temperature in the vacuum chamber is about 13 °C. The variation of average moisture content for vacuum cooling of lettuce is shown in **Figure 5**. The initial moisture contents at the core and surface of lettuce are 73% and 72.3%, respectively The difference of moisture content between the core and surface of lettuce is only 1%. It can be found from **Figure 4** that the average moisture content of lettuce decreases from 71% to 60 % during vacuum cooling. When the vacuum cooling process is finished, the final moisture contents at the core and surface of lettuce are 69.5% and 61 %, respectively.
The difference of moisture content between the core and surface of lettuce is 8.5%. During vacuum cooling, the weight loss mainly comes from water evaporation within lettuce and on the surface of lettuce. It can be concluded that most of cooling effect is mainly contributed to water evaporation on the surface of lettuce during vacuum cooling.

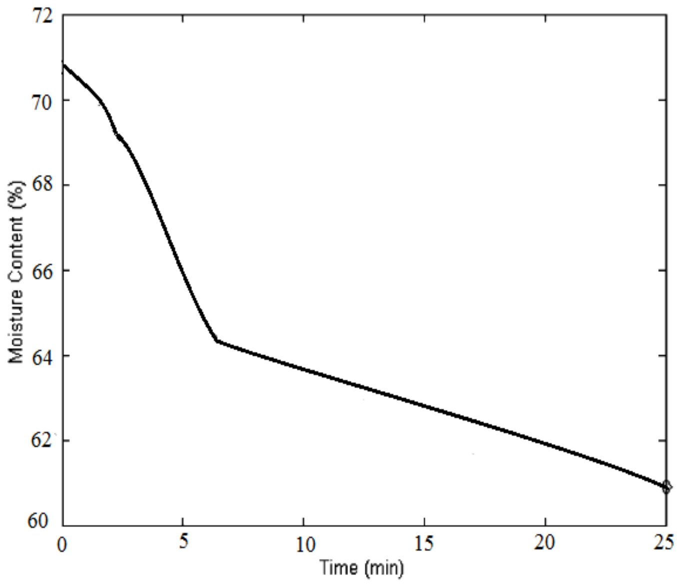

Figure 5. the variation of average moisture content of lettuce during vacuum cooling.

Also the evaporation rate of water during vacuum cooling could be divided into two periods: an accelerating evaporation rate period and a falling evaporation rate period. The transition from the accelerating evaporation rate period to the falling evaporation rate period occurs after about 4 min. During the accelerating evaporation rate period, the evaporation rate is high, it takes only about 4 min that moisture content of lettuce decreases rapidly from 71% to 66%.

Conclusion

Vacuum cooling of lettuce is carried out to investigate the variation of temperature in the vacuum chamber and discuss the variations of moisture content. Some conclusions are as follows: The variation of temperature in the vacuum chamber includes four different phases. Firstly, the temperature in the vacuum chamber drops from the initial temperature, 18 °C, to 10 °C. Secondly, when the time reaches the flash point, the high temperature of water vapor evaporated from lettuce, which causes the increment of the chamber temperature from 10 °C to the maximum temperature, 19 °C. Then the temperature in the vacuum chamber decreases from the maximum temperature, 19 °C, to the minimum temperature, 6 °C. Finally, when the bleeding valve is switched on, the vacuum pressure in the vacuum chamber is kept at the defined pressure, the temperature in the vacuum chamber varies from the minimum temperature, 6 °C, to 13 °C, the final temperature in the vacuum chamber is about 13 °C until vacuum cooling process of lettuce is finished. The average moisture content of lettuce decreases from 71% to 60% during vacuum cooling. The moisture content at the core of lettuce is reduced from 73% to 69.5%. Similarly, the moisture content at the surface of lettuce is also reduced from 72.3% to 61%. Therefore, most of cooling effect comes from water evaporation at the surface of lettuce during vacuum cooling. During vacuum cooling, there were two periods: an accelerating evaporation rate period and a falling evaporation rate period. The transition from the accelerating evaporation rate period to the falling evaporation rate period occurs after about 4 min. During the accelerating evaporation rate period, the evaporation rate is high.

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ارزیابی تغییرات دما در محفظه‌ی خلاء در طول خنک کردن خلائی کاهو

چکیده

پیش‌خنک کردن برای کاهش دمای محصولات کشاورزی کاربرد دارد در حالیکه خنک کردن خلائی به عنوان سریعترین تکنیک خنک کردن برای هر محصول متخلل دارای رطوبت آزاد، شناخته شده است. در این مقاله خنک کردن خلائی کاهو شرح داده شده و تغییرات دمای محفظه خنک خلاء، محتوای رطوبت و نرخ تبخیر مورد ارزیابی قرار گرفته است. نتایج آزمایشات نشان می‌دهد که دمای محفظه در طول خنک کردن خلائی تغییرات بسیاری دارد. این تغییرات شامل چهار مرحله بود: کاهش دمای داخل محفظه از ۱۸ درجه سانتیگراد به ۱۰ درجه سانتیگراد، افزایش دمای محفظه از ۱۰ درجه سانتیگراد به بیشترین دمای محفظه (۱۹درجه سانتیگراد)، کاهش دما از بیشترین درجه (۱۹درجه سانتیگراد) به کمترین دما (٦درجه سانتیگراد) و افزایش دمای محفظه از کمترین دما (٦درجه سانتیگراد) به دمای نهایی محفظه (۱۳ درجه سانتیگراد). هم‌چنین یافت شد که متوسط محتوای روطوبت کاهو از ۷۱٪ به ٦۰/٦۹٪ کاهش یافت. در طول خنک کردن خلائی ۲ دوره وجود داشت: دوره‌ی شتاب و دوره‌ی سقوط. انتقال دوره‌ی شتاب نرخ تبخیر به دوره‌ی سقوط نرخ تبخیر تنها بعد از ۵ دقیقه صورت گرفت.

کلمات کلیدی: خنک‌کردن خلائی، کاهو، دما، محتوای رطوبت، نرخ تبخیر.