VACUUM COOLING OF COOKED MEATS

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Background

Meat is chilled immediately after slaughter. Most of the subsequent operations in the cold chain are designed to maintain the temperature of meat. Cooking is very common operation in the production of many meat products. The aim of any cooking process for meat/meat products is to ensure the destruction of vegetative stages of any pathogenic microorganisms. However, there is always the possibility that the cooking process will not kill some microorganisms that produce spores or that the food can become recontaminated. Therefore, microbiologists recommended that the temperature of the meat should be rapidly reduced, especially from approximately 60 and 5℃, to prevent multiplication of exiting or contaminating bacteria. Rapid cooling is also desirable with cooked products to maintain quality by eliminating the overcooking that occurs during slow cooling.

Some European countries have some similar food safety regulations. Both Irish (Food Safety Advisory Committee, 1991)and UK (Department of Health and Social Security, 1989) government guidelines recommend that cooked meat joints should be cooled from a core temperature of 74℃ to below 10℃ in 2.5h. Chinese government has also made the similar regulations in meats and cooked meats processing (China GB 12694-90). A rapid cooling treatment after cooking can minimize the growth of surviving organism (Burfoot, D, Self, K. P, Hudson, W. R., Wilkins, T. J, & James, S. J. 1990).

Vacuum cooling as rapid evaporative cooling method has been extensively used as an effective method to remove field heat and thus to extend shelf and improve quality for many types of horticultural and floricultural products such as lettuce (Haas & Gur, 1987; Rennie, Raghavan, Vigneault, & Gariepy, 2001), mushroom (Atkins 974), and cut flowers (Sun & Tadhg. Brosnan, 1999). Research has indicated that vacuum cooling can meet both European and USA guidelines. Wang and Sun (2002 part1; 2002 part2; 2004) have developed a mathematical model for describing the vacuum cooling process of large cooked meat joints.

Objectives

In this current study, the previous model is modified and the modified model is further used to analyze the performance of vacuum cooler and the vacuum cooling process of cooked meats.

Mathematical models

Vacuum cooling process includes two fairly distinct phases: (a) the removal of the air in the vacuum chamber from the atmospheric pressure to the saturation pressure at the initial temperature of cooked meats, and (b) the drop of the pressure in the vacuum chamber continuously to the final vacuum pressure. The maximum pressure in the chamber, which can cause water in cooked meats to boil, is the saturation pressure of the water vapour at the initial temperature of cooked meats. The relationship for the saturation pressure of the water vapour in cooked meats and the temperature of cooked meats is determined by (Wang & Sun 2002 part1):

$$P_{sat} = \exp\left(23.209 - \frac{3816.44}{T_K - 46.44}\right)$$

(1)

The total pressure in the vacuum chamber is the sum of the partial of air and water vapour:

$$P_{vc} = P_a + P_v$$

(2)

The decrease rate of total vacuum pressure in the chamber can be calculated by:

$$\frac{dP_{vc}}{dt} = -\frac{S \cdot P_{vc}}{V_f}$$

(3)

In developing the heat and mass transfer models, cooked meats are assumed to be cylindrical in shape with the internal cooling generation due to evaporation. The assumptions of the mathematical models developed can be summarized as follows:

- The initial temperature and moisture content of cooked meats are constant;
- Cooked meats is homogeneous and isotropic;
- The thermal properties of cooked meats are constant;
- The governing equations for the heat and mass transfer are considered as transient.

With the above assumptions, the differential equation for the transient heat transfer can be expressed as:

$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial r}\left(\lambda \frac{\partial T}{\partial r} \right) + \frac{\lambda}{r}\frac{\partial T}{\partial r} + q_v$$

(4)

The initial and boundary conditions for Eq. (4) are:

$$t = 0 \quad , \quad T = T_0$$

(5)

$$t > 0 \quad , \quad r = 0 \quad , \quad \frac{\partial T}{\partial r} = 0$$

(6)

$$t > 0 \quad , \quad r = \frac{D}{2} \quad , \quad -\lambda \frac{\partial T}{\partial r} = \sigma \cdot \varepsilon \cdot (T_{sf}^4 - T_{vc}^4) + q_{sf}$$

(7)

Under vacuum, the heat released from cooked meats to the cooling medium by convection is negligible. The radiative heat transfer is considered. In Eq. (4), q_v is the inner heat per unit volume generated due to water evaporation, q_v can be given by:

$$q_v = -h_{vg} \cdot \dot{m}_v$$

(8)

In Eq. (7), the evaporation heat per unit surface area, q_{sf} can be expressed by:

$$q_{sf} = \frac{D}{4} \cdot q_v = -\frac{D}{4} \cdot h_{vg} \cdot \dot{m}_v$$

(9)

During vacuum cooling, water evaporation occurs from cooked meats, the evaporation rate pre unit volume of cooked meats can be calculated by:

$$\dot{m}_v = \frac{4}{D} h_m (P_{sat} - P_{vc})$$

(10)

Where D is the diameter of the cylindrical cooked meats; P_{sat} and P_{vc} are respectively given in Eq. (1) and Eq. (2). The boiling coefficient, $h_m = 8.4 \times 10^{-7} kg \cdot Pa^{-1} \cdot m^{-2} \cdot s^{-1}$ (Wang & Sun 2002 part2).

In the models, the thermal properties of cooked meats are assumed to be a constant. However, the thermal conductivity and specific heat of cooked meats can be expressed as functions of compositions. The thermal properties strongly depend on the water content of products. The relationships between the thermal properties and water content of products have been summarized as follows (Sweat, 1986):

$$\lambda = 0.148 + 0.493w$$

(11)

$$C = 1.381 + 2.93w$$

(12)

Models validation

The raw meats are brought from the local supermarket. Then, the meats are cooked through the oven (Type of oven is RF-P130Y, China). The diameter of cooked meats is 80 mm. The samples are weighed by the electric balance and weight transducer. A set of T-type copper/constantan thermocouples with an accuracy of ± 0.1 ℃ are used to record the temperature distribution of cooked meats and the temperature of vacuum chamber. The core temperature and the surface temperature of cooked meats are measured respectively during vacuum cooling. The vacuum pressure in the vacuum chamber is measured through the pressure gauge. The data were obtained through the data acquisition system (Agilent 34970A, Agilent Technologies, USA). The free volume of the vacuum chamber is $0.02\,m^3$, and the vacuum pump speed is 14.4 m^3/h. The ambient temperature is 20 ℃. The diameter of cooked meats is 40 mm. Thermal conductivity is 0.5055 $W\cdot m^{-1}\cdot K^{-1}$. Specific heat is 3505.5 $J\cdot kg^{-1}\cdot K^{-1}$. Density is 1093 $kg\cdot m^{-3}$.

Results and discussion

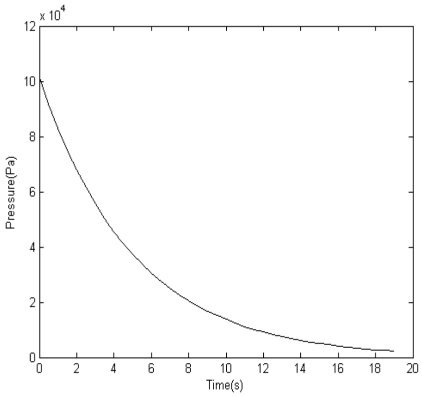

Fig. 1. The vacuum pressure in the vacuum chamber during the first cooling phase

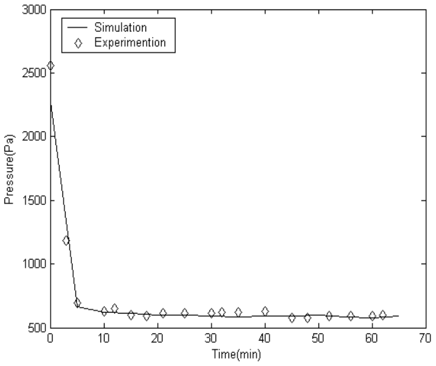

Fig. 2. The variation of vacuum pressure during the final cooling phase

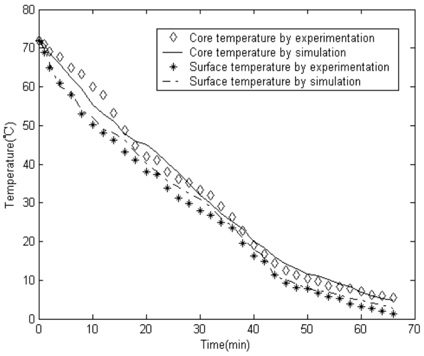

Fig. 3. The variation of temperatures during vacuum cooling

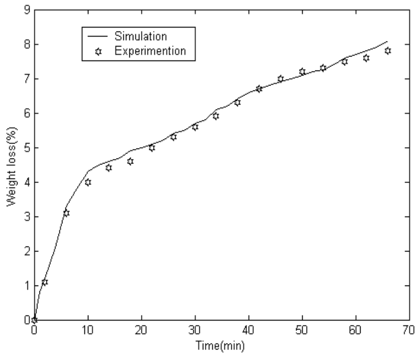

Fig. 4. The variation of weight loss during vacuum cooling

During vacuum cooling, it is assumed that the initial temperature of cooked meats is homogeneous. The curves of vacuum pressure in the vacuum chamber are shown in Figs. 3 and 4. It can be seen that the vacuum pressure in the vacuum chamber ranges from 101325 to 2272.2 Pa in Fig. 3. The pumping time to the flash point is only 19 seconds, which is called the first cooling phase. There is hardly cooling effect in the first phase. Then, the vacuum pressure is reduced from 2272.2 to 620 Pa. The variation of vacuum pressure during the second cooling phase is shown in Fig. 4. It can be seen that the predicted pressure agrees with the experimental value well. However, it can be also found that the experimental pressure can occurs some fluctuations shown in Fig. 4, which is due to the air leakage. Because the defined vacuum pressure, 620 Pa, is maintained by opening the bleeding valve of the vacuum chamber. After the flash point, water in cooked meats begins to evaporate. Therefore, the cooling effect occurs, and the temperature of the cooked meats can reduce because of evaporation of water. It is during the second cooling phase that the cooked meats are cooled until the defined temperature of the cooked meats is reached.

Fig. 5 shows the surface and the core temperature profiles of the cooked meats by experimentation and simulation. The cooked meats are cooled from 72℃ to 5℃ within 70 min. Generally, the conventional cooling methods, such as slow air cooling and air blast cooling, are about form 6 to 10 hrs. Therefore, vacuum cooling is a rapid cooling method compared with the conventional cooling methods. It is shown that the theoretical simulation results agree with the experimental data well in Fig. 5. The differences of temperatures between the simulation and the experimentation are within 5℃. During the simulation of vacuum cooling, the specific heat, the practical thermal conductivity and the density of cooked meats are assumed to be constant. However, the thermal properties of cooked meats vary during the cooling phase. Consequently, the deviation between the simulation and the experimentation occurs. At the same time, because of the inner thermal conductivity of cooked meats, it can be found that the surface temperature is lower than the core temperature during the cooling phase. The final surface temperature of cooked meats is 1.2℃, and the final core temperature of the cooked meats is 5.5℃. During the cooling stage, the temperature of the cooked meats is above 0℃ to avoid freezing in the surface of cooked meats, which can be seen in Fig. 5.

When the vacuum pressure in the vacuum chamber reaches the saturation pressure, the water in cooked meats will boil. Therefore, evaporation of water occurs during the vacuum cooling, which leads to the reduction of weight of the cooked meats, as is shown in Fig. 6. The variation of weight loss during vacuum cooling is shown in Fig. 6. The simulated weight loss result is 8.1%, and the experimental weight loss value is 7.8%. The simulation result of weight loss of cooked meats agrees with the experimentation data. The deviation between the simulation and the experimentation is about 4%.

Conclusions

This paper describes the vacuum cooling of cooked meats. A modified mathematical model is developed to analyze the performance of vacuum cooler and the vacuum cooling process of cooked meats. The model is based on the assumption that the thermal properties of cooked meats are constant. The mathematical model is solved by the Crank-Nicolson method. The model is used to predict the variation of the vacuum pressure in the chamber and the temperature and weight loss profiles of the cylindrical cooked meats.

In order to validate the model, the cylindrical cooked meats are cooled by vacuum cooling from 72℃ to 5℃. The cooling time is only about 70 min, which indicates that vacuum cooling is a rapid cooling method compared with the conventional cooling methods, because the conventional cooling methods are about 6~10 hrs. The experimental data are compared with the simulated results, it is found that the differences of the temperature between the simulation and the experimentation are within 5℃, and the deviation of weight loss between the simulation and the experimentation is 4%. Anyway, the simulation results agree with the experimental data well, which indicates that the developed modified model can predict the variation of the pressure in the vacuum chamber, the temperature and weight loss of cooked meats.

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