Beef Freezing Optimization by Means of Planck Model Through Simulation

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Abstract. Freezing is one of the most commonly used method to preserve beef and other meat products. This present study aimed to optimize freezing time and temperature using Planck equation models. Laboratory-based simulation was performed with different beef size and thickness scenarios. Freezing profiles were described based on beef thermal properties namely heat specific (Cp), thermal conductivity (k) and mass density (p) during freezing. Simulation results showed that all three thermal properties of beef were increased to initial freezing temperature. Specific heat was then decreased gradually until desired temperature was reached. On the other hand, both k and p were still increased exponentially till freezing temperature set point. Moreover, the lower desired freezing temperature, the longer freezing time required. It may conclude that beef freezing can be optimized by modifying freezing temperature setting point that influenced thermal properties during freezing. Optimum freezing time was reached when all three thermal profiles were in steady state.

1. Introduction
Beef and its derivative products are very popular for the people around the world due to its taste and their high nutritional values [1]. Consumers' preferences for beef and meat products take shape in a multifactor interplay of psychological aspects, marketing related aspects and sensory properties of the meat-stuff. Beef normally served after several cooked processing and transformed to other products such as sausage, corned beef or other forms. However, fresh beef and other meat products are very susceptible and easy contaminated by hazardous bacteria and other micro-organisms [2].

To deal with this uncertainty, people normally selected certain stores or meat-shops they trusted to sell safe meat. In another study, consumers of beefsteak were found to value meat safety to be the most important factor and aspect in their decision to buy beef and meat products. Thus, meat or food safety appeared to be far more important than tenderness and freshness of the product [3].

In order to maintain qualities, beef normally were to be frozen or stored in low temperatures. Freezing is a preferred and well known preservation method for maintaining shelf-life of beef and other meat products. This method plays an important role in ensuring the safety of beef and other meat products especially for export market [3]–[5]. Freezing is a practical method for meat preservation but the quality of frozen meat can deteriorate with storage freezing time. Too early beef freezing may cause bacteria contaminations due to water activities. Yet, longer period of storage freezing time will decrease meat qualities due to crystalized ice along the products, these crystalized ice may cause the meat cell walls to be fractured and broken [6].
Most of the beef and other meat materials are distinguished by high water content and nutrient density which make them prone to deterioration and quality losses. During freezing, some part of water content of the beef and meat-stuff are converted into ice crystals due to the transition phase [6], [7]. The amount of water that turns into ice depends on the freezing temperature, freezing time and product compositions [6]. Longer frozen storage time has been reported to cause a decline in meat quality including water holding capacity, colour and tenderness.

Therefore, it is crucial to monitor freezing process and determine the appropriate time and freezing temperatures required to maintain beef and its derivative meat products. Simulation can be used as a method for optimizing beef freezing by simulating thermal properties of those products and further determining optimum freezing time. There are several mathematical models that can be used to determine freezing time and temperature such as Tao and Planck methods [8]. In this present study, a laboratory simulation based was performed to optimize beef freezing in term of freezing time required to extend beef shelf-life. Planck simulation models were used as a basis in developing the simulation models.

Moreover, the International Institute of Refrigeration proposes to consider and recommend that beef and other meat products can be frozen to the temperature lowered to \(-40^\circ \text{C}\) or to a temperature for which 80% of the freeze-able water has been frozen [9], [10]. The freezing rate is the term used to compare the velocity of freezing operation to encompasses through the critical point of ice crystal formation and it determines both the number and the size of the formed ice crystals [11]. Generally, faster freezing rate, leads to a greater number of ice crystals with a smaller median size and more uniform size distribution which results in fewer internal changes in structure of frozen beef and meat-stuff materials [12], [13].

Based on these point of view, we performed a laboratory based simulation to find optimum freezing time required in maintaining beef quality. Simulation was conducted based on thermal properties and characteristics of fresh beef and frozen one. A self-developed computer simulation were developed to find an optimum freezing time based on Planck models.

2. Materials and Methods

2.1. Beef samples

Beef samples were purchased in local auction in Lambaro and Peunayong Banda Aceh, Aceh Province. A total of 3 kg of beef samples were used and half of them were frozen until over frozen to maximum 31 hours.

2.2. Simulation models

In order to find and determine optimum freezing time, Planck models as described bellows, were used to simulate the continuous changes of thermal properties of beef samples.

$$t_F = \frac{\rho L}{T_i - T_{\infty}} \left( \frac{P a}{h} + \frac{Ra^2}{k} \right)$$

(1)

Where \(t_F\) is required freezing time (hour), \(T_{\infty}\) is freezing temperature (°C), \(T_i\) is initial freezing temperature (°C), \(\rho\) is beef density (kg/m³), \(L\) is specific heat of beef samples = 333.32 kJ/kg, \(a\) is the least dimension from beef product (m), \(h\) is heat transfer coefficient (W/m²K), and \(k\) is conduction heat transfer coefficient (W/mK), while \(P\) and \(R\) refer to Planck’s constant used in simulation models.
2.3. Simulation scenarios

Simulation was made to find optimum freezing time and temperature based on beef dimensions, thermal characteristics and properties [14], [15]. Several scenarios were conducted in order to determine the impact of beef dimension and freezing temperature point. In the end, simulation results would describe and summarize the thermal properties of beef samples and optimum freezing time required.

3. Result and discussion

3.1. Simulation interface

Planck equation models and other heat transfer models were derived and coded onto Visual Basic programming language in order to simulate freezing process of beef samples. Graphical user interface (GUI) of developed simulation software was described in Figure 1. At first, splash screen form was shown and user are requested to enter to the main simulation menus by clicking enter to main menu.

Once enter to the main menu, simulation was continued to the main process of finding optimum freezing time required. We performed several scenarios and the input for the example scenario was described in Table 1.

| Parameter          | Input value |
|--------------------|-------------|
| Length (m)         | 0.8         |
| Width (m)          | 0.1         |
| Height (m)         | 0.5         |
| a (m)              | 0.1         |
| P                  | 0.38        |
| R                  | 0.12        |
| Density (kg/m³)    | 1050        |
| Heat specific (kJ/kg) | 248.28    |
| Heat transfer coefficient (W/mK) | 1.108 |
| Heat transfer coefficient (W/m²K) | 20 |
| Freezer temperature (°C) | -30 |
| Initial product temperature (°C) | 15 |

Those inputs scenario were subjected onto simulation program that already developed. Based on simulation results, the optimum freezing time required to perform freezing process was 6.21 hours.
During freezing, thermal properties and characteristics were changed and freezing time was gradually changed exponentially along with freezing temperature as presented in Figure 2.

![Figure 2](image-url)

**Figure 2.** Freezing time and temperature simulation for beef freezing based on Planck model

Freezing simulation indicated that frozen storage could affect the microbiological quality and chemical characteristics of meat, leading to lower quality with increased freezing time [16], [17]. Thus, freezing must be performed optimally. Furthermore, beef density was also changed during freezing and this changes was linearly even freezing was conducted over optimum time as shown in Figure 3.

![Figure 3](image-url)

**Figure 3.** Beef density changes during freezing based on Planck simulation model

During freezing process, a part of the beef water content was changed onto ice crystals due to the transition. The amount of water that turns into ice depends on the freezing temperature and product composition. The ice content at the center of a typical beef freezing as a function of temperature. As it can be seen the majority of ice content is formed at a 5 °C temperature range bellow the initial freezing point. Beef and other meat products reach a critical temperature point at this early stage of freezing and
remains in this zone for a significant duration at which quality degradation of beef occurs as a result of exposure to a highly concentrated aqueous solution. Therefore, the faster the meat product passes through that critical zone, the lower will be the freezing damage. This also in agreement with other literatures that mentioned meat and food products freezing rate is highly affected by the amount of initial water content [3], [18]–[20].

Over freezing time within beef and other meat products may cause several effects including mechanical damage, freeze burn and crystallization. These phenomena may play a substantial role in the disruption of metabolic systems, membrane damage and eventually cell lysis. The heterogeneity of water distribution in meat products lead to a non-uniform volume change throughout the meat-stuff materials. Therefore, it is important to optimize freezing time in order to maintain freezing rate on frozen beef and other products. Obtained simulation results indicated that the freezing rate is the dominant factor affecting the ice crystal size in beef which in turn affects the broken membrane and may decrease beef quality.

4. Conclusion
Based on generated simulation results, it may conclude that freezing time must be optimized in order to maintain and extend shelf-life of frozen beef and meat products. Freezing rate and beef density were changed during freezing and thus affects beef qualities. Those qualities related to nutrient contents such as protein, carbohydrates, fat, minerals and fibres.

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