Vladimir Naumovich ERLIKHMAN, Jury Adgamovich FATYKHOV
Mechanics and Technology Faculty, Kaliningrad State Technical University

Interrelation of quality losses of food products of animal origin at their refrigeration treatment and storage with energy expenses

Summary

Denaturation and oxidation effect in products at their freezing and chilling in a frozen and chilled state on extra heat load and energy expenses of refrigeration unit is demonstrated. The method of their calculation with necessary allowances and calculation formulae are presented. Specific electricity expenses per a ton of frozen product, and specific expenses per a ton a month and 24 hours correspondingly for storing them in a frozen and chilled state correspondingly are suggested as characteristics of extra energy expenses. By way of example close to practical conditions it was demonstrated that extra energy expenses are equal to 3.02 $kW{\cdot}h{\cdot}t^{-1}$ for freezing, 2.6 $kW{\cdot}h{\cdot}t^{-1}24h^{-1}$ for storing frozen product and 7.4 $kW{\cdot}h{\cdot}t^{-1}{\cdot}24^{-1}$ for chilled products. It is recommended to use the results obtained in case if it is necessary to make energy expenses and financial-economical indexes of refrigeration treatment and storing food products more precise.

Słowa kluczowe: *denaturation, bound water, oxidation, heat load, refrigeration unit, energy expenses*

Zależność strat jakościowych produktów pochodzenia zwierzęcego przechowywanych w warunkach chłodniczych oraz koszty energii związane z ich przechowywaniem

Streszczenie

W przeprowadzonych badaniach wykazano wpływ procesów denaturacji i utleniania w produktach podczas ich mrożenia i chłodzenia na dodatkowe nakłady ciepła oraz koszty energii, generowane przez urządzenie chłodnicze. Przedstawiono niezbędne obliczenia, a także formuły tych obliczeń. Określono charakterystyczne nakłady dodatkowej energii związanej z wydatkiem energii elektrycznej na zamrożenie tony produktu w przeliczeniu na miesiąc oraz na 24 h jak również określono wydatki energii elektrycznej w odniesieniu do przechowywania produktów w stanie zamrożonym i w warunkach chłodniczych. Wykazano, że dodatkowe nakłady energii są równe 3,02 $kW{\cdot}h{\cdot}t^{-1}$ w przypadku zamrażania - 2,6 $kW{\cdot}h{\cdot}t^{-1}24h^{-1}$ dla przechowywania produktu w stanie zamrożonym oraz 7,4 $kW{\cdot}h{\cdot}t^{-1}{\cdot}24^{-1}$ dla produktów chłodzonych. Zalecana jest bardziej precyzyjna kalkulacja niniejszych wyników w przypadku obliczeń nakładów energii dla produktów przechowywanych w warunkach chłodniczych.

Key words: *denaturacja, woda związana, utlenianie, obciążenie cieplne, agregat chłodniczy, zużycie energii*

List of signs:

b – share of bound water relation to dry substances, [$kg_{bw}kg^{-1}{}_d$];
c_i – specific heat capacity of ice, c_i= 2.1 [$kJ{\cdot}kg_i^{-1}{\cdot}K^{-1}$];
c_{bw} and c_{fbw} – specific heat capacities of bound water and mixture of frozen and unfrozen bound water at t_v, [$kJ{\cdot}kg_{bw}^{-1}K^{-1}$];
c_d – dry substances specific heat capacity, c_d = 1.24 [$kJ{\cdot}kg^{-1}K^{-1}$];
c_w – water specific heat capacity, c_w=4.19 [$kJ{\cdot}kg^{-1}K^{-1}$];
ω_{bw} – share of frozen part of bound water per a kg of product, [$kg_{ibw}{\cdot}kg^{-1}$].
ε_k - Karno cycle refrigeration coefficient;
η and η_e – reversibility cycle ratio of a refrigeration unit and electric motor efficiency;
L_{bw} – heat capacity of ice formation of bound water, [$kJ{\cdot}kg^{-1}{}_{ibw}$];
P – freezing capacity, [$t{\cdot}h^{-1}$];
T – ambient air temperature, [K];
T_c – temperature of medium cooling which is equal for a plate refrigeration unit t_o a coolant boiling temperature and to air temperature of storing chamber, [K];
W_{bw} – share of bound water per a kg of product, [$kg_{bw}{\cdot}kg^{-1}$];

Introduction

At the processes of refrigeration and storage of refrigerated and chilled products they undergo enzyme and microbiological non-reversable changes which bring about deterioration of their quality in various scientific works (Golovkin, 1984; Artjuhova et al., 2001; Evans, 2010).

The loss of quality of food products at refrigeration is determined primarily by protein denaturation due to the denaturation of bound water with them. Bound water is an additional to free water source of heat load at refrigeration of product and consequently increases energy expenses for refrigeration plant. Unfortunately the works for determining the quality of bound water in the products and changing their share at the refrigeration process are very scarce and that makes analysis of its influencing the energy indexes of refrigeration process more difficult.

From the well known sources the following works should be mentioned (Voskresenskiy, 1957; 1966; Riedel, 1951; Charm, 1966; Rjutov, 1976; Chizhov, 1979; Erlikhman, 2016).

The main reason of food products quality downgrading during their storage is oxidation of fats and proteins. At the processes of refrigeration and chilling oxidation manifests itself but little due to the short period they last in comparing to the time of their storage.

As the process of fats and proteins oxidation is followed by emanation of heat equal to $q_f = 37.7 \cdot 10^3{}_f$ kJ·kg^{-1} and q_p=16.7·10^3 kJ·kg$^{-1}{}_p$ (Artjuhova et al., 2001), then the products storage is also accompanied by extra heat load and energy expenses for a refrigeration plant, the relation between them is known from thermodynamics of refrigeration units (Baranenko et al., 2006).

The chilled products storage is performed at temperatures somewhat higher than initial temperature of tissue juices freezing t_{sf} and it is accompanied by a more intensive products oxidation than at storing frozen products at lower temperatures. It determines less extended storage term of chilled products up to 10-12 days.

Materials and methods

Assessment of extra heat loads and energy expenses due to denaturation of proteins at freezing and oxidation of fats and proteins while storage was performed by way of example on a conditional product (lean fish – haddock, cod) whith the contents of water in relative shares W=0.8, fats F=0.02 and proteins P_p=0.18 with initial product temperature t_s = 15°C and temperature of starting tissue juices freezing t_{sf} = -1°C.

The limit storage period τ for frozen and chilled products is 180 and 6 days correspondingly. The final volume average product temperature after freezing in plate freezer t_v = -20°C. The cooling agent boiling temperature t_o in freezing plant -40°C while that of in cooling instruments of storage chambers for frozen and chilled products -30°C and -10°C at air temperature in them t_a = -20°C and 0°C. Ambient temperature t =30°C.

For determining influence of proteins denaturation at products freezing on extra energy expenses first the shares of frozen bound water $\omega_{b/w}$ and summary share of frozen bound and free water ω in relation to general water contents in product at average volume temperature t_v according to the formulae obtained in works Erlikhman (2016) and Rjutov (1976):

$$\omega_w = 0.134\left[1-\left(\frac{t_{sf}}{t_v}\right)^{0{,}0865}\right] \quad (1)$$

$$\omega = \left(1 - b\frac{1-W}{W}\right)\left(1-\frac{t_{sf}}{t_v}\right) \quad (2)$$

According to data of works Erlikhman (2016) b = 0.31 kg$_{bw}$kg$^{-1}{}_d$. Besides the following values were calculated according to the known functions, specific heat capacity of product prior to ice formation:

$$c_0 = c_w W + c_d(1-W) \quad (3)$$

$$q_{bw} = c_{bw} w_{bw}(t_s - t_{sf}) + L_{bw}\omega_{bw} + c_{fbw}\omega_{bw}(t_{sf} - t_v), \text{ [kJ kg}_{bw}^{-1}\text{K}^{-1}] \quad (8)$$

The freezing process means temperature:

$$\bar{t} = \frac{t_v - t_{sf}}{ln\frac{t_v}{t_{sf}}} \text{ [°C]} \quad (4)$$

The heat of ice formation at mean product temperature $\bar{t}$:

$$L = 334.2 + 2.1\bar{t} \text{ [kJ·kg}^{1}] \quad (5)$$

Specific heat capacity of a frozen product:

$$c_f = c_0 - W\omega \quad (6)$$

Specific heat amount removed at freezing one kg of product:

$$q = c_0(t_s - t_{sf}) + L\omega W + c_f(t_{sf} - t_v), \text{ [kJ kg}^{1}\text{K}^{1}] \quad (7)$$

Specific heat amount removed at freezing bound water is calculated by a similar formula (7) with taking into account shares of bound and frozen bound water per a kg of product.

$$q_{bw} = c_{bw}w_{bw}(t_s - t_{sf}) + L_{bw}\omega_{bw} + \\ + c_{fbw}\omega_{bw}(t_{sf} - t_v)\,[\text{kJ} \cdot \text{kg}_{\text{bw}}^{-1}\text{K}^{-1}] \quad (8)$$

The data of thermophysical properties of bound water and ice from it are practically missing in special literature. The monograph Chizhov (1979) demonstrates on the basis of experiments that they are but little different from the properties of free water and ice. So we take for calculations $c_{bw} = c_w$ and $L_{bw} = L$.

The work Erlikhman (2016) demonstrates the obtained values of bound water and frozen bound water contents per one kg of water in product, which are equal correspondingly to $W_{bw/w}$ = 0.078 kg$_{bw}$·kg$^{-1}{}_w$ and $\omega_{bw/w}$ = 0.03 kg$_{ibw}$·kg$^{-1}{}_w$. As a result of their recalculation for one kg of product it is obtained that $W_{bw} = W \cdot W_{bw/w}$ = 0.0624 kg$_{bw}$·kg^{-1} and $\omega_{bw} = W \cdot \omega_{bw/B}$ = 0.0248 kg$_{ibw}$·kg^{-1}.

The specific heat capacity of mixture of non frozen and frozen shares of bound water is determined by an additivity rule:

$$c_{fbw} = c_w W_{bw} + c_i\omega_{bw} \quad (9)$$

Energy expenses for removal of heat from ice formation in dehydrated from protein bound water at the process of freezing product depend on capacity of refrigeration plant. So it is necessary to determine specific expense of extra energy for freezing one ton of product. To make it possible a formula was obtained on the basis of known dependencies from thermodynamics of refrigeration machines (Baranenko, 2006). Extra heat load:

Erlikhman i Fatykhov, (2016). Interrelation of quality losses of food products of animal origin at their refrigeration treatment and storage with energy expenses. *Inżynieria Przetwórstwa Spożywczego, 3/4*(19), 14-17.

$$\Delta Q_{bw} = P \cdot \Delta q_{bw} \frac{1000}{3600} \text{ [kW]} \qquad \textbf{(10)}$$

Extra power consumed by refrigeration unit compressor electric engine which secure product freezing:

$$\Delta Ne = \frac{\Delta Q_{bw}}{\varepsilon_k \eta \eta_e} \text{ [kW]} \qquad \textbf{(11)}$$

$$\varepsilon_k = \frac{T_c}{T - T_c} \qquad \textbf{(12)}$$

As reversibility ratio is diminishing with lowering temperature of a product being frozen, then values η for conditions of freezing and storing of frozen and chilled products are taken equal to 0.4; 0.5 and 0.6 correspondingly, and η_e for all the variants as equal to 0.85.

It follows from equations (10) and (11) that it is possible to produce a formula for calculation the specific expense of extra energy due to proteins denaturation at product freezing:

$$\Delta e = \frac{\Delta Ne}{P} = 0.278 \frac{\Delta q_b}{\varepsilon_k \eta \eta_e} \text{ [kW·h·t}^{1}\text{]} \qquad \textbf{(13)}$$

Where is 0.278 – transition ratio [kJ·kg^{-1}] into [kW·h·t^{-1}].

Extra energy expenses caused by fat and protein oxidation at the product storage were assessed by extra power per one ton of product.

For calculation the following condition is accepted, on finishing an acceptable term of storage a product is not fit for consumption at δ = 20% oxidation of fats and proteins, which is determined by laboratory research by changing oxidation ratio for fats and nitrogene contents of volatile basis for proteins. Then to calculate the specific heat amount coming into storage chamber from oxidation of one kg of product for 24 hours kJ·kg^{-1}24h^{-1} a formula is valid:

$$\Delta q_{ox} = \delta\left(q_f F + q_p P_p\right)\frac{1}{\tau} \text{ [kJ·kg}^{1}\text{24h}^{1}\text{]} \qquad \textbf{(14)}$$

To determine the expenses of power for driving refrigeration unit compressor in a formula is used:

$$\Delta e_{ox} = 1.158 \cdot 10^{-2} \frac{\Delta q_{ox}}{\varepsilon_k \eta \eta_e} \text{ [kW·t}^{-1}\text{]} \qquad \textbf{(15)}$$

Where 1.158·10^{-2} is a conversion ratio [kJ·kg^{-1}24hours^{-1}] in [kW t^{-1}].

Results and discussion

As a result of calculations for a given example which is close to practical conditions the share of frozen bound water and common share of frozen out moisture correspondingly are $\omega_{b/w}$ = 0.039 and ω = 0.876. The product specific heat capacity prior to ice formation, its mean temperature in the freezing process, ice formation heat, specific heat removal from the product while freezing and specific heat at freezing bound water due to proteins denaturation are equal to c_o = 3.60 kJ·kg^{-1}K^{-1}, $\bar{t} = -6.34$°C, q = 330.29 kJ·kg^{-1} and $q_{bw/w}$ = 12.28 kJ·kg^{-1}. The heat share at freezing bound water in relation to general heat being removed from the product is 3.7%.

Calculation of energy expenses demonstrated that Karno cycle refrigeration coefficient ε_k = 3.33 and extra specific expense of electricity for driving refrigeration unit compressors per a ton of a product being frozen Δe = 3.02 kW·h·t^{-1}. It demands an increase of compressor electric engine power by value of ΔNe = 3.02 kW for refrigeration unit capacity of one ton an hour.

Calculations for determining influence of fats and proteins on extra energy expenses at storage of frozen products give the following results. Specific heat amount coming into storage chamber Δq_{ax} = 4.18 kJ·kg^{-1}24h^{-1} Karno cycle refrigeration coefficient ε_k = 5.06 and extra specific expenses of power for freezing unit compressor electric engine to compensate oxidation heat Δe_{ox} = 0.02 kW·t^{-1}. Storage of one ton of product for 24 hours the extra energy expense is 0.53 kW·h·t^{-1}·24h^{-1} and for a month 15.84 kW·h·t^{-1}·month^{-1}. Storage of chilled products for the accepted conditions Δq_{ox} = 125.33 kJ·kg^{-1}24h^{-1}=1.45 kW·t^{-1}, ε_k = 9.10 and Δe_{ox} = 0.31 kW·t^{-1}, which cause extra energy expeuse per one ton of product at its storage for 24 hours 7.4 kW·h·t^{-1}·24h^{-1}.

The increase of energy expense for heat compensation from fats and proteins oxidation at storing chilled products in comparison with storage of frozen products is determined by a shorter period of storage, intensive emanation of heat at higher temperatures and consequently by a shorter storage period.

Conclusions

The method suggested may be used for determining extra heat loads and energy proteins and fats and proteins oxidation at their freezing and also storing in a frozen or chilled state.

For practical conditions of freezing at capacity of freezing unit of 1 ton an hour the energy consumption due to denaturation of proteins increases by 3 kW·h. The storage of one ton of product for 24 h demands extra electricity of 0.53 kW·h due to fats and proteins oxidation for frozen products and 7.4 kW·h for the chilled ones.

The results obtained may be used for making heat load more precise at designing refrigeration units, calculating extra energy expenses and financial – economic indexes of refrigeration processes and product storage.

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Vladimir Naumovich Erlikhman
Departments Food and Refrigerating Machinery,
Mechanics and Technology Faculty,
Kaliningrad State Technical University,
Sovietsky Prospekt 1,
236022 Kaliningrad, Russia
e-mail: elina@klgtu.ru

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