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IMPROVING HEAT TRANSFER COEFFICIENT DURING DOUBLE-SIDED MEAT FRYING

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Установлено залежність середньоінтегрального температурного напору між температурою поверхні жарення і температурою поверхневого шару м’яса від температури поверхонь жарення. Уточнено методику розрахунку коефіцієнта теплопередачі через парові прошарки під час двостороннього жарення м’яса в умовах стиснення та установлено його залежність від середньоінтегрального температурного напору між поверхнею жарення і поверхневим шаром м’яса

Ключові слова: жарення в умовах стиснення, температурний рівень процесу, теплопередача, температурний напір, парові прошарки

Установлена зависимость среднеинтегрального температурного напора между температурой поверхности жарения и температурой поверхностного слоя мяса от температуры поверхностей жарения. Уточнена методика расчета коэффициента теплопередачи через паровые прослойки во время двустороннего жарения мяса в условиях сжатия и установлена его зависимость от среднеинтегрального температурного напора между поверхностью жарения и поверхностным слоем мяса

Ключевые слова: жарение в условиях сжатия, температурный уровень процесса, теплопередача, температурный напор, паровые прослойки

1. Introduction

The most common among the existing methods of heat treatment of organic meat products in restaurants is conduction. The process is carried out by means of heating the surface of a product that is in direct contact with the heated frying surface or frying on it. Practically valueable during this are the following technological and thermophysical parameters: temperature of the product, temperature of the surface of frying, or fat on it, duration of frying, and specific surface power [1]. Obtaining of a fried product is ensured by constant maintenance of a high-temperature regime (423–473 K), although it adversely affects the quality of the finished product because heterocyclic aromatic amines are formed and accumulated in it [2]. Heterocyclic amines and mutagenic chemicals are formed and accumulated mostly due to the effect of the temperature and duration of the heat treatment process [3]. The content of mutagens in finished products increases proportionately to the temperature of thermal treatment, whereas the mutagenicity of minced meat fried at 473 K is almost twice as high as at 423 K [3, 4]. The process of frying organic meat products is long-lasting and requires considerable energy costs. A relevant task is reducing the specific energy consumption and mass loss of the product during this process.

2. Literature review and problem statement

In order to improve the process of conduction, the authors of [5] proposed to bring heat to the entire surface of the product. Conduction is, thereby, carried out in a functionally closed environment that is formed between two heating surfaces – the bottom and the top, with cavities made according to the geometric sizes of semifinished meat products. This process allows you to adjust the temperature field to the volume of products and reduce the duration of frying meat products by 57–59 %. The sealed medium can increase the output of the finished product by 2.9–3.1 %; in addition, the condensation of water vapor inside the products during their cooling to the temperature of supply to the consumer can increase the output by 6.3–6.7 %. However, from the energy point of view, such a process is not efficient, since it means cooling of the frying machine surface and subsequent switch-over to the required mode after each cycle of the product preparation.

The authors of [6] proposed heating by the electrocontact method combined with traditional or other electrophysical methods of heat transfer. The authors of [7, 8] proposed a method of frying meat products that involves simultaneous surface, infrared and electrocontact heating. In this case, the formation of crust on the surface of products is achieved by surface or infra-red heating, which provides high organoleptic characteristics of the finished product. The supply of electric current to the side surfaces of the product intensifies and provides an even heating of the inner layers of the product in its entire volume. This reduces the time of treatment, increases the yield of the finished product and, respectively, reduces the specific energy consumption.

The heat conduction equation soluable by the Galerkin finite element method laid the basis for the theoretical models of the pan-frying of hamburgers on the surface of the frying pan [9] and double-sided frying of frozen and cooled semi-baked hamburgers [10].

The discussed methods of heating concern only cut meat multi-component products, and their use in the process of pan-frying of organic meat is of little effect, in particular, due to its heterogeneous structure and the presence of fatty inclusions. In addition, the authors did not consider the characteristics of heat transfer from the heating surfaces and heating media to the product during the heat treatment.

Theoretical aspects of intensifying the process of double-sided frying of organic meat products by the physical and electrophysical methods are considered in [11–13] where the authors substantiated that some methods of frying meat form an effective layer of liquid with the coefficient of heat conductivity of liquid. Such a layer can significantly reduce the duration of frying. The authors of [11] proposed to divide the process of double-sided frying by these methods into three main stages in terms of duration and technological impact on the product. The first stage – the stage of heating the surface layers of the product to the evaporation temperature – occurs almost instantaneously. During the second stage, the heat is transferred from the heating surfaces to the product through vapour layers. The second stage ends with the heating of the central layer of of pork products at up to 333 K and beef products – up to 340 K. Upon reaching the appropriate temperature, moisture ceases evaporating to the surfaces because the products acquire the properties of solids. The third stage – the stage of crunching crust – occurs in dry heating. The duration of the third stage regulates the quality and thickness of the crust. The second stage is the most energy consuming of the three stages. The proposed in [11] division of the process into three stages laid the basis for the analysis of the processes of double-sided meat frying affected by physical and electrophysical methods [12]. Study [13] analytically proves the possibility to intensify double-sided meat frying under the effect of the above-mentioned methods. The mechanism of heat transfer to each capillary meniscus through the vapor layer is considered and theoretically justified in [14, 15], and the coefficient of heat transfer k through the vapor layers is proposed to be determined by the following formula:

$$k = \frac{0.05776 \cdot r \cdot d_{cap}}{\Delta \bar{T}^{m} \cdot \Delta \upsilon \cdot \tau_{c}}, \ \text{W/(m}^2\text{·K)}, \qquad (1)$$

where r is the entire heat of vapor condensation at the atmospheric pressure, J/kg; d_{cap} is diameter of the capillary, m; $\Delta \bar{T}^{m}$ is the logarithmic mean temperature difference (LMTD) between the temperature of the frying surface and the temperature of liquid on the surface of the capillary meniscus, K; Δv is a change (decrease) in the specific volume of vapor during full condensation at the atmospheric pressure, m^3/kg; and τ_c is the duration (cycle) of the thermodynamic process 1–2–3, s.

Formula (1) shows that the the coefficient of heat transfer k is primarily affected by two magnitudes. The first is the LMTD between the temperature of the frying surface and the temperature of the liquid on the capillary meniscus surface, $\Delta \bar{T}^{m}$, and the second is the duration of the thermodynamic process (evaporation – condensation), τ_c.

3. The aim and objectives of the study

The aim of the work was to determine the effect of the value of the LMTD $\Delta \bar{T}^{m}$ on the value of the heat transfer coefficient k during double-sided frying of organic meat products under the effect of physical and electrophysical methods.

To achieve the aim, it was necessary to fulfil the following objectives:

– to study the effect of the temperature of the frying surface on the value of the LMTD between the temperature of the frying surface and the temperature of the liquid on the meniscus surface, $\Delta \bar{T}^{m}$;

– to determine the dependence of the heat transfer coefficient k on the value of the LMTD, $\Delta \bar{T}^{m}$;

– to determine the effect of the frying surface temperature on the duration of the process, the output of the finished product, and the specific energy consumption.

4. Materials and methods to study the temperature rate effect on double-sided meat frying under pressure

The research used the test-bed shown in Fig. 1, 2. The test-bed consisted of an experimental sample apparatus to implement double-sided meat frying, PC, a multi-functional energy meter of the type Energy-9 (made in Ukraine), and three digital devices TRD 02 Universal plus (made in Ukraine) with six thermocouples L-0.5. Thermocouples controlled the temperature of the apparatus frying surfaces and measured the temperature of the external and internal layers.

The materials of the study were portions of organic meat products and a pork escalopes made according to the standard documentation [16].

More detailed materials and methods of studying the effect of temperature rate on the process of double-sided meat frying under pressure are described in [17].

5. Research findings on the effect of LMTD on the heat transfer coefficient

Formula (1) needs to be specified to determine how the LMTD affects the coefficient k of heat transfer through vapor layers during double-sided frying of organic meat products. This need arises from the fact that studies [14, 15] of liquid evaporation in the meniscus revealed an inaccuracy in determining the evaporation surface. Studies [14, 15] note that the logarithmic mean surface of the meniscus during evaporation can be calculated as follows:

$$F^{m} = \frac{F_{\max} - F_{\min}}{\ln \dfrac{F_{\max}}{F_{\min}}} = 1.1331 \cdot d_{cap}{}^{2}, \qquad (2)$$

where $F_{\min}$ is the minimum surface of the capillary meniscus, m^2, as a result of the liquid evaporation to the surface layer due to compression:

$$F_{\min} = \pi \cdot d_{cap}{}^2 / 4\,; \tag{3}$$

$F_{\max}$ is the maximum surface of the capillary meniscus, m^2:

$$F_{\max} = \pi \cdot d_{cap}{}^2 / 2\,. \tag{4}$$

However, the contact surface of the meniscus liquid with the frying surface varies in the process of evaporation from

$$\pi \cdot d_{cap}{}^2 / 4$$

and approaches 0 due to the growth of the vapor layer. In view of this, the statement regarding the logarithmic mean surface of the meniscus during evaporation is irrelevant, and relevant is only mean surface of the meniscus $\overline{F}_s$ that is calculated as follows:

$$\overline{F}_s = \pi \cdot d_{cap}{}^2 / 8 \quad \text{m}^2. \tag{5}$$

When vapor is condensed in the meniscus, which is caused by penetration of excess vapor from the meniscus into the environment or an adjacent meniscus, the surface area of the meniscus varies from a hemisphere $\pi \cdot d_{cap}{}^2 / 2$ to 0. An average surface of the meniscus in the process of vapor condensation is determined from the following equation:

$$\overline{F}_{cap} = \pi \cdot d_{cap}{}^2 / 4 \quad \text{m}^2 \tag{6}$$

and the logarithmic mean surface area of heat transfer during evaporation and condensation is calculated as follows:

$$F^m = \frac{\overline{F}_{cap} - \overline{F}_s}{\ln \dfrac{\overline{F}_{cap}}{\overline{F}_s}} = 0.5665 \cdot d_{cap}{}^2. \tag{7}$$

The coefficient of heat transfer from the frying surface to the liquid on the meniscus surface in one thermodynamic process of evaporation and condensation of the vapor under the above conditions will be found in the following way:

$$\begin{aligned} k &= \frac{r \cdot \overline{V}_s}{2 \cdot F^m \Delta \overline{T}^m \cdot \Delta v \cdot \tau_c} = \\ &= \frac{r \cdot \pi \cdot d_{cap}{}^3}{48 \cdot 0.5665 \cdot d_{cap}{}^2 \cdot \Delta \overline{T}^m \cdot \tau_c} = \\ &= \frac{0.11553 \cdot r \cdot d_{cap}}{\Delta \overline{T}^m \cdot \Delta v \cdot \tau_c}, \ \text{W/(m}^2\text{·K)}, \end{aligned} \tag{8}$$

where

$$\overline{V}_s = \pi \cdot d_{cap}{}^3 / 24$$

is the average volume of vapor in a meniscus during evaporation and condensation, m^3.

At the second stage, thermodynamic processes are ensured by a constant difference $\Delta \overline{T}^m$, whereas the specific surface power of each frying surface is calculated as follows:

$$P_s = k \cdot \Delta \overline{T}^m = \frac{0.11553 \cdot r \cdot d_{cap}}{\Delta v \cdot \tau_c}, \ \text{W/m}^2. \tag{9}$$

Due to the known specific surface power P_s, the LMTD and the duration of the thermodynamic process τ_c from formula (9), the capillary diameter during frying is determined as follows:

$$d_{cap} = \frac{P_s \cdot \Delta v \cdot \tau}{0.11553 \cdot r} = \frac{8.6558 \cdot P_s \cdot \Delta v \cdot \tau_c}{r}, \ \text{m}. \tag{10}$$

The frying surface temperature lowered from 423 K to 393 K with an interval of 10 K (Fig. 1) allowed studying the dependence of the LMTD between the frying surface temperature and the temperature of the meniscus surface liquid $\Delta \overline{T}^m$ on the frying surface temperature during double-sided frying of organic meat products by physical and electrophysical methods. The minimum temperature drop on the frying surface at the moment of the meat loading was ensured by the specific surface power of each frying surface of 38 kW/m^2.

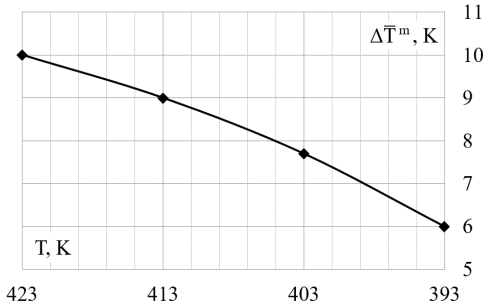

Fig. 1. Dependence of the value of LMTD between the temperature of the frying surface and the temperature of the meniscus surface liquid $\Delta \overline{T}^m$ on the temperature of the frying surface

Fig. 1 shows that a decrease in the initial temperature rate of frying from 423 K to 393 K resulted in a decrease of $\Delta \overline{T}^m$ from 10 K to 6 K according to the nonlinear law. This dependence $\Delta \overline{T}^m$ can be explained by the fact that, regardless of the frying surface temperature, the temperature of the surface layer of the product during the second stage of frying does not exceed 373 K, which is ensured by constant extrusion of the liquid into the surface layer.

Screenshots made in Spectrum Player show the frequency division of the recorded process of double-sided meat frying with excess pressure at the frying surface temperatures of 393 K and 423 K (Fig. 2, 3, respectively).

Fig. 2 shows that sound by the frequency spectrum during double-sided frying is divided into two main bands for the frying surface temperature of 393 K, kHz: 0.1–7 and 9–14. For the temperature of the frying surface of 423 K, the sound is divided into four main bands (Fig. 3), kHz: 0.1–7, 9–14, 16–18, and 19–22. This, obviously, corresponds to the following capillary diameters, m: $34 \cdot 10^{-6}$–$2408 \cdot 10^{-6}$, $17 \cdot 10^{-6}$–$27 \cdot 10^{-6}$, $13 \cdot 10^{-6}$–$15 \cdot 10^{-6}$, and $11 \cdot 10^{-6}$–$12 \cdot 10^{-6}$. The most pronounced, or common, is the range of 0.1–7 kHz with the capillary diameter of $34 \cdot 10^{-6}$–$2408 \cdot 10^{-6}$ m that obviously belongs to peripheral capillaries of the interfiber space filled with free moisture.

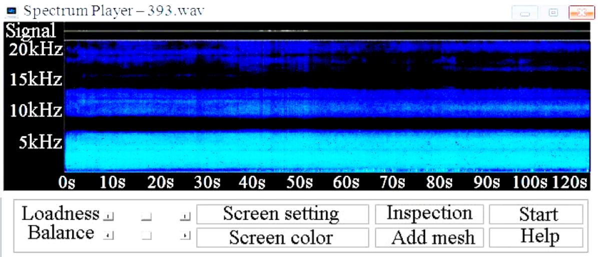

Fig. 2. Spectrum Player screenshot of sound distribution by the frequency spectrum during double-sided meat frying at a marginal pressure for the frying surface temperature of 393 K

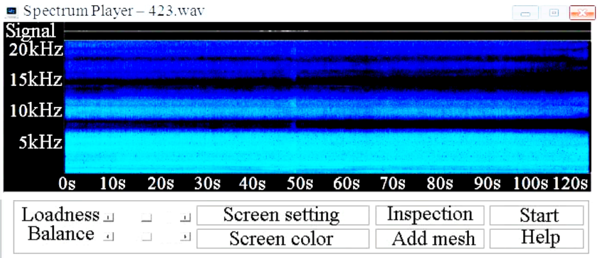

Fig. 3. Spectrum Player screenshot of sound distribution by the frequency spectrum during double-sided meat frying at a marginal pressure for the frying surface temperature of 423 K

The coefficient of heat transfer k=3800 W/(m²·K) corresponds to the frying surface temperature of 423 K, the LMTD $\Delta\bar{T}^{m}=10$ K, and the ratio of $d_{cap}/\tau=0.241$ m/s, $\Delta v=1.653$ m³/kg. The coefficient of heat transfer from vapor to the meniscus liquid in each of the two surface layers is $\alpha_2=2\ k=7600$ W/(m² K). Therefore, the total coefficient of heat transfer from vapor to the meniscus liquid is $\alpha_2=15200$ W/(m² K). When the frying surface temperature decreases to 393 K and, respectively, the LMTD $\Delta\bar{T}^{m}=6$ K, at a constant ratio of $d_{cap}/\tau=0.241$ m/s, $\Delta v=1.653$ m³/kg, the heat transfer coefficient is k=6333.33 W/(m² K). The heat transfer coefficient from vapor to the meniscus liquid in each of the two surface layers is α_2 2 $k=12666.66$ W/(m² K), and the total heat transfer coefficient from vapor to the meniscus liquid is $\alpha_2=25333.32$ W/(m² K).

The coefficient of heat conductivity in the longest muscle of low-fat pork at 293 K and at atmospheric pressure is $\lambda_{m0}=0.54$ W/(m K) [18]; for meat juice under the same conditions, $\lambda_l=0.645$ W/(m K) [19].

When meat is compressed to give excess liquid, $l_{gr}=$ $=11\ 10^3$ Pa, the heat transfer coefficient of meat is approaching $\lambda_{m0}=0.645$ W/(mK), $\rho=960$ kg/m³, and $c=4000$ J/(kg K).

The coefficient of heat conductivity of meat heated up to 345 K is calculated as follows:

$$\alpha=\frac{0.645}{4000\cdot 960}=16.8\cdot 10^{-8}\ \text{m}^2/\text{s}. \qquad (11)$$

Bio criterion for the first stage of frying at the frying surface temperature of 393 K is found in the following way:

$$B_{393}=\frac{25333.32\cdot 0.000093}{0.645}=3.65, \qquad (12)$$

– at the frying surface temperature of 423 K:

$$B_{423}=\frac{15200\cdot 0.000093}{0.645}=2.19, \qquad (13)$$

where 0.000093 m is the radius of the largest capillary in the surface layer of meat;

– for further frying during the second stage:

$$B_{393}=\frac{25333.32\cdot 0.0035}{0.645}=137.47, \qquad (14)$$

$$B_{423}=\frac{15200\cdot 0.0035}{0.645}=82.48, \qquad (15)$$

where 0.0035 m is the half-thickness of meat during frying.

The duration of the first stage of frying from the initial meat temperature of 293 K to the temperature of the surface layer of 373 K at a thickness equal to the radius of the largest capillary ρ=0, is determined from the following equation [20]:

– for the frying surface temperature of 393 K:

$$Fo_{393}^{(0)}=\frac{1}{12}+\frac{1}{3\cdot 3.65}-$$
$$-\frac{2}{3\cdot 3.65^2}\cdot ln\left[1+\frac{1}{2}\cdot 3.65\right]=0.123. \qquad (16)$$

Therefore,

$$Fo_{393}^{I}=$$
$$=\frac{3.65+3}{3\cdot 3.65}ln\left(\frac{2\cdot(393-293)}{(3.65+2)\cdot(379-373)}\right)+0.123=1.20. \qquad (17)$$

Consequently, the duration of the first stage of frying is calculated as follows:

$$\tau_{393}^{I}=\frac{1.2\cdot 0.000093^2}{16.8\cdot 10^{-8}}=0.062\ \text{s}. \qquad (18)$$

The Fourier criterion for the second stage [9] is determined as follows:

$$Fo_{393}^{(0)}=\frac{1}{12}+\frac{1}{3\cdot 137.47}-$$
$$-\frac{2}{3\cdot 137.47^2}\cdot ln\left[1+\frac{1}{2}\cdot 137.47\right]=0.086, \qquad (19)$$

$$Fo_{393}^{I}=\frac{1}{3}ln\left(\frac{137.47\cdot(379-373)}{2\cdot(373-345)}\right)+0.086=0.983. \qquad (20)$$

Therefore, the duration of the second stage of frying is calculated as follows:

$$\tau_{393}=\frac{0.983\cdot 0.0035^2}{16.8\cdot 10^{-8}}=71.68\ \text{s}. \qquad (21)$$

Consequently, the theoretical duration of double-sided meat frying under pressure at the frying surface temperature of 393 K and the center temperature of 345 K is calculated as follows:

$$\tau_{393}^{0}=0.062+71.68=71.742\ \text{s}, \qquad (22)$$

– for the frying surface temperature of 423 K:

$$Fo_{423}^{(0)}=\frac{1}{12}+\frac{1}{3\cdot 2.19}-\frac{2}{3\cdot 2.19^2}\cdot ln\left[1+\frac{1}{2}\cdot 2.19\right]=0.133. \qquad (23)$$

Therefore,

$$Fo_{423}^{I}=\frac{2,19+3}{3\cdot 2.19}\times$$
$$\times ln\left(\frac{2\cdot(423-293)}{(2.19+2)\cdot(383-373)}\right)+0.133=1.575. \qquad (24)$$

Consequently, the duration of the first stage of frying is

$$\tau_{423}^{I}=\frac{1.575\cdot 0,000093^{2}}{16.8\cdot 10^{-8}}=0.081\text{ s.} \qquad (25)$$

The Fourier criterion for the second stage [9] is

$$Fo_{423}^{(0)}=\frac{1}{12}+\frac{1}{3\cdot 82.48}-$$
$$-\frac{2}{3\cdot 82.48^{2}}\cdot ln\left[1+\frac{1}{2}\cdot 82.48\right]=0.087, \qquad (26)$$

$$Fo_{423}^{I}=\frac{1}{3}ln\left(\frac{82.48\cdot(383-373)}{2\cdot(373-345)}\right)+0.087=0.984. \qquad (27)$$

Consequently, the duration of the second stage of frying is

$$\tau_{423}=\frac{0.984\cdot 0.0035^{2}}{16.8\cdot 10^{-8}}=71.75\text{ s.} \qquad (28)$$

Consequently, the theoretical duration of double-sided frying of meat under near-maximum pressure at the frying surface temperature of 423 K and the center temperature of 345 K is calculated as follows:

$$\tau_{423}^{0}=0.081+71.75=71.831\ \text{ s.} \qquad (29)$$

The calculated data completely coincide with the data of double-sided frying of meat at the frying surface temperatures of 393 K and 423 K, which is shown in Fig. 2, 3, respectively.

6. Discussion of the findings on how LMTD affects double-sided meat frying

The dependence of the actual duration of the frying process and the output of the finished product on the temperature of the frying surfaces in the range from 393 K to 423 K is shown in Fig. 4.

Fig. 4 shows that when the frying surface temperature increases from 393 K to 423 K, the duration of double-sided frying of meat under pressure increases from 70 seconds to 76 seconds. This dependence is confirmed by an increase in the LMTD between the frying surface temperature and the temperature of liquid on the meniscus surface. This results in a decrease in the coefficient of heat transfer from the frying surface temperature.

A longer frying process leads to a decrease in the yield of the finished product from 90.6 % to 87.3 %. The output of the finished product reduced by 3.3 % is due to higher moisture. The latter results from a longer evaporation from the semi-finished product and higher temperature of the process, which intensifies vaporization.

A longer frying and reduced output of the finished product, which result from a higher temperature rate, significantly affect the specific energy consumption. Therefore, when the frying surface temperature is 393 K, the specific energy consumption is 0.112 kWh/kg, at a temperature of 403 K – 0.121 kWh/kg, at a temperature of 413 K – 0.129 kWh/kg, and at a temperature of 423 K – 0.135 kWh/kg.

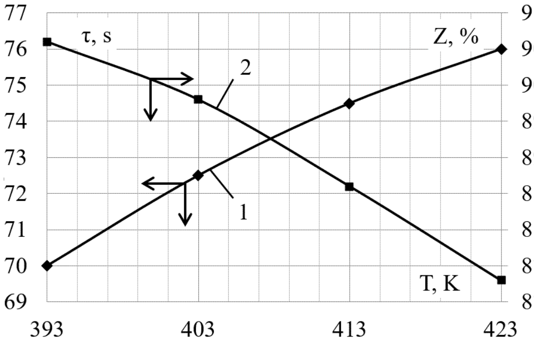

Fig. 4. Dependence of the duration of double-sided frying of meat under pressure, τ (1), and output of the finished product, Z, (2), on the temperature of the frying surface T

All products fried at different temperatures of frying surfaces have reached the state of culinary readiness (the center temperature of 345 K). However, it should be noted that products fried at a temperature of 393 K did not have a typical golden surface, and their taste was more dietary than that of food fried at a temperature of 423 K.

7. Conclusions

1. The specified method of calculating the coefficient of heat transfer through vapor layers takes into account the change in the contact area of the meniscus liquid with the frying surface during evaporation and the area of the meniscus surface in the vapor condensation during double-sided frying of pork under pressure. It has been determined that an increase in the temperature of frying surfaces from 393 K to 423 K lowers the LMTD between the temperature of the frying surface and the temperature of liquid on the meniscus surface from 10 K to 6 K.

2. The study has proved the dependence of the heat transfer coefficient on the LMTD between the temperature of the frying surface and the temperature of liquid on the meniscus surface. The calculated actual heat transfer coefficient from the frying surface to the product is k_{423}=3800 W/(m^2 K) for the LMTD $\Delta\bar{T}^{m}$=10 K, and k_{393}=3800 W/(m^2 K) at $\Delta\bar{T}^{m}=6$ K.

3. It has been proved that when the temperature of the frying surface increases from 393 K to 423 K, the duration of double-sided frying of meat under pressure increases from 70 seconds to 76 seconds, a yield of the finished product decreases from 90.6 % to 87.3 %, and the specific energy consumption grows from 0.112 kWh/kg to 0.135 kWh/kg.

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