Optimization of mass-transfer processes of fish convective dehydration

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Abstract. This article presents the efficiency considerations of the dehydration process in production of dried and cold-smoked fish. Fish loses its moisture more intensively at the stage of constant dehydration rate, then at the stage of drying rate decline the intensity of moisture removal decreases. The task of this research is to design the technology allowing the effective moisture removal not only during the stage of constant dehydration rate, but also during the stage of drying rate decline. During the dehydration the moisture of macro- and microcapillaries of the near-surface area of fish disappear from the product with the most and constant rate. As a result of this phenomenon, a dry area with low moisture conductivity features appear near the surface. The dehydration may be turned to the phase of active moisture transfer, if the crust is removed by refilling the capillaries of the dehydrated area with the remained moisture from inside the product. The suggested method involves looped processes of drying and relaxation of the material at the stage of drying rate decline. The dehydration and eigen relaxation of the material occur on every linear element of transfer. The relaxation of the dehydrated near-surface area is caused from entering the internal moisture of the product in that area. On the next interval of the moisture content change, the product enters the dehydration process with high conductivity features in its all parts again. The calculation method for the beginning of relaxation regime in the dehydration process has been advised. According to the proposed technology of producing smoked fish, the electricity consumption decreases by 8 – 12 % in comparison with the traditional technology at the same process duration.

1. Introduction
Fish dehydration is the main process that defines the duration and power capacity of dried and cold-smoked fish production. Without the optimization of dehydration process it is difficult to rely on cost saving in production of dried and cold-smoked fish. At the same time, it is problematic to optimize those processes without detailed study of fish properties change when receiving the end product [1]. [1].

During the processes of drying or cold-smoking, fish loses its moisture more intensively at the stage of constant dehydration rate, then at the stage of drying rate decline the intensity of moisture removal decreases. The period of drying rate decline requires more time, and the task is to develop the technology of effective moisture removal not only under the constant drying rate, but also at the stage of dehydration rate decline.
As a result of field researches of fish dehydration under the processes of cold-smoking and drying, it has been determined that the coefficient of potential conductivity of internal mass-transfer (diffusion) decreases in 10-15 times of its initial value [2], [3], [4]. The coefficient of potential conductivity of internal mass-transfer, $a_m$, depends on moisture content $U$ in fish under the parabolic law [2]:

$$a_m = a_{m0} + a_{m1} \cdot U + a_{m2} \cdot U^2$$  \hspace{1cm} (1)

Table 1 represents the values of the variables of the equation (1).

| Fish species   | $a_{m0} \cdot 10^9$ | $a_{m1} \cdot 10^9$ | $a_{m2} \cdot 10^9$ |
|----------------|---------------------|---------------------|---------------------|
| cod            | 1.515               | -1.675              | 0.5881              |
| mackerel       | 1.485               | -1.721              | 0.6139              |
| horse mackerel | 1.632               | -1.587              | 0.5776              |

When analyzing the dependency of values of the coefficients of potential conductivity on the change of moisture contents in fish, it may be concluded that moisture conductivity features of fish significantly decrease as fish dehydrates.

Fish is a colloid and deformed during the process of dehydration capillary-porous matter; that is why fish flash is dispensed from moisture during dehydration under the laws of capillary-porous structures.

This implies, that in the beginning of dehydration the moisture of macrocapillaries of the near-surface area of fish disappear from the product with the most and constant rate.

As a result of this phenomenon, a dry area appears near the surface. This area is marked as $\delta$ in the figure 1. Area $\delta$ has low moisture conductivity features.

Figure 1. Curve of dependence of moisture conductivity coefficient $a_m$ of matter $a$ on spatial coordinate $x$ during fish dehydration: $a_{m0} = a_m(\tau_0)$ – the coefficient of moisture diffusion at the start time; $a_{m1} = a_m(\tau_k)$– the coefficient of moisture diffusion in the end of dehydration process; $\delta$ – dehydrated area.
Further dehydration becomes unproductive since a specific crust appears near the surface area and prevents effective moisture removal. It is possible to recover capillaries to microcapillaries if the crust is removed by refilling the capillaries of the dehydrated area with the remained inside the product moisture. Thus, the dehydration may be turned to the phase of active moisture transfer [3], [4].

2. Some methods of intensification of internal moisture diffusion in fish during dehydration

There are several ways of internal moisture diffusion intensification when developing power efficient methods of fish dehydration.

2.1. Periodic fish surface moistening with water during the dehydration

In this case the fish surface is moistened by water spraying at regular intervals. After moistening the process operation is stopped for 30 minutes, then the dehydration continues for 2.5 hours till the next moistening. The total duration of fish dehydration process to the moisture content of 60 % decreases by 18 %. The process efficiency increases if the dehydration is done with higher operating severity [5].

The disadvantage of this method is that in some experiments, the water spraying leads to the soaking of fish product, and appearing of tissue breaks on the near-surface area of dehydrated object. The reason of tissue breaks on the surface of fish is a jump-like increase of moisture gradient in the near-surface moistened layer. The following fast dehydration leads to shrinkage (the decreasing of thickness of the near-surface layer), while the internal layers of fish are still swollen since they contain the excess amount of moisture. The tissue breaks on the near-surface area appear after several cycles of dehydration and moistening. This phenomenon is observed during the dehydration of fish high in fat.

2.2. Fish dehydration, combined with fish surface moistening with salt solution

Due to the osmosis force, the moisture from internal fish layers moves to the near-surface dehydrated area. As a result, intensification of the internal mass transfer is achieved. The fish surface is moistened every 3 hours by short-term brine treatment in enhanced salt concentration [6].

The dehydration efficiency, combined with salting in saturated brine and following dehydration, is higher than with water moistening. The duration of dehydration to the moisture content in fish of 60 % decreases by 34 %. The disadvantage of this method is vegetation of salt on a fish surface. This defect is removed by replacing of two last fish surface moistenings with pregnant salt solution to water.

2.3. Fish dehydration in a layer of several rows on conveyer screens

Fish dehydration by this method increases the power efficiency of drying installations and simplifies the loading of raw material and uploading of the ready product. The method’s principle is that for one dehydration cycle, fish is stirred several times (5-6 times) by pouring from one conveyer of the drying installation to another in the period of 48 hours. By meeting some parameters of fish layer H/B (H – layer thickness, B – fish thickness B), the dehydration speed equality of fish placed by one layer in several rows and one fish placed separately by one layer on the conveyer screen or hanged on bars in the drying chamber may be observed [7].

It should be noted that fish dehydration in a layer on the conveyer screens is possible, in general, for small-sized fish, or, at least, size of the fish should not exceed 250-300 mm. For fish of larger sizes, it is advised to do drying and cold-smoking either on screen carriers, by placing fish in one layer, or hanged on bars in the drying chamber.

3. The principle of technology of convective fish dehydration with the surface layer relaxation

In the traditional technology of dehydration when smoking and drying fish, the impact of the dehydrated surface area on the process is not taken into consideration. This may result in the moisture content \( w_1 \) tending to the final moisture content of fish \( w_f \). At the same time, the moisture gradient
appears in the fish thickness, and the dehydration process becomes non-effective because of the impact of the dehydrated surface area with low moisture conductivity features.

Figure 2 shows the example of a product continuous dehydration within the change of moisture content from the initial value $w_0$ to the final value $w_k$.

![Figure 2](image)

**Figure 2.** Curves showing the moisture distribution during dehydration: non-stationary moisture transfer phase – curve 1; the quasi-stationary moisture transfer phase – curve 2; thickness of the area of active humidity change – $q_1(\tau)$; the value of curve’s maximum change for the quasi-stationary phase of moisture transfer – $q_2(\tau)$; humidity distribution at some moment of quasi-stationary transfer phase – curve 3.

The quasi-stationary phase of moisture transfer begins when dehydration affects the entire thickness of the object of drying, following by the moisture content decreasing in the center of fish. On figure 2 this is a symmetry plane, where $x = 0$. The moisture transfer in this phase becomes complicated by the presence of the dehydrated near-surface area $\delta$ with low moisture conductivity features (figure 1), as well as by the route length of moisture particles leaving the material. The curve of quasi-stationary phase of transfer (figure 2, curve 3) shows the moisture content distribution at some time interval. This phase of dehydration is characterized by the moisture on a surface has low values. Moisture falls away from the product slower. In order to maintain the dehydration rate, more energy requires for moisture removal from the central layers. As a result, the form of curve 3 becomes more slanting. For the ideal dehydration process, the curve 3 will tend to have a form of linear dependency with the value of moisture content $w_k$ (figure 2, dashed line). The quasi-stationary transfer phase is considered to be finished at the moment $\tau''$, when the current $w$ and final $w_k$ moisture content of the object coincide in the material’s symmetry plane $x = 0$: $w (0, \tau'') = w_k$.

The authors suggest the method of mass transfer intensification at the time of dehydration rate decrease. This method can be implemented in the traditional process after appearing of the second critical point $K_2$ on the kinetics curves of dehydration in the period of time $\tau_k$, and is valid on the interval $\tau_k > \tau \geq \tau''$. The proposed method of dehydration involves looped processes of drying and moisture redistribution (relaxation of dehydrated surface layer). For the moisture redistribution, the following conditions are created in the drying chamber: heating of the heat transfer agent is stopped,
and its rate is decreased to the rate of natural convection. It is advised to increase the relaxation duration, for example, by the linear dependence. In this regard, the interval from the second critical moisture content \( w_{k2} \) to the final moisture content \( w_k \) is divided into \( n \) parts:

\[
w_{k2} = w_{i0} > w_{i2} > w_{i3} > ... > w_{in} = w_k
\]

On every linear element of mass transfer \( \Delta w_i = w_{i-1} - w_i \) (i = 1, 2, ..., n), the dehydration and moisture redistribution in fish for decreasing the influence of dry surface layer with low conductivity features. The moisture content on fish surface sinks from the value \( \Delta w_{i-1} \) to the value \( \Delta w_i \). The proposed method of mass transfer optimization creates the conditions for supporting the humidity level of \( \Delta w_i \) during the whole non-stationary and quasi-stationary phases of the interval \( \Delta w_i \). This not only decreases the existence time of the quasi-stationary phase, but also leads to the relaxation of the dry surface area \( \delta \) at the cost of entering the internal moisture of the product in that area. The appearance of moisture in the surface allows the capillaries expanding, increasing their conductivity features. On the next interval of the moisture content change \( \Delta w_{i+1} \), the product enters the dehydration process with high conductivity features in its all parts again.

It should be noted, that on the first intervals of fish dehydration with relaxation, the moisture redistribution inside the product is the most effective. It could be explained by the fact, that the surface layer has higher diffusion properties, and the moisture content of the central parts of fish tends to the initial moisture content \( w_0 \). That is why the relaxation on these intervals has the minimal duration values [1].

Graphically the processes of fish dehydration are represented by the kinetics curves of dehydration. The functional dependency of the average medium-value moisture content of fish \( w_i \) on time of the process \( \tau : w_i = f(\tau) \) is used. The kinetics curves of fish dehydration are similar to ones of other food materials, although, there are some important differences. As time passes, the intensity of moisture loss is decreasing with the same operating conditions of dehydration process. There are critical points \( K_1 \) and \( K_2 \) marked on the kinetics curves, that correspond with the first \( w_{k1} \) and the second \( w_{k2} \) critical moisture content. The critical points appear when the moisture with lower bound energy is completely removed, and then the moisture with higher bound energy begins to be removed. The critical point \( K_2 \) appears for the kinetics curves of fish dehydration in the period of dehydration rate decline [1]. This could be explained by the fact, that during the fish dehydration, the microcapillaries contract, and, therefore, the bound energy of the moisture with the material increases. When reaching the critical point \( K_2 \), the moisture bound energy increases significantly [8, 9]. Thus, in order to choose the time of the beginning of relaxation, it is agreed to align with the time of point \( K_2 \) appearing on the kinetics curve of dehydration.

4. The implementation of technology of convective fish dehydration with elements of dehydrated surface area relaxation

The intensity of dehydration process from the initial to some final moisture content value may be compared, if an average speed \( v (\%/h) \) of dehydration for every process is calculated [7]:

\[
v = (w_0^c - w_i^c)/\tau,
\]

where \( w_0^c \) – the initial moisture content of fish on dry weight basis, %;
\( w_i^c \) – the final moisture content of fish on dry weight basis, %;
\( \tau \) – the duration of dehydration to the moisture content \( w_i^c \), h.

In order to evaluate the efficiency of designed technology of fish dehydration with dehydrated surface area relaxation, the following requirements have been formulated:
at minimum, the equality of the average rates of the dehydration with relaxation \( v_{rel} \) and the continuous method \( v_{cont} \) (the continuous method is used as a control process) or, at maximum, predominance of the rate of the dehydration with the surface layer relaxation over the rate of continuous process;
- the critical point \( K_2 \), appearing on the kinetics curve of dehydration, is a mark of the beginning of the dehydration with surface layer relaxation;
- the dehydration of compared processes finishes when the final moisture content \( w_c^e \), on dry weight basis of 100 %, is achieved;
- electricity saving up to 8-10 % and more for the fish dehydration with relaxation in comparison with the continuous dehydration;
- the appearance improvement of the end product (the appearance is controlled by the organoleptic evaluation).

The method of the calculation of the beginning of dehydration with surface layer relaxation has been proposed.

The first and the second critical points \( K_1 \) and \( K_2 \) align with the critical moisture contents \( w_c^{k1} \) and \( w_c^{k2} \). These critical moisture contents for fish could be found by calculation.

The values \( w_c^{k1} \), \( w_c^{k2} \) depend on the initial moisture content of fish \( w_c^0 \), and could be calculated by the formulas [7]:

\[
\begin{align*}
    w_c^{k1} &= 1,069 \ w_c^0^{0.969}, \tag{4} \\
    w_c^{k2} &= 0,784 \ w_c^0 + 2. \tag{5}
\end{align*}
\]

The beginning of regimes of using dehydration with relaxation \( \tau_{rel} \), hours, is calculated by the formula:

\[
\tau_{rel} = \tau_{k2} + K_{rel} \tag{6}
\]

where \( \tau_{k2} \) – the dehydration duration before the second critical moisture content \( w_c^{k2} \); \( K_{rel} \) – the empiric coefficient, \( K_{rel} = 1.5 \).

The duration of dehydration to the second critical point \( K_2 \), is calculated by the formula (7), [8], [9]:

\[
\tau_{k2} = (\tau_{k1} \tau_{k2} \exp(6.84 - 6.30(w_c^{k2}/w_c^{k1})))^{0.5}. \tag{7}
\]

The unknown variable of the product \( \tau_{k1} \tau_{k2} \) in formula (7) could be found by using the dependence when determining the moisture content on dry weight basis \( w_c^{r=24} \), when the process duration \( \tau \) equals 24 hours [8]:

\[
\begin{align*}
    w_c^{r=24} &= w_c^0 - 3.024 \ X_P^{0.25} \ (w_c^0 - 50)(10S/m - 0.6)^{0.5} \tag{8}
\end{align*}
\]

The formula (8) has constraints: 0.11 \( \leq S/m \leq 0.23 \); 5 \( \leq X_P \leq 22 \),

where \( S/m \) – the specific surface area of fish; \( X_P \) – the operating severity of dehydration:

\[
X_P = \bar{\varphi}(1 - \bar{\varphi}/100), \tag{9}
\]

where \( \bar{\varphi} \) – an average relative moisture content of the drying agent, %; \( \bar{\varphi} \) – an average temperature of the drying agent, °C.
For fish with the specific surface area \( S/m > 0.23 \), the following dependence is used for calculating the moisture content of the drying agent \( w^o_\tau=6 \) while the process duration \( \tau \) equals 6 hours [9]:

\[
w^o_\tau=6 = w^o_0 - X_P^{0.25}(w^o_0 - 50)1.158/(1 - 1.591 S/m + 0.848(S/m)^2)\]  \( (10) \)

The formula (10) has constraints: \( 0.23 \, m^2/kg \leq S/m \leq 0.73 \, m^2/kg; \ 5 \leq X_P \leq 22 \)

Calculated values of the moisture content \( w^o \) from the formulas (8) or (10), under the corresponding duration of dehydration process \( \tau \), could be put to the equation (7) for calculating the unknown variable \( \tau_{\text{rel}} \):

\[
\tau_{\text{rel}} = \tau / (\exp(6.84 - 6.30(w^o/w_c1))(w^o/w_c2)))\]  \( (11) \)

Considering the combined dehydration regime of the back of poutassou.

The beginning of relaxation regimes \( \tau_{\text{rel}} \) could be calculated by the formula (6), \( \tau_{\text{rel}} = 7.7 \) hours

The fish dehydration with relaxation is done according to the schema: 2 hours of dehydration; 0.5 hours of relaxation.

The drying agent parameters in the installation during dehydration regime: temperature \( t \) is 25 °C, the relative moisture content \( \phi \) is 40 %, speed of the drying agent in the chamber \( \nu \) is 2.5 m/s. The drying agent parameters in the installation during relaxation regime: an average temperature is 17 °C, speed of the drying agent in the chamber \( \nu \) is 1 m/s. The continuous dehydration has been used as a control. The characteristic of treated object and the values of the dehydration rates for the processes under study are represented in the table 2.

**Table 2.** The characteristics of treated object and the dehydration rate values

| Initial moisture content of fish on dry weight basis \( \omega^f \), % | Mass content of salt in fish, % | The specific surface area of samples \( S/m \), m²/kg | The continuous dehydration speed \( v_{\text{cont}}^{100} \), %/hour | The speed of fish dehydration with relaxation \( v_{\text{rel}} \), %/hour | The total time of the cycles of relaxation \( \text{per process, hour} \) |
|---|---|---|---|---|---|
| 408,6 | 2,4 | 0,16 | 10,5 | 10,5 | 7,7 |

The kinetics curves of dehydration of the given drying methods are shown in the Figure 3.

From the table 2 it is obvious, that the minimal requirement for the efficiency evaluation of the designed technology is achieved, as the average rates of the dehydration with relaxation \( v_{\text{rel}} \) and the continuous method \( v_{\text{cont}} \) are equal. Figure 3 shows the kinetics curves of fish dehydration of the processes under study. Graphical dependency of the kinetics of dehydration with relaxation and continuous method follow the same shape and almost align. The total time of the periodic processes of dehydrated surface layer relaxation is 7,7 hours. The cost impact of the proposed technology depends on the duration of the relaxation regimes. During the relaxation of the fish surface layer, the drying installation has the minimal electricity consumption. Based on the results, it may be concluded that applying the regimes of fish relaxation after the critical point \( K \) allows to save electricity without increasing the total duration of the process of dehydration. The amount of consumed electricity has been calculated. For the continuous dehydration process the required electrical energy 288 kW, for the process with applying the relaxation of the drying matter – 252 kW. Electricity saving is about 12,5 % at the same process duration.
Figure 3. The kinetics curves of the dehydration with applied surface layer relaxation and the continuous method of dehydration (as a control)

5. Conclusion
The aim of the designed technology of producing dried and smoked products is to increase the power efficiency. The experiments show, that during the production of the mentioned products, the electricity consumption decreases by 8 – 12 % in comparison with the traditional technology. The cost impact is achieved by applying the special combined regimes of dehydration and relaxation to the traditional way of dehydration. By applying these regimes, it is possible to modify the process with the rational use of the diffusion properties of treated material.

The designed method of dehydration allows increasing the recourses of drying equipment by reasonable use of the heat transfer agent during the process of drying. This technology does not require heavy expenses for its adaptation on the drying equipment in use.

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