Computer Simulation Study on Thermal Processing of Potatoes Chips in Food Industry

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Abstract

The quality of potatoes chips produced in food industry is influenced by residual humidity and by quantity of Acrylamide produced during potatoes frying process on temperatures higher than 120 °C. Moisture influences the shelf life, and Acrylamide is a carcinogen substance. These two qualitative parameters are influenced by the temperature, the frying time and the thickness of the potato slice. At the Transilvania University specialized software was developed to simulate the process of potatoes chips frying. With this software, a study regarding the influence of all three technological parameters (temperature, frying time and thickness of the potato slice) on the qualitative parameters (humidity and tendency to form Acrylamide) of the potatoes chips was conducted. Based on the results, the recommended conditions for an optimized processing were established.

Keywords

computer simulation, potatoes chips, food industry, acrylamide

1. Introduction

Many of the food industry products require thermal processing. This involves a complex physical and chemical process (heat transfer, phase transformations, chemical reactions, diffusion processes, etc.) that ultimately determines product quality, material, energy consumption and cost.

A much-needed and consumed product on the food market is potatoes chips. These are obtained by heat treatment (oil frying) of thin potato slices. The food and commercial quality of the chips is determined by the residual humidity, the uniformity of frying, the degree of burning, the taste and the food flavours.

Potato slices subjected to frying have high water content (80-90%). At harvest the content is higher (90%) but after long storage in dry environments, humidity decreases (up to 80%). Water is chemically bonded in the solid substance (hydrocarbons). Residual humidity is important because it influences the chips conserving capacity. A large residual humidity reduces the shelf life because it promotes the development of bacteria and moulding alteration [17, 18, 19].

Another important quality parameter for chips is the Acrylamide content. Acrylamide is a substance that is formed between 120 and 180 °C when food is fryed in oils that do not resist on high temperatures (sunflower oil, margarine, butter). Acrylamide affects the central nervous system and promotes cancer. Therefore, the content of Acrylamide in fryed foods, including chips, should be as low as possible (zero, if possible).

Acrylamide is found in all roasted foods: peanuts, almonds, cereals, chips, bread, small barbecue, etc. In the case of frying foods rich in protein (meat, fish), smaller amounts of Acrylamide are produced. In case of roasting foods rich in carbohydrates (potatoes, cereals), higher amounts of Acrylamide are generated [17, 18, 19, 21, 22].

The third qualitative parameter of the chips (flavour) depends less on the thermal processing, because processing in this sense is applied after roasting, mixing with specific additives (salt, flavours, spices, etc.).

The remaining moisture and the amount of Acrylamide in the chips are influenced by technological factors (oil temperature, roasting time), dimensional factors of the semi-products (potato slices thickness and diameter), the qualitative characteristics of the potatoes (initial moisture, starch content), constructive factors of ovens (the geometry and dimensions of the working space, the position and speed of the transport elements inside of oven.

Temperature and processing time adversely affect the two qualitative parameters of the chips. If the temperature and frying time increase, the residual humidity decreases, but the amount of Acrylamide increases. So increasing the temperature and frying time is favourable from the humidity point of view, but it is disadvantageous in terms of Acrylamide. This antagonistic influence of the thermal processing conditions on the two qualitative parameters of the chips requires the performing of technological parameters optimization studies.

The optimization of technological processes can be done on the basis of experimental research or computer simulation studies. Given the existence of software that correctly reproduces technological processes, computer simulation is much more advantageous because:

- allows the progressive modification of all influence parameters;
- permits to evaluate the evolution of any size that characterizes the quality of the products at any point and at any time;
- does not require materials, installations, devices, equipment for experimentation and measurement;
- labour consumption and working time are much lower;
- can be more precise because often devices measuring some parameters (e.g. thermocouples for temperature measurement) have inertia or cause process disturbances;
- is much faster because it does not require device execution, installation modifications, testing time, sample preparation and testing.

Systematic research of the thermal processes in the chips production plants by experimental methods under industrial or laboratory conditions is difficult to be achieved especially due to the complexity of the installations and due to the difficulty of measuring some parameters (temperature, humidity, Acrylamide, etc.) in the inside of the potatoes during processing. For this reason, a systematized and detailed study of this process can only be accomplished by simulating the frying process on the computer.

By simulating the chips roasting process for optimization, it is necessary to consider the following:

- the temperature field of the potato slices according to the roasting time;
- the tendency to form Acrylamide;
- residual humidity;
- the analysis of the influence of some functional and constructive parameters of the roasting installations on the roasting process.

The optimization of the process based on the analysis of these factors has in view the followings;

- determination of the potato slicing time;
- establishing the optimum thickness of potato slices;
- setting the temperature of the cooking oil.

The mathematical modelling of potato slices frying consists in the mathematical equation of the thermal processes and the phase transformation (evaporation) from the inside of the potato slices and from the roasting plant. There is currently no specialized software for simulating the chips roasting process. Making such software requires first of all a mathematical model of this process. Having in view of these considerations, a mathematical model and a special software designed to simulate frying chips or frying potatoes were developed at Transylvania University in Brasov.

Depending on the geometry and size of the products and installations, mathematical models and software for simulation of thermal processes can be done in 2D or 3D coordinate systems, respectively in Cartesian, cylindrical or spherical coordinates.

Models and 2D simulation software for thermal processes are applicable to cases where the heat transfer is predominantly in two directions. This corresponds to systems that exhibit translational or rotation symmetry. 2D simulation has the following advantages:

- simpler computing;
- simpler software structure;
- much less time to perform simulations.

Mathematical models and 3D simulation of thermal processes are applicable to heating products with complex geometry when heat exchange is asymmetrical in the three directions. 3D simulation has some drawbacks:

- software structure is more complex;
- computational relationships are more complicated,
- the volume of the larger calculations;
- requires computers with higher memory capacity;
- the duration of the simulations is much higher.

Due to the development of computer technology over the last two decades worldwide, research in the field of modelling and simulation of industrial thermal processes has seen a great development. Especially software has been developed to simulate such processes for the metallurgical industry. This is because manufacturing costs, labour, materials and energy consumption, as well as environmental impact, are very high in this industry. Such high-performance software was also developed at the Faculty of Materials Science and Engineering at Transilvania University of Brasov [1 ... 5, 20].

The simulation of the thermal processing of foodstuffs has a high importance for the optimization of their quality. In the case of chips, the simulation of the roasting process allows to highlight aspects that cannot be outlined experimentally such as the temperature evolution in points inside the potato slices, the distribution of the temperature inside the potato slices, the influence of the dimensions and the technological parameters on these factors, the distribution of residual humidity, the Acrylamide formation tendency, etc.

2. The Principle of Mathematical Modelling of Chips Frying

So far, no custom software has been developed to simulate the thermal processes from chips roasting. However, simulations with general software designed to simulate heating and diffusion protocols (e.g. COMSOL software) [13] have been carried out but they do not analyse the tendency of Acrylamide formation. That is why at Transilvania University of Brasov a mathematical model and software was developed to simulate this process [23].

Taking into account the chips processing geometry with continuous symmetry of the chips processing systems (continuous-flow tunnel furnaces and belt conveyor) and the geometry of the processed slices of potato slices - thin slices, the software use a 2D Cartesian coordinate system. Due to the symmetry of the potato slices, this coordinate system allows simulation of the roasting process in volume. The 2D simulation of the roasting process is applicable to studying the thermal processes that take place in systems with translational or rotation symmetry. Continuous tunnelling machines (fryers, ovens) where chips are processed meet this condition. 2D chips simulation models consider heat transmission only in two directions (in a Cartesian xOy axis system) through the cross section of the oil potato oven assembly. This mode of transmission of heat is close to reality for the cross section and for systems that are long in length relative to the other two dimensions. The 2D mathematical model developed by Transilvania University is based on the experience gained at the Materials Science Department at Transilvania University of Brasov on the occasion of realizing mathematical models and 2D and 3D software designed to simulate the solidification of castings made of metal alloys. They are used to simulate thermal processes and liquid-solid phase transformations that take place when solid metal castings of liquid alloys are solidified.

The relationships that shape potato roasting are adapted to this process, taking into account the presence and evaporation of moisture in potato slices and the Acrylamide formation process at temperatures between 120-180 °C. The mathematical model achieved uses the finite difference method. The cross-section through the continuous-operation tunnel-potato-oil furnace assembly is divided into square elements having the side Δ. The sides of the elements are parallel to the axes of a Cartesian system xOy, as shown in Figure 1.

The mathematical model is based on the differential equation of thermal transfer between elements of the division network. The side of the network elements (Δ) must be chosen so that the elements are homogeneous from the point of view of the material (consist of a single material, oil, metal or potato). The frying time is also divided into very small "τ" intervals. The accuracy of the calculation is even greater as the meshing of space and time is finer. For the model to be solvable, step "τ", must be correlated with the step of the network (Δ). The deeper the meshing (for Δ - smaller, "τ" has to be smaller).

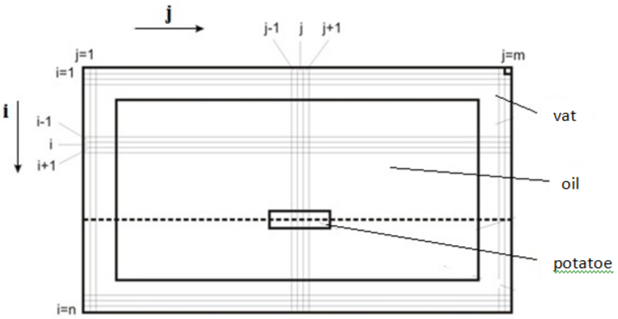

Fig. 1. Scheme of oil tanker - oil - potato slice division
into Cartesian coordinate finite elements for 2D modelling

3. Hypotheses of the Mathematical Model

When developing the 2D mathematical model, the following hypotheses [23] were considered for chips roasting:

- initially, at ambient temperature, the potato slices are made of solid substance (cellular - fibrous material, with a complex chemical composition, which starch, proteins, mineral salts and vitamins and chemically bound humidity);
- at each moment the state of an element in the network is characterized by the temperature, the amount of solid substrate, the humidity and the value of the thermophysical characteristics;
- the initial state of each element in the system is known;
- on heating the solid potato slices decompose chemically by releasing the water by evaporation at the temperature of the T_V = 100 °C;
- the water evaporates at constant temperature by absorbing the latent heat of vaporization;
- during evaporation of water from a network element, its temperature remains constant equal to the vaporization temperature T_V = 100 °C;
- after sewage from potato slices, its place is taken from the food oil;
- the heat transfer processes in the elements inside the system are taken into account by equivalent thermal conductivity;
- the heat transmission is carried out in the directions Ox, Oy which correspond to the symmetry axes of the cross section of the potato slice;
- the contact between the elements in the network is perfect throughout the process;
- the heat exchange between the furnace and the environment is taken into account by an equivalent heat transfer coefficient;
- the initial chemically bound humidity in potato slices is u_0 = 0.9 (in practice it has values u_0 = 0.8 – 0.9, depending on potato type, duration and storage conditions);
- at a temperature of $T \leq 100$ °C, the solid potato fraction (ξ) consists of the solid residue (r_S) - which is constant and the chemically bound humidity in the hydrocarbons and other substances (u);
- the non-volatile solid residue in the potato structure is $r_S = 0.1$ (10%);
- during frying, the solid fraction (ξ) changes as a result of evaporation of water between 1 and 0.1 (i.e. between 100% and 10%);
- Acrylamide is formed in the temperature range 120-180 °C;
- the Acrylamide formation tendency is proportional to the volume of elements having a temperature $T \geq 120$ °C;
- the roasting system assembly can comprise four materials (potato consisting of solid organic chemicals and chemically bonded moisture, evaporated moisture, food oil, furnace wall);
- the variation of volume and hence of density with temperature is neglected;
- evaporated moisture is removed from the potato slice at 100 °C as the latent evaporation heat is absorbed;
- the potato slice floats in the food oil environment (it is surrounded by oil on all surfaces).

Modelling with finite differences requires a steady maintenance of the dividing line step. In this situation, density variation with temperature cannot be taken into account.

4. Equations of the Mathematical Model

After a certain time interval from the beginning of the process, at any moment, the state of a certain element in the network with numerical coordinates "*i*, *j*" is characterized by a certain amount of time $\tau^k = k\cdot\tau$ (τ - time step, k - numerical time coordinate) through the T_{ij}^k temperature and the residual fraction ξ_{ij}^k of the sunk potato (which is made of non-vaporous solid material plus un-evaporated moisture). In the case of potato slices processing in chips, the only elements that undergo phase transformations by latent heat absorption (evaporation of water) are the elements from the slicing of potato slices. The fraction of residual humidity (not depleted) at any given time is denoted by these elements we will call it a solid fraction. Network elements (which correspond to the furnace housing or heating medium - food oil) do not undergo phase transformation. At the initial time (with numerical time $k = 0$) these sizes are denoted by T_{ij}^0 and ξ_{ij}^0, respectively. For the elements corresponding to the oil and the carcass (fryer), the untransformed (solid or liquid) initial fraction is $\xi_{ij}^0 = 1$. For elements corresponding to potato slices, which are at the initial temperature (T_{ij}^0 = 20 °C) or below the water vaporization temperature (T_{ij}^k <100 °C), the fraction not transformed at a given time to is $\xi_{ij}^0 = 1$ and, respectively, $\xi_{ij}^k = 1$. For potato slices, which are at the water vaporization temperature $T_{ij}^k = T_V$ = 100 °C, the residual fraction is $0.1 < \xi_{ij}^k < 1$. For potato items that are at temperatures higher than the $T_{ij}^k > T_V$ = 100 °C water vaporisation temperature, the residual potato fraction is $\xi_{ij}^k = 0.1$ (equals the solid residue that undergoes overheating (and above 120 °C transforms into Acrylamide.) For a network volume element with the numerical coordinates "*i*, *j*" in the potato slices can be written the relation [24]:

$$\xi_{ij}^k = u_{ij}^k + r_{ij}^k, \tag{1}$$

where: u_{ij}^k is the unpowered humidity in the element at the numerical moment "k"; r_{ij}^k - residual potato salt (made up of non-volatile solids) which turns to acrylamide when heated between 120-180 °C (overcooling). As shown in the model assumptions, it is assumed that the value of r_{ij}^k remains constant at the initial value. In the case of the simulations carried out, the case $r_{ij}^k = r_{ij}^0 = 0.1$ was considered, corresponding to an initial moisture content of the 90% potato slice.

From the relationship (1) it is calculated the unevaporated moisture (residual) in the potato slice at a numerical moment "k" by the relation:

$$u_{ij}^k = \xi_{ij}^k - r_{ij}^k = \xi_{ij}^k - 0.1 \tag{2}$$

It follows from the relationship (2) that the variation of the humidity ($\Delta u_{ij}^{k,k+1}$) as a result of the evaporation of the water at 100 °C, in a time interval τ between two values of the time coordinate k and k+1 is equal to the variation of the solid fraction, according to the following relationship:

$$\Delta u_{ij}^{k,k+1} = u_{ij}^{k+1} - u_{ij}^k = \left(\xi_{ij}^{k+1} - 0.1\right) - \left(\xi_{ij}^k - 0.1\right) = \xi_{ij}^{k+1} - \xi_{ij}^k = \Delta\xi_{ij}^{k,k+1} \tag{3}$$

To write the equations of the mathematical model, any element of the coordinate form "*i*, *j*" is surrounded by four other elements, according to the diagram in Figure 2. The state of the respective elements at time τ^k (for time coordinate "k") is characterized by the temperatures and solid fractions specified on the drawing.

At the initial simulation (k = 0) these sizes are known. Due to the difference in temperature between the central element "*i*,*j*" and the neighbouring elements, a heat exchange $(\Delta Q_{ij}^k)_S$ occurs in a time interval "τ". As a result, the central element suffers a variation of internal heat $(\Delta Q_{ij}^k)_M$.

The mathematical model is based on the thermal balance equation for some element "*i*,*j*" of the form assembly, corresponding to an elemental time interval τ [1÷5, 23]. This equation is:

$$\left(\Delta Q_{ij}^k\right)_M = \left(\Delta Q_{ij}^k\right)_S \tag{4}$$

The heat transmitted by the element "*i*,*j*" of the neighbouring elements through the contact surfaces (the dimension in the direction of the third direction Oz, perpendicular to the plane of the section is considered equal to the unit) is expressed by the relation:

$$\left(\Delta Q_{ij}^{k}\right)_{ced} = \begin{bmatrix} \alpha s_{i,j}^{k} \cdot \left(T_{i,j}^{k} - T_{i,j-1}^{k}\right) + \alpha d_{i,j}^{k} \cdot \left(T_{i,j}^{k} - T_{i,j+1}^{k}\right) + \alpha h_{i,j}^{k} \cdot \left(T_{i,j}^{k} - T_{i-1,j}^{k}\right) + \\ + \alpha j_{i,j}^{k} \cdot \left(T_{i,j}^{k} - T_{i+1,j}^{k}\right) \cdot \Delta \cdot \tau \end{bmatrix} \qquad (5)$$

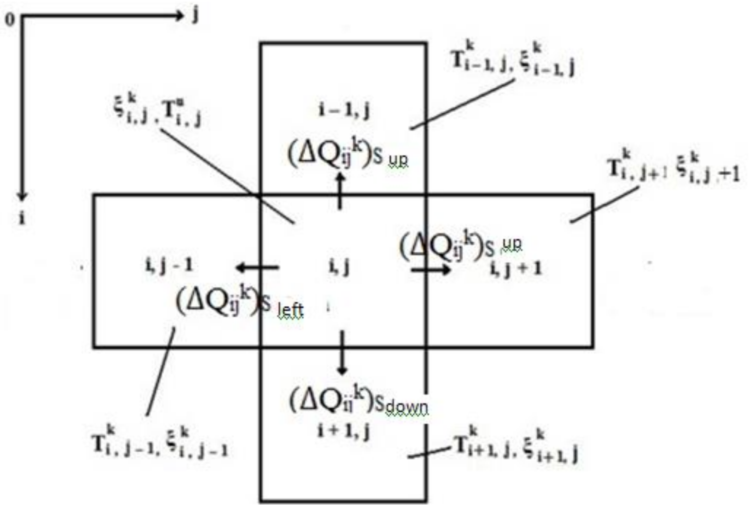

Fig. 2. Heat transfer scheme and notation of temperatures and residual solid fraction of the elements involved in the thermal balance equation

In the calculation of this heat the following convention of signs was adopted: the heat exchanged by an element "*i, j*" with the neighbouring elements is considered positive when the central element is warmer and yields heat to the neighbouring elements. In the case of elements in the potato slice, the heat absorbed by the neighbouring elements may have three consequences on the element temperature:
- below the vaporization temperature (below T_V = 100 °C) leads to increased temperature;
- at the vaporization temperature (at TV = 100 °C, evaporation of chemically bonded water by the absorption of latent heat of evaporation (thus changing the residual moisture and the residual solid fraction of the potato slice) at constant temperature;
- above the T_V vaporization temperature = 100 °C, temperature rise also occurs, with the consequence that over 120 °C, the residual solid matter of the potato starts to turn into Acrylamide.

In the case of the elements corresponding to the potato slice (in which the water evaporation at the temperature of the T_V = 100 °C occurs), nine situations are encountered in calculating the internal heat variation of the elements Q_{ij}^{k} at time step "τ" (T_{ij}^{k} and ξ_{ij}^{k}) and their final state at time τ^{k+1} (given by T_{ij}^{k+1} and ξ_{ij}^{k+1}). The nine cases are determined by the position of the initial T_{ij}^{k} temperature and the final temperature T_{ij}^{k+1} in relation to the phase transformation temperature (T_V). In the practice of thermal processing of the chips, this is not the case, since practically no chip reclamation and restoration of the chemical bonds and the initial cellular structure can occur. Cases have been included in the mathematical model of the need for it to be complete (to include all possible cases). The mathematical model and the software also apply to modelling the thermal processing of other food products that would eventually involve such cases.

According to the sign convention adopted above for $(\Delta Q_{ij}^{k})_S$ the internal heat variation $(\Delta Q_{ij}^{k})_M$ is considered negative when the temperature of the element "*i, j*" increases and the fraction of the solid decreases respectively (the residual humidity in the potato falls).

5. Solving the Mathematical Model

The solving of the mathematical model aims at determining the evolution of the temperature and of the fraction of solid (or of the residual humidity - chemically bound in the potato slice) for each element in which the furnace-chip system is divided [23]. These are determined by solving the thermal balance equation (4) for each element in the sequence of time intervals. In the thermal balance equation (4) the expressions of the two heat $(\Delta Q_{ij}^{k})_S$ and $(\Delta Q_{ij}^{k})_M$ are replaced. The solving scheme is based on the fact that at a moment τ^k (which corresponds to the numerical time code "k") the temperature T_{ij}^{k} and the fraction of solid ξ_{ij}^{k} are known for all elements. The solving of the thermal balance equation (4) for each element allows to determine the temperatures and the fraction of solid (i.e. residual humidity) (T_{ij}^{k+1}, ξ_{ij}^{k+1} and u_{ij}^{k}) at the next time step, i.e. at moment τ^{k+1} for the time code "k+1").

The mathematical model conceived follows a conditional relationship solving scheme, which takes into account the initial and final solids temperatures and fractions at the moments τ^k and τ^{k+1}, of the elements in the network (respectively the values T_{ij}^{k}, ξ_{ij}^{k} and T_{ij}^{k+1}, ξ_{ij}^{k+1}).

The solving scheme for determining the final state of the elements assumes in a first phase that after the time τ, the temperature of the element becomes equal to the water vaporization temperature (i.e. T_{ij}^{k+1} = T_V). In this condition, the residual solid fraction (and the chemically bound residual humidity) is calculated at the next time step ξ_{ij}^{k+1} (u_{ij}^{k}) at time t^{k+1}. If the calculated solid fraction is in the range of [0; 1] (i.e. the boundary humidity is between 0 and 0.9), the assumption is correct and the result (the ξ_{ij}^{k+1} and T_{ij}^{k+1} values) of the calculation is compatible with the assumption (with the calculation hypothesis). If the calculated solid fraction does not converge in the range [0; 1] (i.e. if the boundary humidity is not between 0 and 0.9) return to the thermal balance equation and then calculate the correct T_{ij}^{k+1} temperature.

6. Results Provided by the Software

Based on the mathematical model and its solving scheme, a software for the 2D simulation of chip thermal processing was developed. The structure of the software looks at the mathematical model [23]. The software uses the MATLAB programming system. It offers several advantages for simulating physical processes:

- simplicity and speed in performing mathematical calculations that use mathematical symbols and functions;
- the possibility of working with spatial matrices;
- easy processing of results;
- features in graphic representation of results under various aspects (curves, histograms, colour map, etc.).

The software designed to simulate thermal chip processing at Transilvania University of Brasov provides the following results related to this process:

- the temperature evolution at any point of the potato slice;
- the evolution of moisture at any point of the potato slice;
- determination of average residual moisture in the potato slice and its evolution over time;
- the distribution of temperatures in the system section at any time;
- the distribution of moisture in the potato slices section at any time,
- the distribution of the acrylamide formation trend on the potato slices section at any time;
- the heating time to a given temperature at any point in the system;

Using the software allows you to perform the following studies:

- influence of geometry and sizes of potato slices (thickness, diameter, etc.) on heating parameters and on qualitative parameters (temperature and heating time, residual humidity, Acrylamide formation tendency, etc.);
- the influence of the initial humidity of potato slices on the mentioned parameters (heating temperature, humidity, Acrylamide, etc.);
- the influence of the heating time in the plant on the parameters mentioned (heating temperature, humidity, Acrylamide, etc.);
- influence of the temperature of the food oil on the mentioned parameters (heating temperature, humidity, Acrylamide, etc.);
- the influence of the thermophysical characteristics of the roasting medium (food oil) on the mentioned parameters (heating temperature, humidity, Acrylamide, etc.);

-influence of the geometry and dimensions of the processing plant on the parameters mentioned (heating temperature, humidity, Acrylamide, etc.).

7. Methods of Research through Simulation

The software was used to carry out concrete studies on the influence of some technological parameters on the roasting process.

The influence of potato slices thickness and frying time and influence of food oil temperature and frying time on chips frying parameters [23] were studied. They pursued the following:

- the temperature evolution at various points of the potato slice;
- humidity evolution at various points of the potato slice;
- temperature distribution at various times on the potato slice section;
- the evolution of residual moisture (wet) in the potato slices section;
- the tendency to form acrylamide in the chips section.

Average moisture in the potato slice section was calculated by:

$$U_{\text{med}} = \frac{\sum_1^N u_{ij}^k}{N} = \frac{\sum_1^N u_{ij}^k}{n \cdot m} \tag{6}$$

where u_{ij}^k - represents the humidity at the moment "k" of the element with coordinates "i, j", N - the total number of elements in which the potato slices are divided, n - the number of lines in the potato slice, m columns corresponding to the potato slice.

The Acrylamide formation trend was calculated by the percentage weight of the number of volume elements (N_{120}) reaching the initial Acrylamide formation temperature (T_{ij}^k = 120 °C) in relation to the total number of elements (N) in which the slice of potato is divided. The calculation of the relation is:

$$TA = \frac{N_{120}}{N} \cdot 100\% \tag{7}$$

At the end of a simulation, the software directly displays the average moisture and the Acrylamide formation trend.

The scheme of the roasting system taken into account for the simulations is shown in Figure 3. It reproduces the section on a small scale through a continuous furnace-type tunnel for roasting chips. The processing area is a rectangular box made of stainless steel. Its interior is filled with food oil initially heated to the working temperature. Inside the enclosure was considered a potato slice. The sketch in Figure 3 also shows the dimensions of the pot and the potato slice. The thickness of the potato slice is marked "h" and the length "L". We did not consider the modifying oil heating element to simulate the structure of the software. The section considered of the cuvette - food oil - potato slice is divided into square elements with the side Δ. The elements resulting from the division of the section are arranged on lines and columns. Figure 4 shows the splitting of the potato slice and the points in which the evolution of the remaining temperature and humidity was analysed by simulation. Potato slices were divided into three overlapping layers.

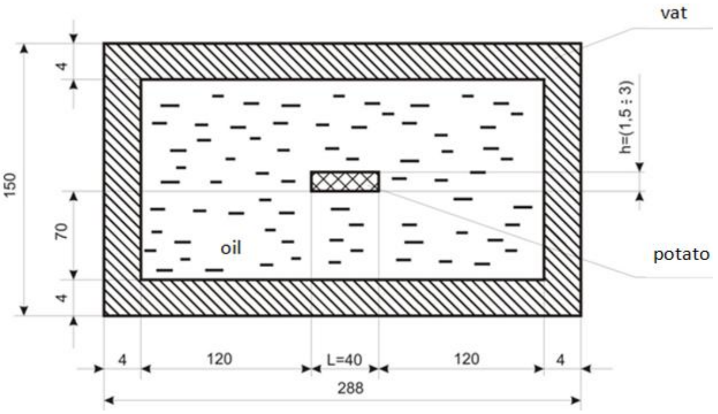

Fig. 3. Section dimensions through the tank - oil - potato slice assembly used in the simulation study

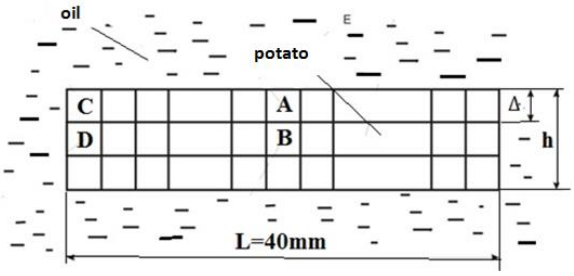

Fig. 4. The splitting of the potato slice and the points (A, B, C, D) in which the evolution of the residual humidity was analysed

As a result, the dividing line step was $\Delta = h / 3$ (h = the thickness of the potato slice). The working pattern used is close to the actual chips roasting conditions in an industrial plant. In the industrial plants a larger quantity of potato slices is placed, placed on the conveyor in a layer. It can be thought that due to the stirring of the oil, slice frying is surrounded by the food oil. As a result, simulating the roasting of a single potato slicer is close to the real situation. A real value of the ratio between the oil volume and the chip volume was researched. Oil heaters play an important role in heating the oil during commissioning of the system. Ignoring the heat source does not cause large errors, especially since the frying time in industrial practice is relatively small (3-4 minutes). The initial humidity of potato slices was assumed to be $u_0 = 0.9$ ($u_0 = 90\%$). The formation of acrylamide has been considered at 120 °C. In this context, the acrylamide formation trend was calculated based on the number of cells in the cross-sectional division network of the potato slice, reaching a temperature equal to or greater than 120 °C.

For the simulation, the following values were used for the thermophysical characteristics: initial temperature of the potato slice $T_{C0} = 20$ °C, thermal conductivity coefficient for potato $\lambda_{C0} = 0.5$ W/mK (below 100 °C) and $\lambda_{C1} = 0.35$ W/mK (over 100 °C), potato density $\rho_C = 1095$ kg/m^3, specific heat for potato $c_{C0} = 3100$ J/kg·K (under 100 °C) and $c_{C1} = 2500$ J/kg·K (over 100 °C), latent water vaporization $L_A = 2260$ kJ/$p_U = 920$ kg/m^3, thermal conductivity coefficient $\lambda_{C0} = 0.9$ W/mK, specific heat oil $c_U = 2200$ J/kg·K [6, 7, 8, 10, 11, 12, 15].

8. Results on the Influence of Potato Slices Thickness on Chips Processing

In this study, the thickness of the potato slices ("h") was modified. It has been considered that the thickness of potato slices commonly used in the food industry is between 1.6 - 1.9 mm. In the simulation study, the potato slice thickness varied between $h = 1.5$ mm and $h = 3$ mm (are used step $\Delta = 0.3$ mm). In this study it was considered that the food oil had a Tule temperature = 180 °C. This corresponds to the temperature normally used in industrial practice when toasting chips. The influence of the thickness of the potato slice and of the roasting time on the evolution of temperature, humidity and the tendency of acrylamide formation was followed. The frying time was $t = 5$ minutes.

Table 1 gives the residual moisture values based on the frying time at various points of the potato slice. Tables 2 and 3 show results on the influence of potato slices thickness on average relative humidity and on the acrylamide formation trend.

Figures 5 to 7 are graphically represented by these results.

Figure 5 illustrates graphically the influence of potato slices thickness on relative humidity at point A (center of the top surface of the slice).

Figures 6 and 7 illustrate the influence of potato slices thickness on medium humidity and the Acrylamide formation trend calculated by relation (7).

The results obtained by simulation in Tables 1÷3 and Figures 5÷7 lead to the following observations:

- the temperature in the analysed potato slices section reaches 100 °C very quickly, the heating time at this temperature being less than one minute;
- the average moisture content of the potato slices begins to decrease considerably after the potatoes have been introduced into the heated oil;
- the thickness of potato slices also greatly influences the removal of water from potato slices;
- for slices of 1.5 mm thickness, humidity is eliminated in five minutes;

Table 1. Results on the relative humidity of the potato slice in points A, B, C, D, depending on the potato slice thickness and the heating time (oil temperature Tu = 180 °C)

No.	Thickness of the slice	Time	Relative humidity			
			Point A surface	Point B middle	Point C corner	Point D margin
	h [mm]	*t* [s]	U_A [%]	U_B [%]	U_C [%]	U_D [%]
1	1.5	0	90	90	90	90
		60	35.883	90	0	0
		120	4.897	90	0	0
		180	0	59.822	0	0
		240	0	21.732	0	0
		300	0	0	0	0
2	1.8	0	90	90	90	90
		60	48.247	90	0	0
		120	22.512	90	0	0
		180	2.430	80.932	0	0
		240	0	62.001	0	0
		300	0	34.192	0	0
3	2.1	0	90	90	90	90
		60	57.034	90	0	0
		120	35.055	90	0	0
		180	17.878	90	0	0
		240	3.058	90	0	0
		300	0	74.976	0	0
4	2.4	0	90	90	90	90
		60	63.586	90	0	0
		120	44.439	90	0	0
		180	29.455	90	0	0
		240	16.538	90	0	0
		300	4.837	90	0	0
5	2.7	0	90	90	90	90
		60	68.647	90	0	0
		120	51.708	90	0	0
		180	38.418	90	0	0
		240	26.954	90	0	0
		300	16.584	90	0	0
6	3.0	0	90	90	90	90
		60	72.664	90	11.734	53.735
		120	57.508	90	0	0
		180	45.594	90	0	0
		240	45.322	90	0	0
		300	26.043	90	0	0

Table 2. Evidence of relative average humidity in the potato slice, depending on the slice thickness (oil temperature Tu = 180 °C)

No.	Thickness of the slice	Relative humidity, wet depending on time					
		time $t = 0$ s	time $t = 60$ s	time $t = 120$ s	time $t = 180$ s	time $t = 240$ s	time $t = 300$ s
Symbol	h	$Umed_{0}$	$Umed_{60}$	$Umed_{120}$	$Umed_{180}$	$Umed_{240}$	$Umed_{300}$
u.m.	mm	%	%	%	%	%	%
1	1.5	90	49.10	26.70	12.85	2.89	0
2	1.8	90	57.70	37.67	23.23	13.02	4.87
3	2.1	90	63.79	46.54	33.54	23.30	15.80
4	2.4	90	68.46	53.20	41.35	31.61	23.58
5	2.7	90	71.97	58.21	47.92	38.48	30.70
6	3.0	90	74.94	62.43	52.71	49.75	44.63

Table 3. Results on Acrylamide formation trend in chips section, depending on time and thickness of potato slice (oil temperature Tu = 180 °C)

No.	Thickness of the slice	The trend of Acrylamide formation (TA), depending on time					
		time *t* = 0 s	time *t* = 60 s	time *t* = 120 s	time *t* = 180 s	time *t* = 240 s	time *t* = 300 s
Symbol	*h* [mm]	TA [%]	TA [%]	TA [%]	TA [%]	TA [%]	TA [%]
1	1.5	0	2.5	9.17	20.0	41.57	100
2	1.8	0	2.98	5.97	11.94	21.89	36.81
3	2.1	0	2.34	3.5	9.36	12.86	21.05
4	2.4	0	0	4.0	6.67	10.67	14.67
5	2.7	0	0	4.54	4.54	7.57	12.12
6	30	0	0	0	5.0	5.0	5.0

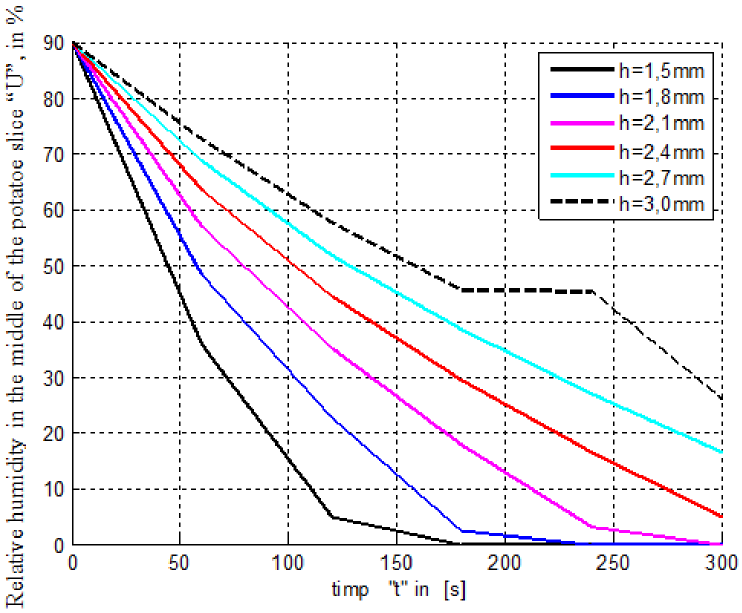

Fig. 5. Relative humidity in the centre of the surface of the chips (point A) depending on time for various thicknesses of potato slices "*h*" (oil temperature Tu = 180 °C)

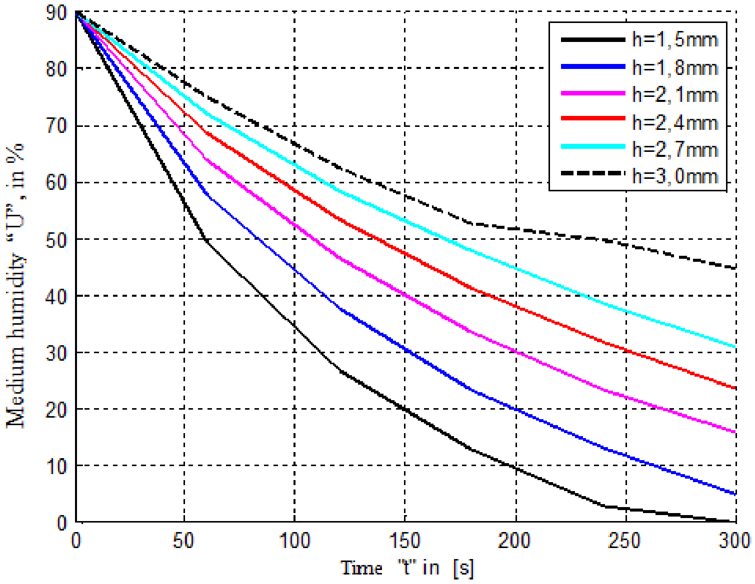

Fig. 6. The residual average humidity of the chips according to time, for various thickness "*h*" of potato slices (food oil temperature, Tu = 180 °C)

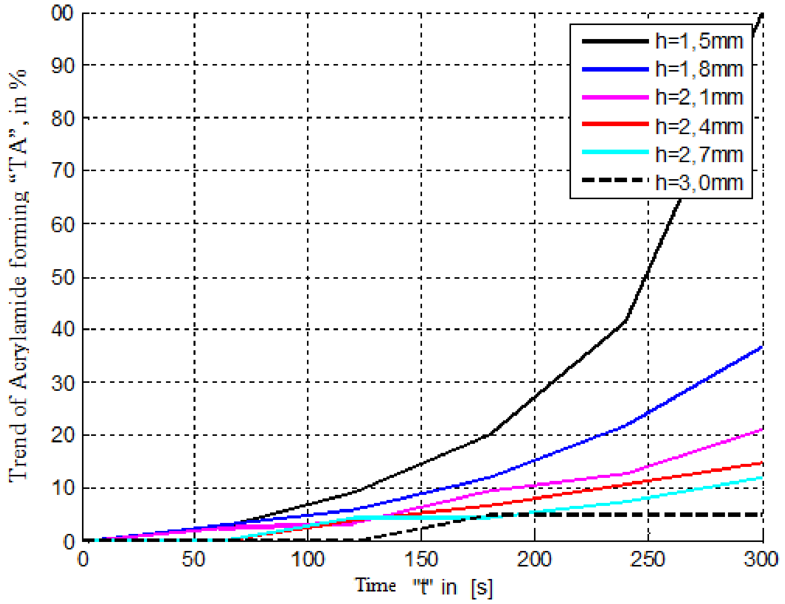

Fig. 7 The trend of Acrylamide forming (TA) in chips for various "*h*" thicknesses of potato slices (oil temperature Tu = 180 °C)

- in the case of slices of 3 mm thickness, the average moisture remaining after 5 minutes is still high, around 30% due to the fact that in the centre of the section the water does not evaporate altogether;
- the corners and side edges of the potato slices reach very quickly at temperatures above 100 °C and lose moisture very quickly, shortly after being introduced into the hot oil (at intervals of seconds);
- formation of Acrylamide begins to appear visibly after approx. 1.5 - 2 minutes from the beginning of roasting;
- in the case of very thin slices of 1.5 - 1.8 mm thick, the tendency to form Acrylamide increases considerably over 4 minutes;
- for a given temperature, the time of roasting the chips must be correlated with the thickness of the potatoes;
- for potato slices of 1.8 mm thick, the optimum roasting time is approx. 3 minutes, duration at which the residual average humidity is approx. 23%, and the acrylamide formation trend is approximately 12%.

These observations lead to the conclusion that the optimum thickness of potato slices for the production of chips at 180 °C oil temperature is h = 1.8 mm.

9. Results on the Influence of Oil Temperature on Chip Processing

Frying potato slices of thickness h = 1.8 mm was studied. The thickness of the potato slices commonly used in the food industry was considered. In this study, the temperature of the cooking oil was changed between 140 °C and 200 °C. The influence of oil temperature and roasting time on the temperature distribution in the potato slice, the residual moisture of the chips, and the acrylamide formation tendency were monitored. The frying time was *t* = 5 minutes. The same values of the thermophysical parameters for potatoes and oil were used.

The study looked at the evolution of temperature and humidity in the same four points of the potato slice (points A, B, C and D in Figure 4). The points are located on the vertical axis and on the side edge of the potato slice. The results on the influence of the temperature of the food oil on the relative humidity evolution at these points are given in Table 4. Tables 5 and 6 gives the results of the influence of the oil on average relative humidity and on the acrylamide formation trend.

Figure 8 graphically shows the time evolution of moisture at point A (in the centre of the surface). Figures 9 and 10 illustrate graphically the influence of the temperature of the cooking oil and the roasting time on the residual average moisture content of the chips and the acrylamide formation tendency in the case of roasting potato slices of 1.8 mm.

Table 4. Results on the relative humidity of the potato slice in points A, B, C, D, depending on the oil temperature Tu (potato slice thickness *h* = 1.8 mm)

No.	Oil temperature	Time	Relative humidity			
			Point A surface	Point B middle	Point C corner	Point D margin
Symbol	Tu	t	U_A	U_B	U_C	U_D
u.m.	°C	s	%	%	%	%
1	140	0	90	90	90	90
		60	75.887	90	0	49.502
		120	63.300	90	0	0
		180	53.356	90	0	0
		240	44.775	90	0	0
		300	37.034	90	0	0
2	160	0	90	90	90	90
		60	62.481	90	0	1.421
		120	42.947	90	0	0
		180	27.905	90	0	0
		240	14.945	90	0	0
		300	3.246	88.534	0	0
3	180	0	90	90	90	90
		60	48.247	90	0	0
		120	22.512	90	0	0
		180	2.43	80.932	0	0
		240	0	62.001	0	0
		300	0	34.192	0	0
4	200	0	90	90	90	90
		60	34.368	90	0	0
		120	2.128	90	0	0
		180	0	50.92	0	0
		240	0	9.129	0	0
		300	0	0	0	0

Table 5. Evidence of average relative humidity in potato slice, depending on the temperature of the cooking oil (potato slice thickness *h* = 1.8 mm)

No.	Oil temperature	Relative residual humidity U_{med}, depending on time					
		time *t* = 0 s	time *t* = 60 s	time *t* = 120 s	time *t* = 180 s	time *t* = 240 s	time *t* = 300 s
Symbol	Tu	$Umed_{0}$	$Umed_{60}$	$Umed_{120}$	$Umed_{180}$	$Umed_{240}$	$Umed_{300}$
u.m.	°C	%	%	%	%	%	%
1	140	90	77.79	67.12	59.47	51.04	44.59
2	160	90	67.64	52.01	39.65	29.54	21.50
3	180	90	57.70	37.67	23.23	13.02	4.87
4	200	90	49.1	26.70	12.86	2.89	0

Table 6. Results on Acrylamide formation tendency by oil temperature (potato slice thickness *h* = 1.8 mm)

No.	Oil temperature	Trend of Acrylamide forming (TA), depending on time					
		time *t* = 0 s	time *t* = 60 s	time *t* = 120 s	time *t* = 180 s	time *t* = 240 s	time *t* = 300 s
Symbol	Tu [°C]	TA [%]	TA [%]	TA [%]	TA [%]	TA [%]	TA [%]
1	140	0	0	0	0	0	0
2	160	0	0	0	2.98	7.96	11.94
3	180	0	2.98	5.97	11.94	21.89	36.81
4	200	0	4.97	11.94	23.88	52.73	100

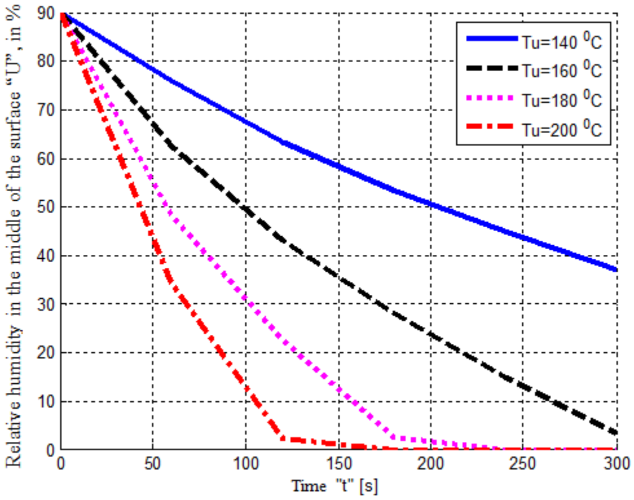

Fig. 8. Relative humidity in the middle of the chip surface (point A) depending on time for different temperatures of the cooking oil (potato slices thickness *h* = 1.8 mm)

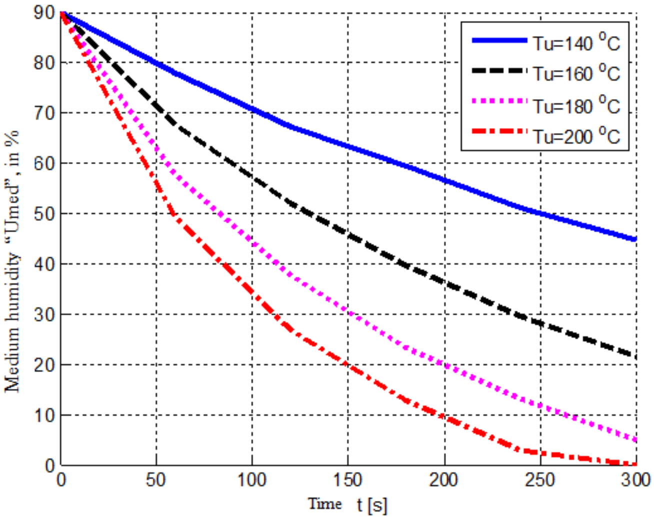

Fig. 9. The time-based evolution of the residual average humidity of the chips for various food oil temperatures (potato slices thickness *h* = 1.8 mm)

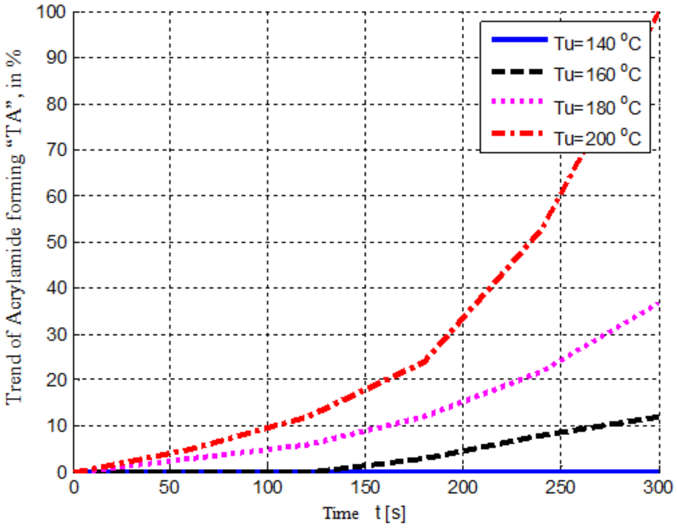

Fig. 10. Evolution of the Acrylamide (TA) trend in chips for various temperatures Tu of the food oil (potato slice thickness *h* = 1.8 mm)

The results in Tables 4 to 6 and Figures 8 to 10 lead to the following conclusions:

- at all four values of the temperature of the oil for which the study was conducted, after 5 minutes, the temperature in the centre of the potato slice (point B) is practically the same, i.e. 100 °C;
- the oil temperature (in the range of studied values) has a noticeable influence on the heating of the edges and corners of the potato slices;
- when the oil temperature rises, the corners and edges heat up much more intensely (except when the oil is 200 °C, in which case the central part of the slice is heated to 100 °C at 5 minutes);
- in the case of 140 °C oil, the residual average moisture content of the chips (at thickness *h* = 1.8 mm) is maintained at high levels (over 40%) even at five minutes of roasting, which affects their quality by a high percentage of acrylamide;
- when the oil temperature exceeds 180 °C (for example at 200 °C), the acrylamide formation tendency increases considerably;
- for potato slices of *h* = 1.8 mm thickness and temperature of Tu = 200 °C, the Acrylamide is formed on the whole section of the potato slice because the temperature exceeds 120 °C at all sections of the section;
- if the oil temperature is Tu = 140 °C, the tendency to form acrylamide on the potato slice section is zero, but the residual moisture in the potato is very high (over 40%), which affects the preservation time.

The results of these studies lead to the following conclusions regarding the optimization of chip processing technology. The optimum thickness of potato slices for the production of chips is 1.8 mm, the recommended oil temperature is 160-180 °C and the roasting time is four minutes.

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