Journal of Food Engineering
Manuscript Draft

Manuscript Number: JFOODENG-D-11-00654

Title: Mathematical modelling of mixing of salt in minced meat by bowl-cutter

Article Type: Research Article

Keywords: Salt; mathematical model; minced meat; mixing equation

Abstract: Salting is one of the basic procedures in the food processing. The NaCl concentration influences water holding properties, viscosity, texture, emulsification. It is important to study and model mixing process by mathematical methods to predict properties of the matrix and the food quality. The objective of this study was to develop a mathematical model of the mixing of salt and meat in a bowl cutter and verify this with experimental data. The bowl cutter is described as a continuous stirred tank reactor, combined with a plug flow reactor in a repetitive series-model. The theoretical model shows that 30 rounds are sufficient to get a salt concentration in the whole bulk of meat with a deviation between maximum and minimum values of about 5%. The comparison of the theoretically predicted salt gradient and the experimental results showed that the current mathematical equation is appropriate for description of the process.

*Manuscript
Click here to view linked References

Mathematical modelling of mixing of salt in minced meat by bowl-cutter

Vodyanova, I.V.*, Storrø, I.**, Olsen A.** and Rustad, T.*
* - Department of Biotechnology, NTNU, N-7491, Trondheim, Norway
** - SINTEF, Fisheries and Aquaculture, N-7465, Trondheim, Norway
For contacts: **Irina.vodyanova@biotech.ntnu.no**

Abstract

Salting is one of the basic procedures in the food processing. The NaCl concentration influences water holding properties, viscosity, texture, emulsification. It is important to study and model mixing process by mathematical methods to predict properties of the matrix and the food quality. The objective of this study was to develop a mathematical model of the mixing of salt and meat in a bowl cutter and verify this with experimental data. The bowl cutter is described as a continuous stirred tank reactor, combined with a plug flow reactor in a repetitive series-model. The theoretical model shows that 30 rounds are sufficient to get a salt concentration in the whole bulk of meat with a deviation between maximum and minimum values of about 5%. The comparison of the theoretically predicted salt gradient and the experimental results showed that the current mathematical equation is appropriate for description of the process.

Keywords: Salt; mathematical model; minced meat; mixing equation

Introduction

Salting is one of the oldest and the cheapest methods of food preservation; is used to prolong the shelf life of the product by reducing its water activity (Albarracin 2011). Salt is a source of mineral ions – Na (39%) and Cl (61%), which are important for vital body functions (Lang 1971; Parker and Parker 2004). However a too high sodium intake has negative health effects (Datta 2007), such as osteoporosis, asthma, kidney disease and is closely related to cancer of the stomach. Dietary advice is to reduce the amount of consumed sodium (Skurihin 1991; Bona 2007; Albarracin 2011) and develop products with reduced salt content (Ruusunen 2005). The sodium chloride concentration influences the properties of food systems, such as the physiochemical properties (water holding properties, viscosity, texture, emulsification etc.) by influencing the properties of the proteins (Costa-Corredor, Mucoz et al. 2010; Nguyen, Arason et al. 2010). From this point of view it is important to study and model mixing of NaCl not only to understand the mixing process, but also to predict changes in concentrations during the process and their influence on the matrix by mathematical methods.

Cutting is one of the basic procedures in making minced meat products. Within this complex process the particle size of the raw material is reduced, the proteins are hydrated, the fat emulsified and other ingredients are mixed to give a homogenous mixture. This process leads to binding of the necessary amount of water, influencing the taste (flavor) and juiciness of the products. The bowl cutter is the most used equipment for industrial mincing and mixing of meat and fish products. Cutting using a bowl cutter allows a higher end product yield due to reduced cooking loss and shrinkage (Dolata 1977). More knowledge on the mincing process will thus enable development of products with reduced salt content and with a high and stable quality. To reach an even distribution of salt in the products are important and might reduce the limit of salt into the recipe.

The process of mixing multi-phase mediums and pastes are widely used in chemical and food industry (Seborg 2004). Effective mixing is one of the important stages of processing which defines the success of the whole process. The aims of the mixing process are: to obtain homogeneous systems with equal properties in all points of the system; efficient mass-transfer processes in homogeneous and heterogeneous systems; and high rates of chemical reactions (Aynstein 2006).

Many scientific studies, both theoretical and experimental have been devoted to mathematical description of processes in food systems. All interactions taking place during food processing can be presented as dynamic models. The models can be used to improve understanding of the process dynamics and to develop a control strategy for a new process (Datta 2007).

Models can be classified as:

(a) Theoretical models developed using the principles of chemistry, physics, and biology;

(b) Empirical models obtained by fitting experimental data;

(c) Semi-empirical models that are a combination of the models in category (a) and (b); where the numerical values of one or more of the parameters in a theoretical model are calculated from experimental data.

It is not easy to describe real processes by theoretical models only as a full understanding of all aspects of complex food systems is not available. Empirical models only describe systems at specific conditions and therefore, semi-empirical models are widely used in the industry. However, a process model is only a mathematical abstraction of a real process. The model equations are at best an approximation to the real process and cannot incorporate all macroscopic and microscopic features of the real process (Brauer 1994).

To study complicated and complex processes such as mixing, is necessary to take into account parameters of equipment and quality of raw materials as well as interactions in the matrix. The number and shape of knives and the speed of the cutter bowl influence the mechanical stress of the medium and therefore affect the softness of sausages (Brauer 1994). The shape and speed of knives, the cutting time, and the temperature in the medium, the chemical composition and structure of the meat influence the mixing process, and thus affect the quality of the end product (Micklisch 2004; Kosoy 2006). The quality of the mixing process depends on the properties in the bulk of material. More studies are needed on the influence of different parameters on the mixing process.

A bowl cutter can be described with a theoretical model consisting of a continuous stirred tank reactor (CSTR) and a plug flow reactor (PFR) in repetitive series. The CSTR part is the mixing part where the knives operate and the PFR is the revolving bowl. A better description will be a CSTR with recycling of the outlet, because we do not expect any mixing to take place during the transport of material outside the CSTR in the bowl (Felder 1986).

Mixing of salt in the meat was described by the following equation, where the steady state gain, K_P, - is defined as the magnitude of the change in output at steady state divided by the magnitude of the change in the input into the CSTR. This gives a useful, general form [1]:

, [1]

where Ci – is concentration of a salt in the meat entering the mixing zone (0 – in the beginning, *i* – in the *i*-th period of time);

τ - time;

K_P- steady state gain, – change in output / change in input.

The mathematical model developed for describing mixing of salt and meat, was based on equations describing unit operation in the chemical process industry (Hangos and Cameron 2001). Equations describing the steady state value can be used to identify the model of an unknown process from raw process data. The mixing process can be described as steps, which are repeated in “fixed” points of bulk meat after each round, Figure 1:

Figure 1.

In discrete form the following transformation occur in the mixing zone [2]:

, [2]

Where V – volume of meat in the mixing zone, cm^3;
ΔC_1 – the change of salt concentration, g/cm^3;
F – flow through the mixing zone, dependent on the speed of the rotating device w_2 in rpm;
Δt – change in time

The first time the meat goes through the mixer, the concentration can be described as [3]:

, [3]

Where C_1– concentration of salt before mixing, in the beginning of the process at time $t = 0$,
$C_1(t)$ - concentration of salt at time t;
$\delta(t)$ - is a unit impulse function;
$T = L / w_1$ - the time needed to make a complete rotation; (*L* – medium circumference of the tube, w_1 is rotation speed in rpm.)
$\tau = V / F$ - the ratio between the flow through the mixing zone and the volume of feed in the mixing zone.
The concentration at each point of bulk meat in the bowl can be represented as:

[concentration] = [in] – [out] + [accumulated]

When the meat enters the mixer for the second time the salt concentration is a function of the salt concentration profile from the previous run. Thus, the equation for this process will be as follows [4]:

, [4]

The differential equations can be solved as follows [5]:

, [5]

The concentration of salt on the *n*th stage can be found by the following equation [6]:

, [6]

with abbreviation as defined in equations 1-3.

The objective of this study was to develop a mathematical model of the mixing of salt and meat in a bowl cutter and verify this with experimental data. The salt spreads in the bulk of meat during the complex process: cutting and rotation of knives, rotation of the bowl itself and interaction between the compounds in the minced meat (Acton 1982).

2. Materials and methods

2.1 Materials

Frozen bovine and pork hearts were used as material for the experiment. The hearts were stored at -18°C. Before use, the meat was defrosted for 24 hours at + 4°C. Directly before cutting, the temperature of meat was – 4 – 6°C. For each experiment, 10 kg batches of meat and 0.3 kg of ordinary table salt (sodium chloride) were used.

2.2 Equipment

A Talsa bowl cutter with 50 L capacity, bowl diameter – 76 cm and bowl depth 14.5 cm, was used. The length of the cutting zone was 4.8 cm, and contained six knives with a working length of 14.0 cm. With 10 kg of meat in the bowl cutter, the volume of the cutting/mixing zone was 338 cm^3. A schematic picture of a bowl cutter is shown in Figure 2.

Figure 2.

2.3 Methods

The sodium chloride content was determined by the Volhard method (AOAC. 1990). The mathematical modeling was developed using Matlab 7.4.0 (R2007a).

2.4 Experimental description

The defrosted meat was cut in the bowl cutter to a homogenous mince (2-3 min at high speed, 18.28 rpm). The whole amount of salt was added at once, in a line perpendicular to the rotation of the bowl cutter. During the experiment, the rotation speed was set at a low level, (rotation speed 9.15 rpm).

Sampling has been done along the outer diameter of the bowl, from the line of addition of salt, following the direction of rotation of the cutter-bowl.

Three experiments were carried out to verify the model. To check the effect of the orientation of the knives influenced the mixing, the position was changed between the first and the second experiment. The position of the knives for the two experiments is shown in Figure 3:

Figure 3.

The first experiment was carried out using the standard-set position of knives; the cutting/mixing zone had the knives positioned with equal distance between each knife-pair, as shown in the figure. In the second experiment, the position of knives was changed; two pairs of the knives were close together with the third a little further apart.

To check for radial mixing, sampling was done along the radius. Samples were taken in 3 positions, The first was taken in a point close to the bowl wall, near the outer perimeter; the second in the middle of the bowl and the third close to the inner bowl wall. Results of the experiment were calculated based on the arithmetical mean of all three positions for each sampling point.

Sampling was done by sampling at regular intervals (10 cm) around the bowl by taking advantage of the predicted values for NaCl concentration by the model.

The whole length of circuit of the bowl (along the outer diameter) was divided into fifteen parts with equal steps of ten centimeters between the first four points and twenty centimeters between the rest. After the first round, four samples were taken from point number one to four (addition of salt), after the second – five samples in the same way. After the third round, six samples were taken, but after the fourth round – six samples were taken from the second point (excluding the number one point). The seven samples after the fifth round were taken in the first, third and the following points, missing the second one. Samples from the last rounds were taken close to the end of circuit in the last seven points. Each position of sampling was numbered from the line of salt addition along the direction of movement of the bowl, according to the experimental set-up, as shown in Figure 4:

Figure 4.

One example is shown in the table below:

Table 1.

In the third reported experiment – the position of knives were as in the first experiment, samples were taken after 1, 2, 3, 4, 5, 10, 15, 20, 30 rounds.

The results from the first two experiments showed that there was no significant difference between the salt concentration in the second and third positions of the sampling point, probably due to the practical spread of the added salt line. It was therefore decided to take samples only in two positions, – in a point close to the inner bowl wall, and in the middle of the bowl along the diameter. Sampling was done at fixed points around the bowl, from the line of salt addition. The distance between sampling points were equal, determined by dividing the whole outer perimeter into eight parts giving a distance of about 30 cm. Samples were taken in all points after each round. Results of the experiment where calculated based on the arithmetical mean of both positions for each sampling point.

To compare the theoretical equation and the experimental data, the initial concentration of salt was defined based on the parameters for the real system. C_0 – ratio of the whole amount of added salt to mass of meat in the mixing zone, calculated based on real equipment size. The minced meat relocates by the cutting knives, by movement of the bowl and, partially, by its own flow movement. The size of the cutting zone was 5 cm (according to the length (l = 4.8 cm) of zone occupied by knives), the size of the practical mixing zone was found to be 15 cm. This practical mixing zone is thought to be the distance the meat is thrown up streams by the knives during the cutting process.

3. Results and discussion

3.1 Mathematical modelling of salt mixing process

The theoretically predicted change in salt concentration in the bulk of material is a function of mixing time. This can be symbolized as a distance, on which salt was distributed from the point of its addition. If the initial concentration of salt is set to $C_0 = 1$, the mathematical model gives curves as shown in Figure 5:

Figure 5.

According to the model, the salt concentration profile changes in the following way: in the beginning, the first round shows a standard wash out curve from a CSTR. In the first five rounds, the salt concentration is high in the first points of the curve and no salt is found in the last sampling points. In the next 10-120 rounds salt spreads along the whole length of the cutter and concentration gradually becomes equal in the whole bulk of meat. The last curves show that the level of salt concentration goes from zero to between 0.05 and 0.1 g/cm^3. This means that salt content in the bulk of mince spreads gradually, in direct ratio to distance or depending on the time of treatment. The difference between the maximum and minimum salt concentration decreases significantly and after approximately 120 rounds the difference is less than 5 %, and the mixing is assumed to be complete.
The experimental data showed that the distribution of NaCl changes in the direction of the bowl, opposite to direction of the meat flow. This main finding may be explained by the interaction between the cutting of knives, the movement of the bowl, and the movement of the mass of mince related to this. The direction of mass relative to the knife is shown schematically in Figure 6:

Figure 6.

A good cutting action was obtained. When meat passes through the mixing zone, it is cut several times. Within the real size of equipment and real salt concentration in the beginning of the whole process – C_0, changes in theoretical formula have been set. For comparison of the theoretical and experimental data, the result of the first two experiments is shown in Figure 7. The real size values of the equipment and the real amount of salt was fed into the theoretical model and Figure 7 shows the association of the resulting curves with the experimentally determined values. Predicted theoretical curves from the first to the twentieth rounds and experimental data from the same rounds are shown in the same graph:

Figure 7.

The theoretical curves are presented with unbroken lines; experimental data are presented with broken lines with differently shaped markers. The curves in the plot demonstrate concentration value of salt in each point after the given number of rotations. Distance in centimeters along the outer circumference, measured up stream of the material flow.

As shown in Figure 7, the range of salt concentration within the mixing process does not leave the range of predicted values; but at the same time, theoretical and experimental values for corresponding sample-points do not coincide closely. However, the results from the last rounds fit well with the predicted values. This is shown in more detail in Figure 8:

Figure 8.

Both the first and the second experiments are described by curves that do not coincide closely to the curves from the theoretical model. Results from the first experiment, with the normal position of knives (a), fit better with the theoretical values than results for the second experiment.

The change of position of knives influenced the mixing pattern, these results were in consistence with other studies (Micklisch 2004). Based on this, the sampling of the third experiment was planned. In the third experiment, the standard-set position of knives was used as in the first experiment, samples were taken after 1, 2, 3, 4, 5, 10, 15, 20, 30 rounds, at each point along the diameter of the bowl, with 30 centimeters between each sampling point, (Figure 9):

Figure 9.

The third experiment was carried out to check the reproducibility of the process. More sampling points were taken as described in the experimental setup. In total 30 rounds were run, with 8 sampling points along the bowl, this gave sufficient amount of results to compare experimental data with the model.

The concentration of salt changes during the process. When 300 g of salt is added to 10 kg of meat, the final concentration of sodium chloride should be 0.03 g/cm^3 in the whole mince. As shown in Figure 10, the theoretical curves tend to level off at a salt concentration of 0.01 g/cm^3. The experimental graphs have a tendency to level off at close to 0.04 g/cm^3. The NaCl concentration in the fresh meat is 0 – 0.4 % Cl^- -ions.
This was the expected final concentration according to the amount of sodium chloride added. While running of experiment has been respected original size of bowl-cutter, amount of materials according to recipe. The initial concentration of NaCl, $C_0 = 5.0$, according to mass of material in assumed mixing zone.
The following plots present the correspondence of the experimentally obtained data of the third experiment to theoretical model: the separate illustration of shapes of the graphs is shown in Figure 10:

Where the unbroken line is the theoretical curve and the interrupted line is the experimental data. (X-axis - Distance in the cutter along the diameter, cm; Y-axis – Concentration NaCl, g/cm^3)

Figure 10.

Comparison of the shape of the curves shows unexpected good fit between the theoretical and the experimental curves in the last rounds. In the first rounds, – from the first till the tenth, the beginning of experimental data curves is in the range, corresponding to the level of real salt concentration – 0.04 g/cm^3 NaCl, while the correspondent theoretical curves begin from zero (from second till tenth rounds except for the first). Thus requires further refinement of equation.

4. Conclusions

Mixing of salt and meat in a bowl cutter was modeled as a continuous stirred tank reactor, the flow and the process of salt mixing have been described by equation for a continuous process [6]:

, [6]

where C_n is salt concentration. The current model describes the process of mixing, spreading of sodium chloride as expected. The change of position of knives influenced the mixing pattern. The experimental result shows that approximately 30 rounds, instead of theoretical predicted 120, are sufficient to get a homogenous salt distribution with a deviation of 5% in the whole bulk of meat. The experimental curves for the spread of salt fit reasonably well with the theoretical model. The salt concentration profile movement is in the same direction as the movement to the meat flow. The developed model can, with some adjustments and taking the variable conditions of real systems into account, be used to model mixing of salt in a bowl cutter.

References:

Acton, J. C., Ziegler, Gregory R., Burge, Donald L.,Froning, Glenn W. (1982). "Functionality of muscle constituents in the processing of comminuted meat products." CRC Critical Reviews in Food Science and Nutrition **18**(2): 99 - 121.

Albarracin, W., Sanchez, Ivan C., Grau, Raul., Barat, Jose M. (2011). "Salt in food processing; usage and reduction: a review." International Journal of Food Science and Technology: 1-8.

AOAC. (1990). "Official methods of analysis." Washington, DC, USA : Association of Official Analytical Chemists. **937.09**.

Aynstein, V. G., Zaharov, M.K., Nosov, G.A., et al. (2006). "Processes and apparatus of chemical technology." Logos publishing, second edition: 436.

Bona, E., Carneiro, R. L., Borsato, D., Silva, R. S. S. F., Fidelis, D. A. S., Monken e Silva, L. H. (2007). "Simulation of NaCl and KCl mass transfer during salting of Prato cheese in brine with agitation: a numerical solution." Brazilian Journal of Chemical Engineering **24 no.3** pp. 337-349.

Brauer, H. (1994). "The quality of frankfurter-type sausages. Influence of sausage mixture temperature, knife revolutions and cutter processing time." Die Fleischwirtschaft(74/10): 1082-1083.
Costa-Corredor, A., I. Mucoz, et al. (2010). "Ion uptakes and diffusivities in pork meat brine-salted with NaCl and K-lactate." LWT-Food Science and Technology(43): 1226-1233.
Datta, A. K., Sablani, S.S., et al. (2007). "Mathematical modelling techniques in food and bioprocesses: An overview." Food and Bioprocesses Modeling Techniques. CRC Press, Canada: 1-11.
Dolata, W. (1977). "The relationship of the blade angels of silent cutter knives." Die Fleischwirtschaft **77**(8): 700.
Felder, R. M. a. R. W. R. (1986). "Elementary Principles of Chemical Processes." John Wiley, 2nd Edition: 83-84.
Hangos, K. M. and I. T. Cameron (2001). Process modelling and model analysis. San Diego, Academic Press. **xvi:** 543 s.
Kosoy, V. D., Dorochov, V.P. (2006). "Calculation methodology of grinding operation of fresh chorizos meat." The Meat Industry: 58-61.
Lang, K., Fekl, Werner., Berg, Gerhard. (1971). "Balanced nutrition and therapy: Bilanzierte Ernährung in der Therapie. International symposium in Nuremberg, April 10-12, 1970." Internationales Symposium bilanzierte Ernæhrung in der, Therapie **xi**: 282 s.
Micklisch, I., Schnackel, Wolfram., Krickmeier, Janet., Haack, Eberhard., Ehrle, Egon. (2004). "Verwendung unterschiedlicher Messerformen im Kutter : Bestimmung der Brät- und Endproduktqualität von Brühwürsten=Determination of the quality of lean minced meat and end-products." **84**(12): 100-105.
Nguyen, M. V., S. Arason, et al. (2010). "Influence of salt concentration on the salting kinetics of cod loin (Gadus morhua) during brine salting." Journal of Food Engineering(100): 225-231.
Parker, P. M. and J. N. Parker (2004). Balanced diet: a medical dictionary, bibliography, and annotated research guide to Internet references. San Diego, CA, ICON Health Publications.
Ruusunen, M., Puolanne, Eero. (2005). "Reducing sodium intake from meat products." Meat Science; 50-th International Congress of Meat Science and Technology,(ICoMST), 8-13 August 2004, Helsinki, Finland **70**(3): 531-541.
Seborg, D. E., Edgar, Thomas F., Mellichamp, Duncan A. (2004). "Process dynamics and control." **XV**: 713 s.
Skurihin, I. M., Nechaev, A.P. (1991). "Everything about the food by chemistry’s point of view." High School publishing: 288 s.

HIGHLIGHTS

Mixing of salt and meat in a bowl cutter was modeled as a continuous stirred tank reactor;
The change of position of knives influenced the mixing pattern;
The experimental result shows that approximately 30 rounds, instead of theoretical predicted 120, are sufficient to get a homogenous salt distribution with a deviation of 5% in the whole bulk of meat;
The developed model can be used to model mixing of salt in a bowl cutter.

List of captions.

Figure 1. Steps of mixing.

Figure 2. **a**. – The knives; **b**. – The scheme of a bowl cutter

Figure 3. Scheme of position of knives : **a**. – first; **b**. – second experiment.

Figure 4. Scheme of sampling in a bowl cutter for the first and the second experiments.

Figure 5. Theoretically predicted concentration curves, according to the mathematical model.
The 1 round – interrupted line, 2 – interrupted with dots, 3 – line with star-markers, 4 – thin line with dot-markers, 5 round – dots-line, 10 – line with o-markers, 20 – line, 30 – line with *-markers, 40 – thick line with dot-markers, 50 – line with xx-markers.

Figure 6. The scheme of the direction of movement of the bulk of mince, related to rotation in the bowl cutter. Where Force 1 – throws meat in a direction opposite of movement of meat; Force 2 – cutting action of knife

Figure 7. The concentration of salt in the meat after mixing by bowl cutter. Model and experimental data

Figure 8. The concentration of salt in the meat after mixing by bowl cutter. Comparison of the results of first two experiments

Figure 9. The concentration of salt in the meat after mixing by bowl cutter. The third experiment. Experimental data.

Figure 10. The spread of salt in the meat after mixing by bowl cutter. The third experiment. The comparison of curve shapes. Where the unbroken line is the theoretical curve and the interrupted line is the experimental data. (X-axis - Distance in the cutter along the diameter, cm; Y-axis – Concentration NaCl, g/cm^3)

Table 1. Sampling scheme for the first and the second experiments

Figure

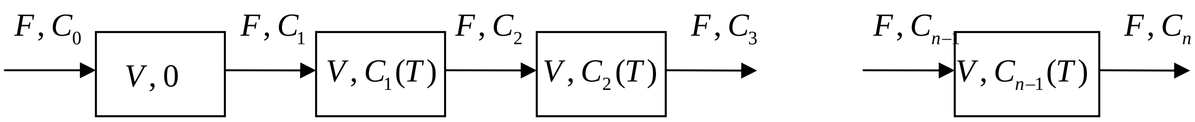
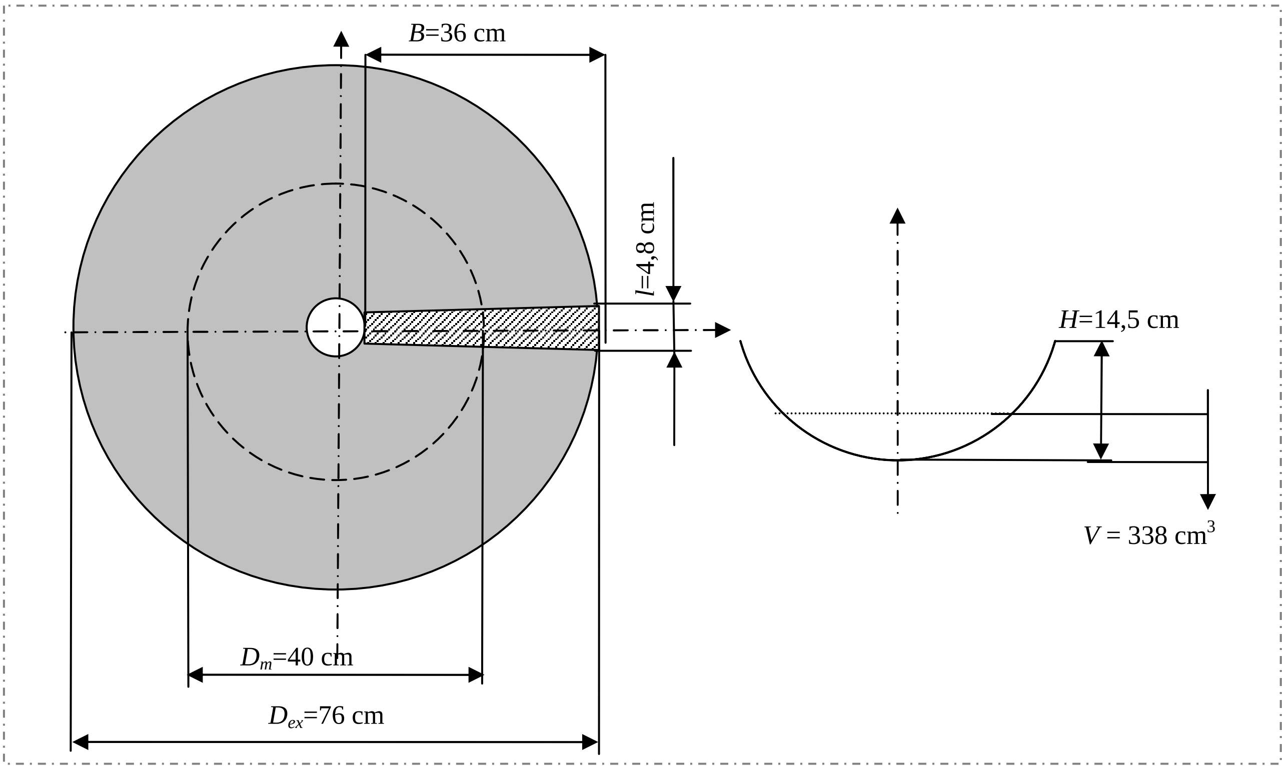


Figure Captions

Figure 1. Steps of mixing.

Figure

a.

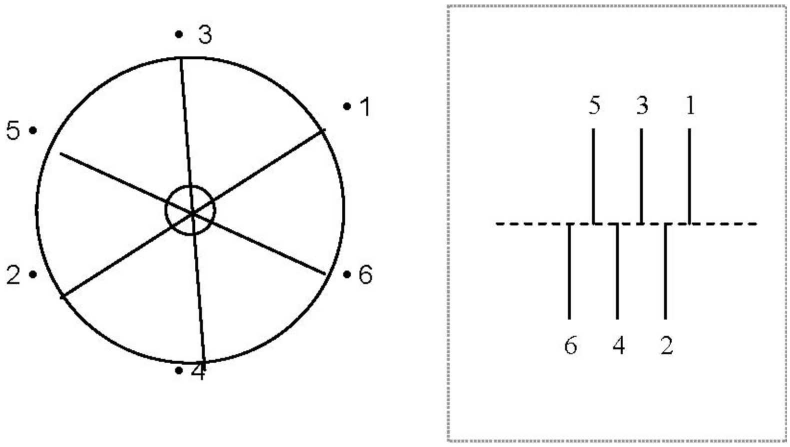


b.

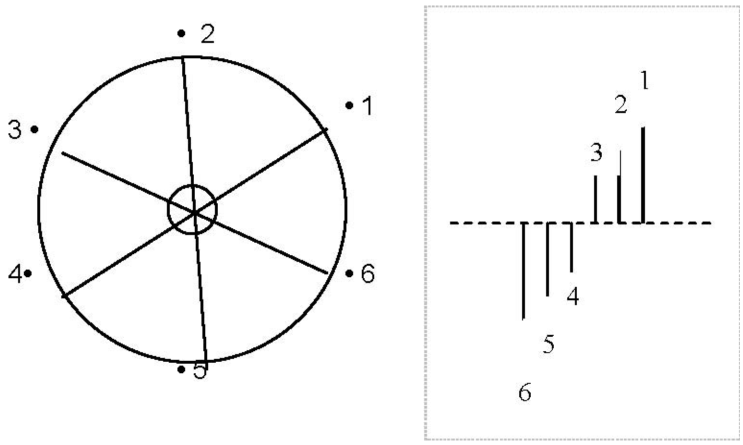
Figure Captions

Figure 2. **a**. – The knives; **b**. – The scheme of a bowl cutter

Figure



a.



b.

Figure Captions

Figure 3. Scheme of position of knives : **a**. – first; **b**. – second experiment.

Figure

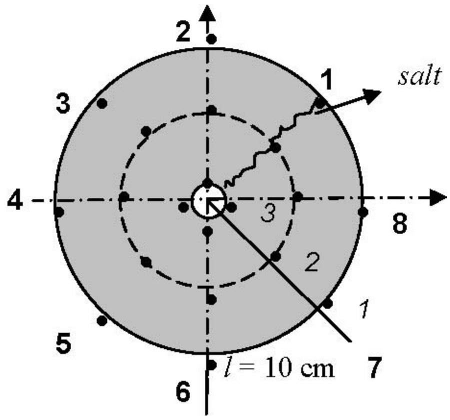
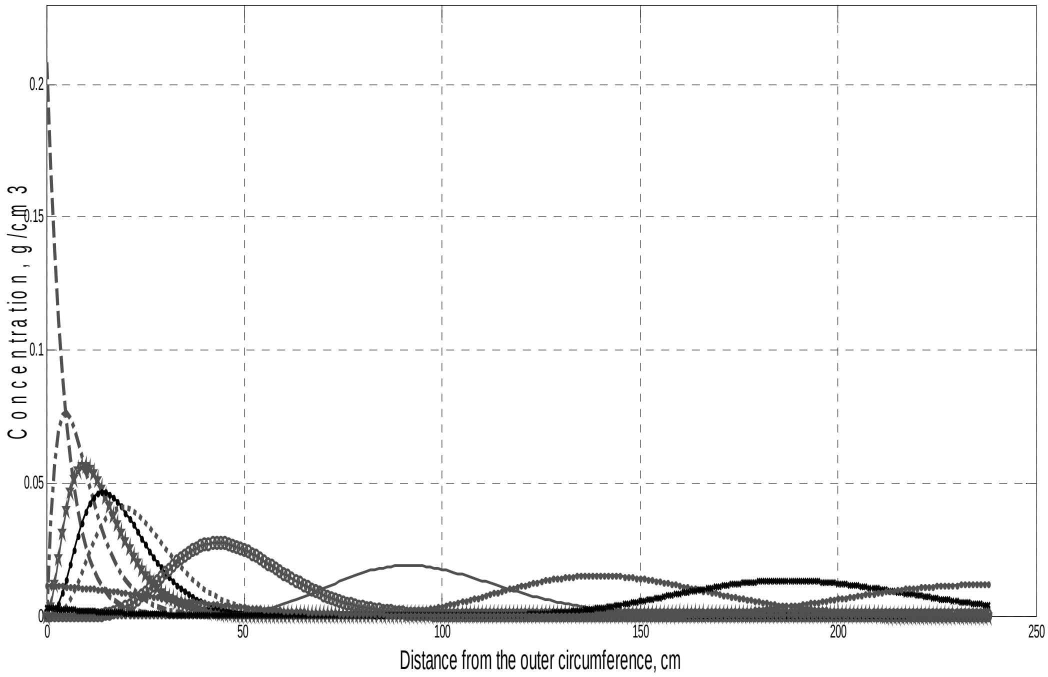


Figure Captions

Figure 4. Scheme of sampling in a bowl cutter for the first and the second experiments.

Figure



Rounds 1,2,3,4,5,10,20,30,40,50.

Figure Captions

Figure 5. Theoretically predicted concentration curves, according to the mathematical model. The 1 round – interrupted line, 2 – interrupted with dots, 3 – line with star-markers, 4 – thin line with dot-markers, 5 round – dots-line, 10 – line with o-markers, 20 – line, 30 – line with *-markers, 40 – thick line with dot-markers, 50 – line with xx-markers.

Figure

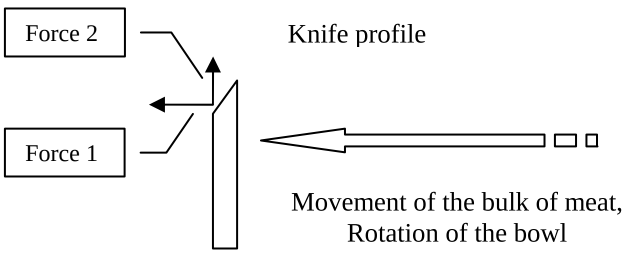
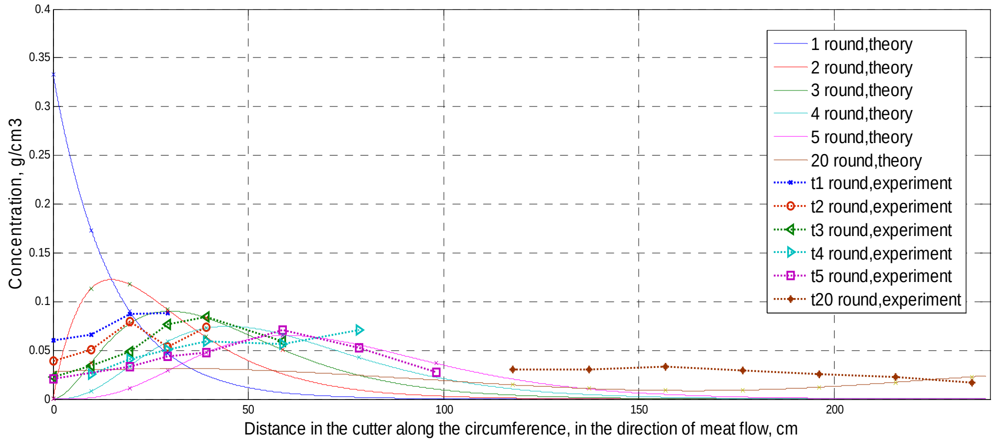

Force 2
Knife profile
Force 1
Movement of the bulk of meat,
Rotation of the bowl

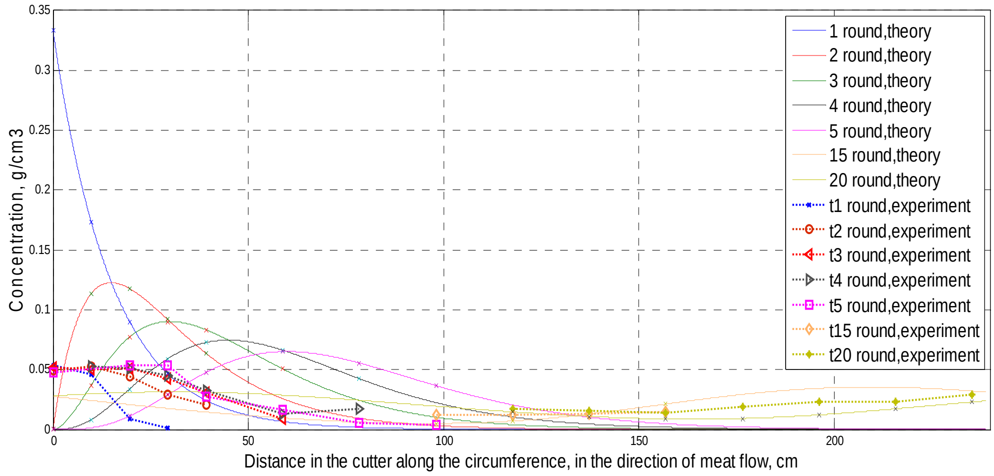
Figure Captions

Figure 6. The scheme of the direction of movement of the bulk of mince, related to rotation in the bowl cutter. Where Force 1 – throws meat in a direction opposite of movement of meat; Force 2 – cutting action of knife

Figure



a. The first experiment

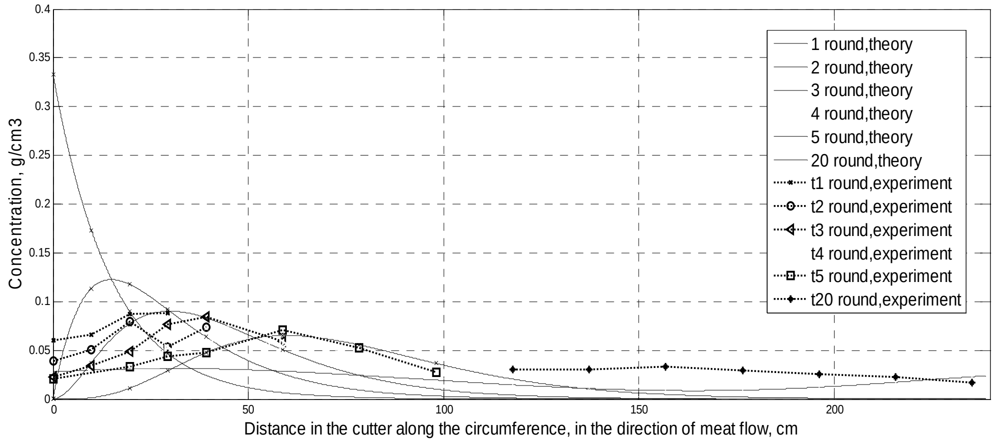


b. The second experiment

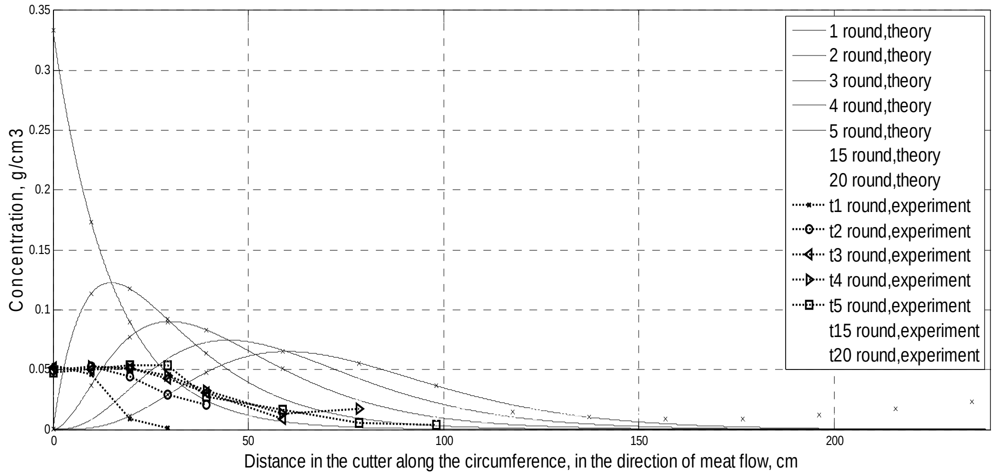
Figure Captions

Figure 7. The concentration of salt in the meat after mixing by bowl cutter. Model and experimental data

Figure



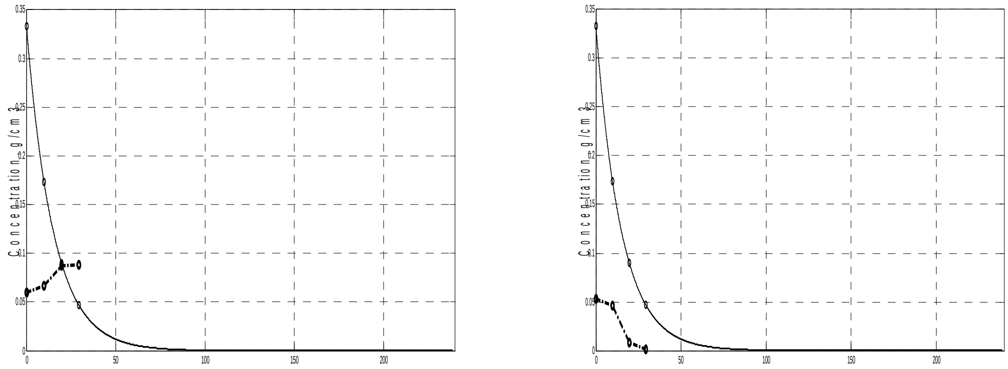
a. The first experiment



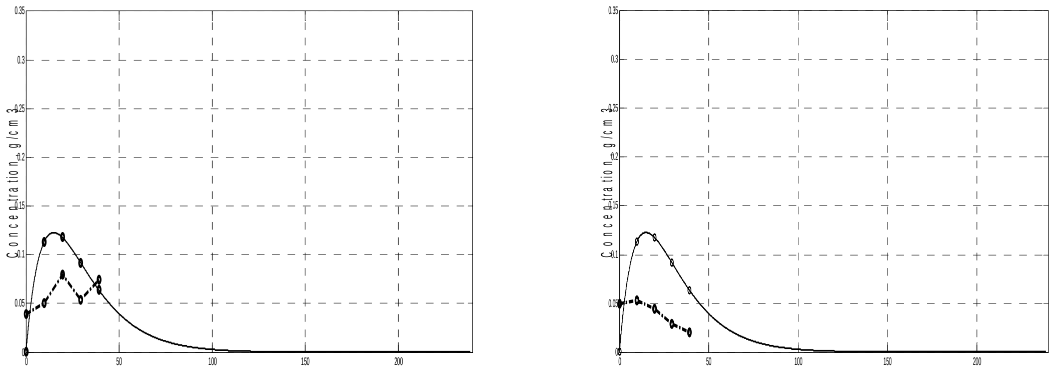
b. The second experiment

Figure

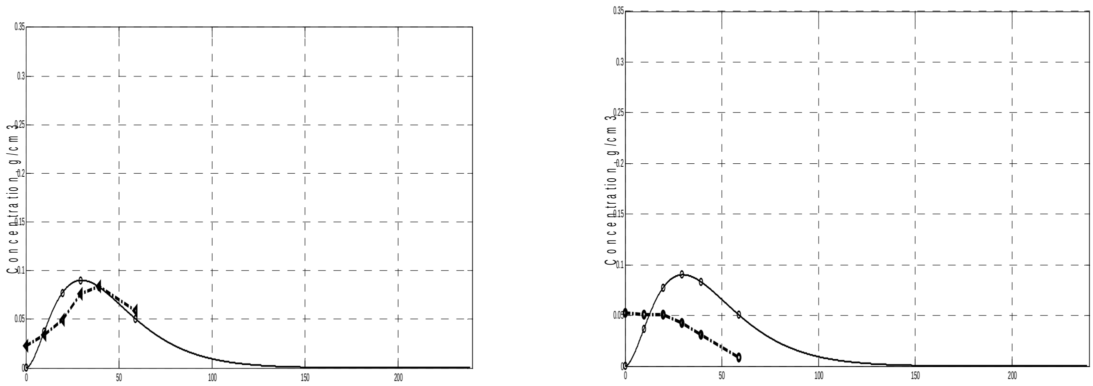
Experiment 1: Experiment 2:



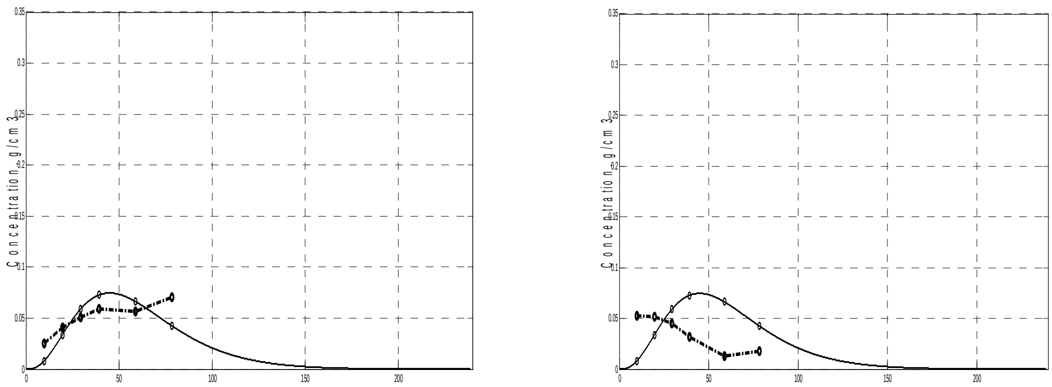
First round



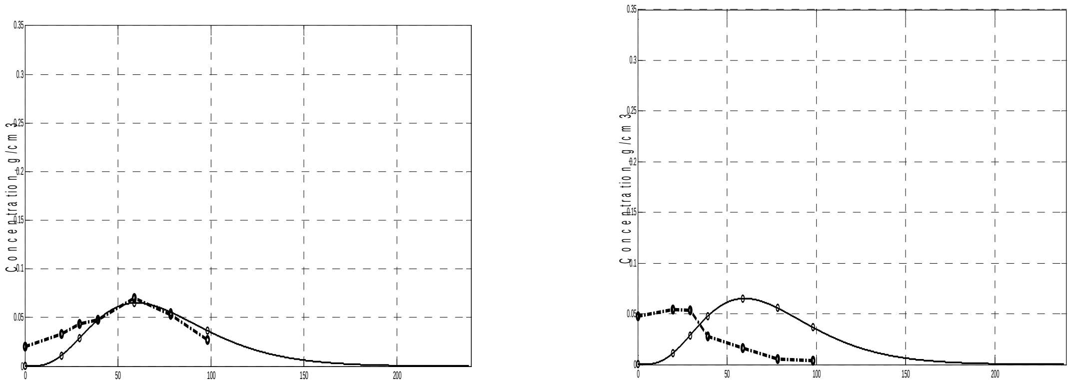
Second round



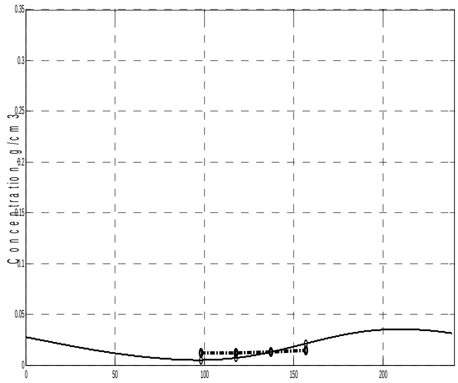
Third round



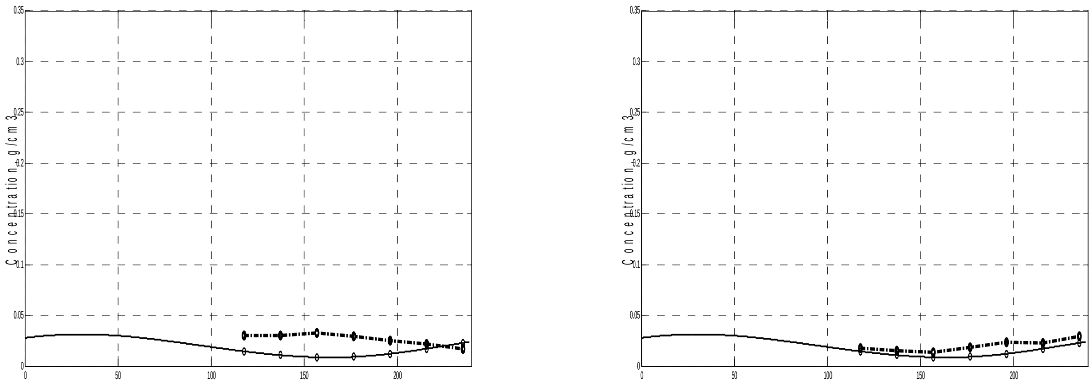
Fourth round



Fifth round



Fifteenth round

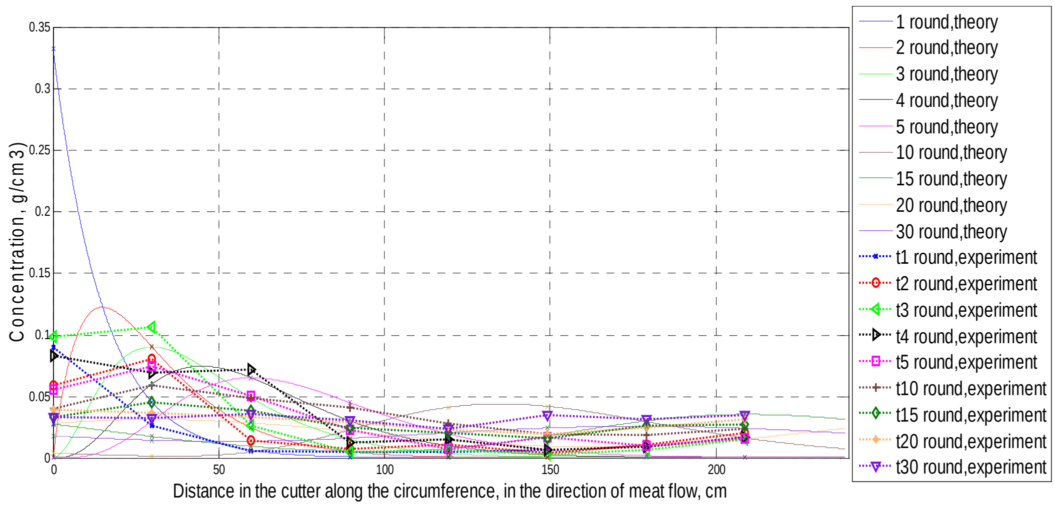


Twentieth round

Figure Captions

Figure 8. The concentration of salt in the meat after mixing by bowl cutter. Comparison of the results of first two experiments

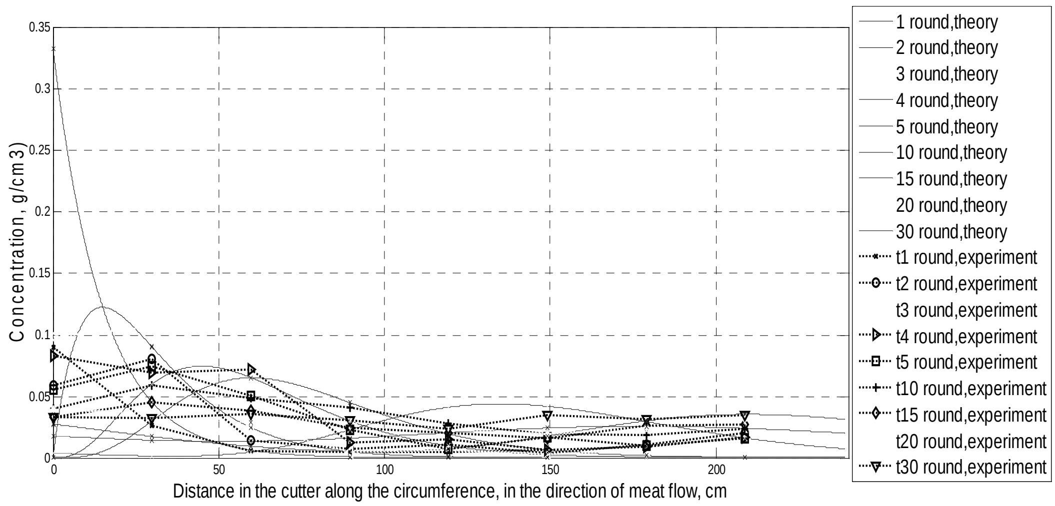
Figure



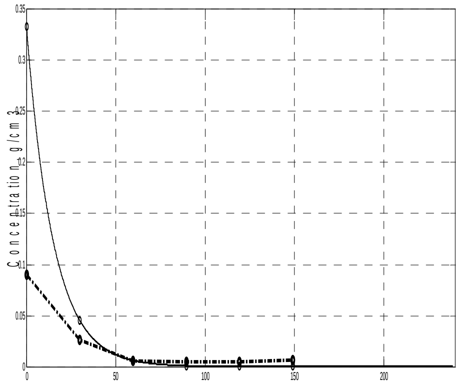
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Concentration, g/cm3)
0
50
100
150
200
Distance in the cutter along the circumference, in the direction of meat flow, cm
1 round,theory
2 round,theory
3 round,theory
4 round,theory
5 round,theory
10 round,theory
15 round,theory
20 round,theory
30 round,theory
t1 round,experiment
t2 round,experiment
t3 round,experiment
t4 round,experiment
t5 round,experiment
t10 round,experiment
t15 round,experiment
t20 round,experiment
t30 round,experiment

Figure 9. The concentration of salt in the meat after mixing by bowl cutter. The third experiment. Experimental data.

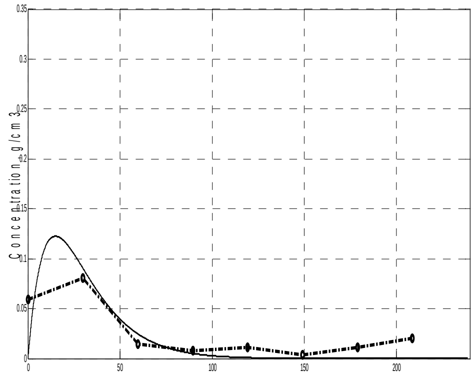
Figure


0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Concentration, g/cm3)
0
50
100
150
200
Distance in the cutter along the circumference, in the direction of meat flow, cm
1 round,theory
2 round,theory
3 round,theory
4 round,theory
5 round,theory
10 round,theory
15 round,theory
20 round,theory
30 round,theory
t1 round,experiment
t2 round,experiment
t3 round,experiment
t4 round,experiment
t5 round,experiment
t10 round,experiment
t15 round,experiment
t20 round,experiment
t30 round,experiment

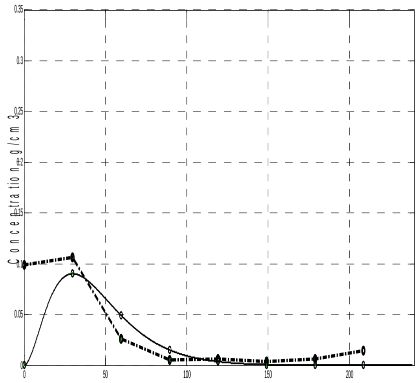
Figure



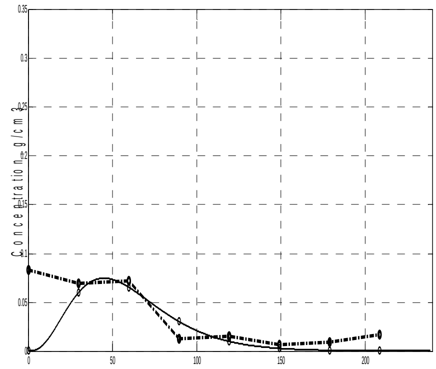
First round



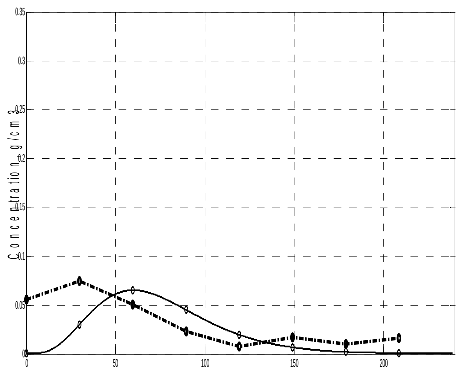
Second round



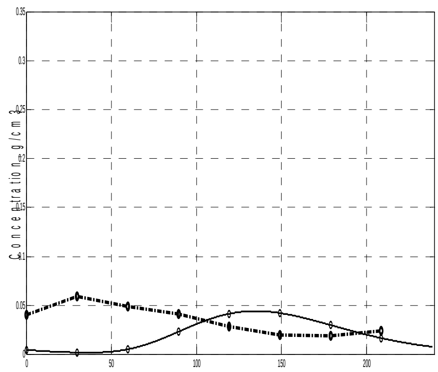
Third round



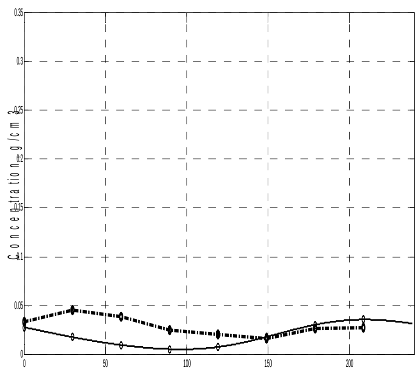
Fourth round



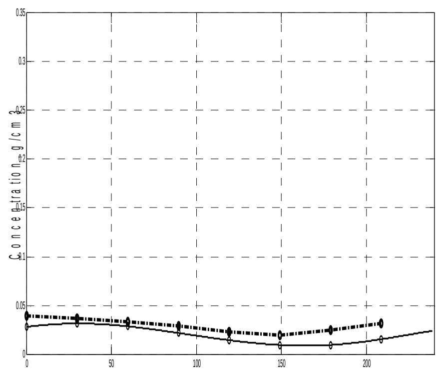
Fifth round



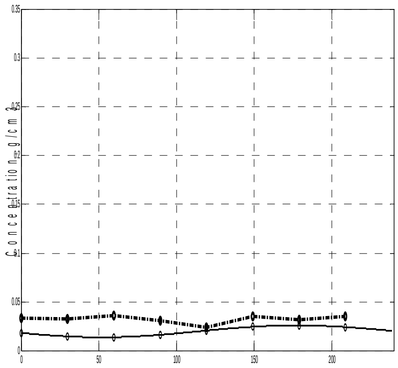
Tenth round



Fifteenth round



Twentieth round



Thirtieth round

Figure Captions

Figure 10. The spread of salt in the meat after mixing by bowl cutter. The third experiment. The comparison of curve shapes. Where the unbroken line is the theoretical curve and the interrupted line is the experimental data. (X-axis - Distance in the cutter along the diameter, cm; Y-axis – Concentration NaCl, g/cm^3)

Table

Distance from the salt addition line, cm	0	10	20	30	40	60	80	100	120	140	160	180	200	220	240
Number of sample	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Rounds															
1	X	X	X	X											
2	X	X	X	X	X										
3	X	X	X	X	X	X									
4		X	X	X	X	X	X								
5	X		X	X	X	X	X	X							
15								X	X	X	X				
20									X	X	X	X	X	X	X

Figure

$$\tau \frac{d}{dt} C_i + C_i = K_p C_0(t) \text{, [1]}$$

Figure

$$[accumulation] = [in] - [out]\,; \quad \Delta C_1 \cdot V = (F \cdot C_0 - F \cdot C_1)\Delta t \quad , [2]$$

Figure

$$\frac{dC_1(t)}{dt} + \frac{1}{\tau} C_1(t) = \frac{1}{\tau} C_0 \delta(t), \quad t = [0, T] \quad , [3]$$

$$C_1(0) = 0$$

Figure

$$\frac{dC_2(t)}{dt} + \frac{1}{\tau}C_2(t) = \frac{1}{\tau}C_1(t), \quad [4]$$

$$C_2(0) = C_1(T)$$

Figure

$$C_1(t) = \frac{C_0}{\tau} e^{-t/\tau}, \quad t = 0 \ldots T \qquad \text{and} \quad C_2(t) = \frac{C_0}{\tau^2} t e^{-t/\tau} + C_1(T) e^{-t/\tau}, \quad t = 0 \ldots T \quad , [5]$$

Figure

$$C_n(t) = \frac{C_0}{\tau^n (n-1)!} t^{n-1} e^{-t/\tau} + \sum_{i=1}^{n-1} \frac{C_i(T)}{\tau^{n-1-i}(n-1-i)!} t^{n-1-i} e^{-t/\tau}, \quad t = 0 \ldots T \text{ , [6]}$$