# PS4.04 Mechanism of water transport in meat during the roasting process 96.00

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***Abstract*— Mass and heat transfer play an important role in the roasting of meat. It is essential that the mechanisms are well understood for controlling and optimising the roasting process. This paper focuses on the mechanism of water transport during roasting of meat in a convection oven. A theoretical assessment was made from literature data on change in structure, water holding capacity and shrinkage. A current hypothesis of water transport predicts a rise of the water content at the center; this was tested by measuring the spatial distribution of the local moisture content. For different periods of roasting shrinkage of meat samples was measured in 3 dimensions and mass loss was measured. Several shrinking phenomena could be distinguished, which have different effects on water transport. For low fat meat, the quantity of dissolved solids lost (DSL) with water during roasting was found to be very small and can be neglected.**

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## I. INTRODUCTION

Roasting in a convection oven is a common way of frying whole meat in households, in professional kitchens and in the ready-meal industry. Setting the process parameters to obtain a culinary optimal result of the roasting process is, however, mostly done on an empirical basis, i.e. based on the judgment, experience and skills of the cook or the operator. Roasting is considered an art, and the aphorism of the founder of gastronomy, Brillat-Savarin (1826) still holds true: "A cook may be taught, but a man who can roast, is born with the faculty" "[1]" This situation, which is not confined to oven roasting of meat but is common to many food processes, makes it difficult to scale up the oven roasting process and to predict the result of transferring the process to new equipment or to apply automatic process control. Scaling up would be facilitated if a more quantitative understanding of the meat frying process was available [2].

Modelling studies of meat frying processes have hitherto largely been concerned with contact frying of meat patties or deep-fat frying of (battered) meat products, reflecting the wide-spread industrial interest in these types of products [3-5]. There are some earlier modelling studies of the oven roasting process, which all emphasize the crucial effect on the energy transfer from water evaporating from the meat [6-8]. As shown already in the now classical study by Skjöldebrand and Hallström (1980), the transport of water inside the meat is coupled to the heat transfer in a complex and yet not fully understood way. Most of the existing models are based on Fickian diffusion of the water [5, 9]. However, the shrinking of the meat due to heat denaturation means that water transport inside the meat is also driven by pressure gradients [10-11]. No study has yet, however, considered all significant aspects of the mechanism of water transport, as discussed below. It is the aim of this paper to test different hypotheses of water transport and investigate the mechanisms which govern the transformation of raw meat into a palatable steak by the convective transfer of heat from the circulating hot air in a convection oven.

## II. MECHANISM OF WATER TRANSPORT DURING THE ROASTING PROCESS

Several researchers have formulated different hypotheses to model mass transfer during roasting, mostly from the perspective of diffusion [5, 9] while disagreements are often seen with regard to other types of water transport mechanisms [10, 12]. Diffusion based models do not adequately describe the moisture transport phenomena during meat cooking [10, 12], because the effects of water binding capacity and shrinkage phenomena are not considered. These are, however, main driving mechanisms for the exudation of water during the cooking or roasting of meat, as is argued in the following: Roasting of meat causes the muscle protein to denature, resulting in a decrease in water holding capacity and leading to shrinkage of the protein network. Shrinkage of protein in meat occurs at different temperatures. Shrinkage transverse to the fibre axis occurs mainly at 40–60$^{O}$C and it widens the gap between the fibres and their surrounding endomysium [13]. Connective tissue network and muscle fibres cooperatively shrink longitudinally at 60–70$^{O}$C [13]. This shrinkage exerts a pressure on the aqueous solution in the extracellular void, and the liquid will flow because the meat tissue has become porous with the transverse shrinkage. Outside the field of meat science, such physics occur during syneresis of curd [14] and polymer gels [15] and models are based on poroelastic theory. A similar approach was also applied in meat science for first time by Van der Sman to study water transport during meat cooking [16]. Van der Sman, however, predicted a quite large rise in the moisture content at the centre of whole meat, which is in disagreement with the observations of Wahlby and Skjöldebrand [12]. Although Skjöldebrand and Thorvaldsson in their earlier [10] study on pre-cooked meat observed a slight rise in water content at the center of the sample, they did not observe any rise in water content in their later study on the roasting of *raw* whole meat [12]. The reasons for the disagreement between theory and observation are: 1) raw and pre-cooked meat are different in their microstructure and composition and behaviour during heating; 2) misinterpretation of the results of previous work and 3) lack of sufficient data on local water content for verification. Item 1) will be expounded on below.

The dynamic change of the microstructure of meat during the heating process plays a great role in water transport. This is often neglected, however, and this leads to ambiguity in the description and modelling of the water transport, as discussed above. The structure of pre-cooked meat is quite different from that of the raw meat. The pre-cooked meat has relatively large pore spaces from the beginning because of the pre-cooking, which gives the pre-cooked meat a low resistance to water transport. This allows the local water content to rise at the centre if there is a temperature gradient towards the centre. On the contrary, in the case of raw meat, the structure is intact at the start of the cooking process, and water transport is hindered towards the centre, despite the temperature and pressure gradients. During the roasting of the raw meat dramatic changes in the microstructure are induced. Spatial variation in temperature creates spatial difference in permeability and elastic modulus, where parts of the meat sample closer to the surface have larger permeability and elastic modulus than the parts closer to the centre. There is therefore a much larger resistance to water flux towards the centre than towards the surface of the meat piece. Since water moves in the direction of least resistance, the water will preferentially flow towards the surface against the temperature gradient and form exudate. It is therefore predicted that migration of water towards the centre is insignificant, in contrast to what Van der Sman predicted [16]. This prediction needs experimental verification, and this verification is the major purpose of this paper.

## III. MATERIALS AND METHODS

### *A. Sample Preparation*

Pork meat (*Longissimus-dorsi*) was bought from the local butchery. It was kept in a plastic bag and stored at 5°C before sample preparation to avoid moisture loss. For all experiments, the fat layer of the meat was removed before the samples were prepared for the required shape (see below, section C).

### *B. Oven setting*

A professional oven, Rational Combi-steamer ccc, with an oven space of 0.83x0.645x0.495 m$^3$ was used for the roasting process. Dry hot air is circulated inside the oven by a fan, which reverses its direction of rotation every 1-2 min to ensure a more uniform heat transfer from the hot air to the product. The temperature of the hot air is controlled by the oven thermostat and was found to be stable by ± 3°C. The oven was set to dry air (no humidification), 50% of the maximum fan speed and an oven temperature of 175°C. The meat samples are placed in the oven on a stainless steel baking tray.

### *C. Measurements*

#### *1) Local moisture content*

Rectangular block samples of pork of an approximate size of $54\times40\times40\ mm^3$ were prepared by hand cutting. The meat samples were roasted in the convection oven for a specified period of time of 8, 11, 15, 20, 25, 30 and 35 min respectively. Each sample was instantaneously taken from the convection oven and immersed in liquid nitrogen for approximate 30 s to stop water migration by freezing. The samples were placed in a freezer for 2-4 hours. Then the sample was sliced with a meat slicer and a knife into small sub-samples of approximately 4×4×4 mm$^3$. The moisture content of each local sample was determined using oven drying at 105°C for 24 hours [17].

### *2) Overall shrinkage*

Meat samples were prepared as rectangular blocks of the same dimensions as in 1). For all the samples, the length (*L)* direction was assigned along the fibre orientation (in the x-direction), and width (*W)* and height (*H)* were assigned across the fibre orientation (in the y and z direction, respectively). Samples were measured using a digital vernier caliper both before and after roasting. Initial dimensions (‘$L_o$’, ‘$W_o$’ and ‘$H_o$’) and mass ($M_o$) of each sample were measured. The convection oven was heated to 175°C and samples were placed in the oven and heated for a specified time. At time t, the sample was instantly taken from the oven and its dimensions (*L, W and H*) and mass (*M*) were measured. Then, the sample was placed back in the oven. This procedure was repeated at all specified times.

### *3) DSL during roasting*

16 meat samples were roasted (under the same condition as above) and their initial ($M_o$) and final mass were measured. A sample was taken from the oven and the dry matter lost with the exudate left on the tray was collected after the water had been evaporated in the oven. The solid residual was removed from the tray with a knife and its mass was determined. These procedures were repeated for all samples.

## IV. RESULTS AND DISCUSSION

### *A. Local moisture content*

The local water content of the meat was determined at different positions and time as shown in Table 1. A local water content rise towards the center (16-20) was not observed: This result agrees well with the work of Skjöldebrand in (2001) [12]. Generally, the local water content decreases with an increase in distance from the centre and decreases with increasing roasting time (with few exceptions). The local water content at position (0-4) decreases steadily for the initial stage up to t = 20 min (to 0.646 kg of water/kg of sample). Then at t = 25 min it increases (to 0.705 kg of water/kg of sample) and then later on it decreases again. The increased water content near the surface at t = 25 min, is probably due to the large outward water flux directing water from the center of the piece of meat to the surface. A rapid drop in water binding capacity and a large pressure gradient at the center, and larger permeability in the outer part (0-4) than in the inside part (16-20) causes the water to move faster towards the surface. When the internal water flux is larger than the transport flux of water away from the surface, water is accumulated near the surface ( 0-4), and consequently the local water content rises. Later on the internal flux decreases and the local water content continues to drop for the remaining time of the roasting experiment.

In later work not reported here, we have occasionally observed a slight moisture rise (up to 0.03 kg water/kg of sample) near the centre after 15 and 20 min of roasting in the convection oven. Still, that level of increase of the moisture content is far below Van der Sman’s prediction (0.1 kg of water/kg of sample, 10% rise) [16]: The rise of the local water content is not necessarily observed at the center of the meat piece; the local rise can be anywhere within the sample, depending on the magnitude of pressure gradients and the permeability of the medium. Our hypothesis is that the onset of heat denaturation and shrinking may give rise to occasional crevices in the meat because the shrinking causes uneven stresses in the meat piece. This will be investigated in future work and does not distract from the overall conclusion that the water transport towards the centre is negligible because of the low permeability of the raw meat.

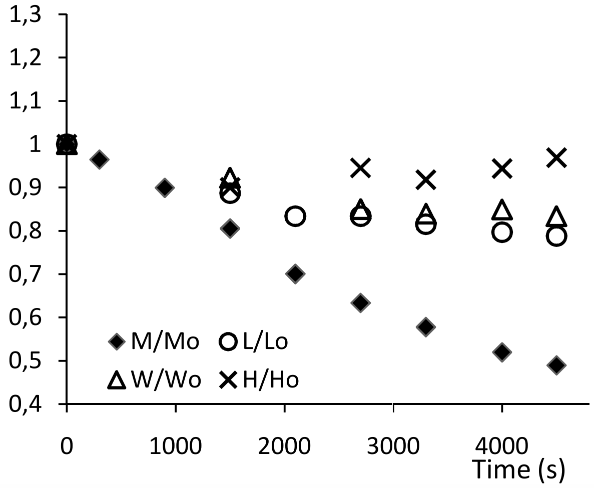
**Table 1 Local water content (kg of $H_2O$ per kg of sample)**

| Time( in min) | Position(mm) from surface to center | | | | |
|---|---|---|---|---|---|
| | (0-4) *Surface* | (4-8) | (8-12) | (12-16) | (16-20) *center* |
| 0 | 0.746 | 0.752 | 0.748 | 0.745 | 0.720 |
| 8 | 0.720 | 0.730 | 0.740 | 0.730 | 0.740 |
| 11 | 0.701 | 0.716 | 0.727 | 0.737 | 0.745 |
| 15 | 0.690 | 0.720 | 0.730 | 0.730 | 0.740 |
| 20 | 0.646 | 0.727 | 0.744 | 0.741 | 0.736 |
| 25 | 0.705 | 0.706 | 0.727 | 0.732 | 0.736 |
| 30 | 0.693 | 0.712 | 0.719 | 0.716 | 0.734 |
| 35 | 0.659 | 0.618 | 0.665 | 0.667 | 0.681 |

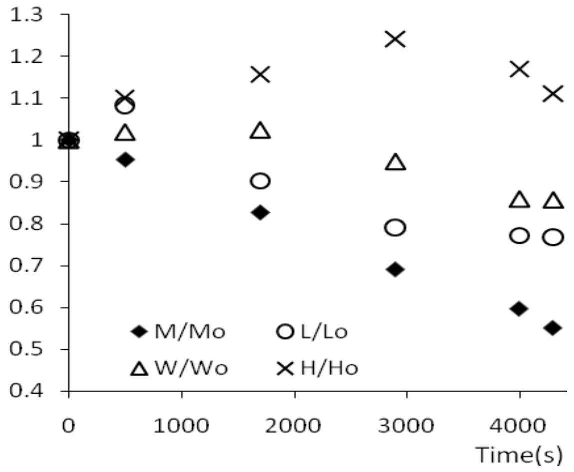
Position is distance from surface in mm, 0 and 20 are surface and center respectively.

### *B. Shrinkage*

Fig 1 a and b show that relative dimensions (L/Lo, W/Wo and H/Ho) and relative mass (M/Mo) as function of time for two samples, taken out of 5 samples showing extreme shrinkage phenomena. Meat samples shrink in the length and width direction: with larger shrinkage in the length direction. The rate of shrinkage is large from t=900 to t= 2100 s, Fig 1a and from t=500 to t=2900 s, Fig 1b and the corresponding mass loss rate is also large in the same range, relative mass decrease from 90 to 70% and 90 to 69%, respectively. This verifies that shrinkage is the basis for larger water loss which agrees with the hypothesis of Godsalve [10]. However, later on, after 2700 s (Fig 1a) the rate of shrinkage is considerably reduced, a change of 4% in the length and 2% in the width from t = 2700 to t = 4500 s. The most probable reason for such reduction shrinkage rate is that the elastic modulus of the meat increases drastically when the meat is heated above $65^{O}C$ [13].



a)



b)

**Figure 1 Shrinkage and mass loss as function of time: a) meat sample shrinking in 3 directions; b) meat sample shrinking in x and y-direction and expanding in the z direction (height). M is mass (g), L, W and H are length width and height (mm), respectively. Subscript 'o' refers to initial state**

Another interesting observation was that mass loss is larger if the sample is shrinking in all directions (Fig. 1a) compared to a situation where it is expanding in one of its directions (Fig 1b). This can be explained by the fact that the stress is larger when the meat shrinks in all directions than when it expands in one of its directions. Larger stress causes a greater squeezing pressure, which means more water is squeezed to the surface (larger mass loss). The exact cause for the differences in shrinking behaviour between meat samples is not identified, but must be related to the fact that the biological variation between the same muscles but from different animals is considerable.

### *C. Dry matter loss with water as drip*

Meat with low fat content was used for our study to avoid complication from fat transport. To test the validity of this assumption, the percentage of DSL was estimated as 1.33±0.18% of the total weight loss. Thus, it is quite a small fraction of the total loss (1.33 g per 100 g of total loss) and it substantiates the hypothesis of mass transfer based on water transport alone.

## V. CONCLUSION

A mechanism for water transport during roasting of meat is proposed and partially substantiated by experimental data. Spatial distribution of the local moisture content in meat was studied, and a large rise of the water content was not observed in the center of the meat. Our hypothesis of water transport is that shrinkage plays a great role in water transport mechanisms that cause large water losses during meat roasting. Different shrinkage phenomena can result in substantial differences in mass loss: shrinkage in all directions leads to greater mass loss than if the meat piece expands in one of its directions.

The novelty of the present work lies in the emerging mechanistic understanding of water transport in meat during roasting. This understanding is corroborated by measurements of spatial local moisture content and overall shrinkage. The dynamic change of permeability plays a crucial role in the water transport mechanism and its effect needs to be considered in the future modelling of heat and mass transfer during meat roasting processes.

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## REFERENCES

[1] Anthelme Brillat-Savarin (1755-1826). (2007). The physiology of taste. eBooks@Adelaide.

[2] Singh, R. P. & Vijayan J.(1998). Predictive modeling in food process design. Food Science and Technology International, 4(5):303-310.

[3] Dincer, I. (1996). Modelling for heat and mass transfer parameters in deep-frying of products. Heat Mass Transfer, 32(1-2):109-113.

[4] Pan, Z., Singh R.P., & Rumsey, T.R. (2000). Predictive modeling of contact-heating process for cooking a hamburger patty. Journal of Food Engineering, 10/1;46(1):9-19.

[5] Ngadi, M.O., Watts, K.C., & Correia, L.R. (1997). Finite element method modelling of moisture transfer in chicken drum during deep-fat frying. Journal of Food Engineering, 4;32(1):11-20.

[6] Skjoeldebrand, C., & Hallström, B. (1980). Convection oven frying. Heat and mass transport in the product. Journal of Food Science,45(5):1347-1353.

[7] Singh, N., Akins, R.G., & Erickson, L.E. (1984). Modeling heat and mass transfer during the oven roasting of meat. Journal Food of Process Engineering, 7(3):205-2207.

[8] Chang, H.C., & Carpenter, J.A., Toledo, R.T. (1998). Modeling heat transfer during oven roasting of unstuffed turkeys. Journal of Food of Science, 63(2):257-261.

[9] Huang, E., & Mittal, G.S. (1995). Meatball Cooking - Modeling and Simulation. Journal of Food Engineering, 24(1):87-100.

[10] Godsalve, E.W., Davis, E.A., Gordon, J., & Davis, H.T. (1977). Water loss rates and temperature profiles of dry cooked bovine muscle. Journal of Food Science, 42(4):1038-1045.

[11] Thorvaldsson, K., & Skjöldebrand, C.(1996). Water transport in meat during reheating. Journal of Food Engineering, 7;29(1):13-21.

[12] Wählby, U., & Skjöldebrand, C. (2001). NIR-measurements of moisture changes in foods. Journal of Food Engineering, 3;47(4):303-312.

[13] Tornberg, E. (2005). Effects of heat on meat proteins – Implications on structure and quality of meat products. Meat Science,7;70(3):493-508.

[14] Tijskens, E., & De Baerdemaeker, J., (2004) Mathematical modelling of syneresis of cheese curd. Mathematics and Computers in Simulation,65(1-2):165-175.

[15] Barriere, B., & Leibler, L. (2003). Kinetics of solvent absorption and permeation through a highly swellable elastomeric network. Journal of Polymer Science Part B-Polymer Physics 15;41(2):166-182.

[16] Van der Sman, R.G.M. (2007). Moisture transport during cooking of meat: An analysis based on Flory–Rehner theory. Meat Science,76(4):730-738.

[17] Nielsen, S. S. (ed.). (1994). Introduction to Chemical Analysis of Foods, Jones and Bartlett, Boston, pp. 94-100.