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Project Work

Internship at SINTEF Energi AS

Convective Drying and Sorption Characteristics of Cured Meat Slices

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Statement of Authorship

I hereby certify that this bachelor thesis has been composed by myself, and describes my own work, unless otherwise acknowledged in the text. All references and verbatim extracts have been quoted, and all sources of information have been specifically acknowledged. This bachelor thesis has not been accepted in any previous application for a degree.

Trondheim, 28.02.2014 _____

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CONVECTIVE DRYING AND SORPTION CHARACTERISTICS OF CURED MEAT SLICES

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Summary

Drying of cured meat is a time- and energy-consuming process, since the dehydration is controlled by the slow product specific diffusion. In order to optimize this process it is necessary to determine and model the drying kinetics of the cured meat.

The aim of this project was to determine the influence of temperature, air humidity and salt content on the drying kinetics of pork.

Experiments with small slices of the pork muscle Semimembranosus (100-200g per slice) were carried out under different conditions. Unsalted, low salted and high salted slices were used for each experiment. The experiments with varied air humidity (60%, 68%, 80%) have been performed at 13 °C and experiments with varied temperature (10 °C, 13 °C, 16 °C) at 68 % air humidity. The values of temperature and air humidity are in accordance with the conditions which are used in industrial producing of ham. The air velocity has only a minor influence on the drying process and was kept constant at approximately 0.4 m sec^{-1}, which is similar to industrial drying conditions.

Unsalted pork has the highest water content (X) at the beginning and high-salted pork the lowest.

The drying rate for the different products showed that meat with the lowest salt content dries fastest, while the high-salted meat showed the slowest drying rate. The variation of air humidity has caused higher changes in the drying kinetics than the variation of temperature thus the air humidity is the main controlling factor in these experiments.

With the obtained results a physical model was applied. It was also tested if this model is still valid under alternating conditions within one drying process. Therefore an experiment was performed at 13 °C and with alternating air humidity between 60% and 80%.

For the application of the physical model the sorption isotherms were required of the used substance (muscle Semimembranosus). Due to the fact that the sorption isotherms for each substance are different, the sorption isotherms of unsalted, low salted and high salted samples were determined in additional experiments.

The difficulties in this project have been that the samples of meat vary in composition for example of muscles and fat and also the properties change with time.

Table of contents

Nomenclature

Symbol	Unit	Meaning
A	m^2	Area
a_w	$-$	Water activity
c_s	$-$	Salt content
d	m	Dry layer thickness
D_{eff}	$\frac{m^2}{s}$	Effective diffusion coefficient
D_G	$\frac{m^2}{s}$	Diffusion coefficient of water in air
h	m	Height
l	m	Characteristic length; Thickness of meat slices
m	kg	Mass
Δm	kg	Loss of mass from start mass
$\Delta m_{\%}$	$-$	Loss of mass from start mass in % of start mass
$\dot{m}_\omega$	$\frac{kg}{m^2 * s}$	Drying rate
M_i	$\frac{g}{mol}$	Molar mass
p	Pa	Overall pressure
p_i	Pa	Partial pressure of component i
p_ω°	Pa	Saturated vapour pressure
R	$\frac{kJ}{kg * K}$	Special gas constant
$\tilde{R}$	$\frac{kJ}{kmol * K}$	Universal gas constant
RH	$-$	Relative humidity
s	kg	Amount of salt
SD	$-$	Standard deviation
t	s	Time
T	$°C; K$	Temperature
u	$-$	Standard uncertainty
U	$-$	Expanded measurement uncertainty
v	$\frac{m}{s}$	Velocity
V	m^3	Volume
w	kg	Amount of water
X	$-$	Water content with regard to dry mass
X_e	$-$	Water content at equilibrium

X_w	$-$	Water content with regard to total mass
β	$\frac{m}{s}$	Mass transfer coefficient
μ	$-$	Diffusion resistance coefficient
η	$Pas; \frac{kg}{ms}$	Dynamic viscosity
ρ	$\frac{kg}{m^3}$	Density
ρ_{dm}	$\frac{kg}{m^3}$	Dry mass density, salt excluded
$\rho_{dm,s}$	$\frac{kg}{m^3}$	Dry mass density, salt included
υ	$\frac{m^2}{s}$	Kinematic viscosity
$\emptyset$		Average
Indices		
a		Air
dm		Dry mass; salt excluded
dm, s		Dry mass; salt included
end		Final state
$evap$		Evaporated
hs		High salted
i		Inner
ls		Low salted
ms		Medium salted
s		Salt
t		Total
us		Unsalted
w		Water
0		Initial state
Dimensionless Numbers		
Re		Reynolds number
Sc		Schmidt number
Sh		Sherwood number

List of Figures

List of Tables

1. Summary

Drying of cured meat is a time- and energy-consuming process, since the dehydration is controlled by the slow product specific diffusion. In order to optimize this process it is necessary to determine and model the drying kinetics of the cured meat. The aim of this project was to determine the influence of temperature, air humidity and salt content on the drying kinetics of pork.

The drying process for ham is characterized by a falling drying period, which is controlled by diffusion and internal resistance due to e.g. salt crystallization, dry layer thickness and biochemical reactions (ripening). Drying mechanism during this period is product specific and need to be determined in industrial or laboratory experiments. The correct knowledge of the drying parameters is the basic requirement in order to design industrial sized drying camber with respect to size, drying capacity and dewatering equipment.
Small scale experiments of the pork muscle Semimembranosus (50-200g per slice) were carried out under different conditions. Unsalted, low salted, medium salted and high salted slices were used for each experiment. The experiments with varied air humidity (60%, 68%, 80%) have been performed at 13°C and experiments with varied temperature (10°C, 13°C, 16°C) at 68% air humidity. The values of temperature and air humidity are in accordance with the conditions which are used in industrial producing of ham. The air velocity has only a minor influence on the drying process and was kept constant at approximately 0.4 m sec^{-1}, which is similar to industrial drying conditions.

The higher relative humidity and the higher salt content the slower the drying rate. The variation of air humidity has caused higher changes in the drying kinetics than the variation of salt content. Temperature has no recognizable influence in the applied range. Thus the air humidity is the main controlling factor in these experiments.
With the obtained results a physical model was applied. By means of an experiment performed at 13°C and with alternating air humidity between 60% and 80% it was verified that this model is also valid under alternating conditions within one drying process.

For the application of the physical model the sorption isotherms were required of the used substance (muscle Semimembranosus). Due to the fact that the sorption isotherms for several products are different, the sorption isotherms of

unsalted, low salted, medium salted and high salted samples were determined in additional experiments.

The challenges in this project have been that the samples of meat vary in composition for example of muscles and fat. Also meat looses water during storage so that the initial water content is lower than determined if stored too long. To ensure correct results the meat was used as fresh as possible.

2. The Company

SINTEF is a Norwegian research organisation which is divided in the eight institutes: ICT, Building and Infrastructure, MARTINEK, Fisheries and Aquaculture, Materials and Chemistry, Energy Research, Petroleum Research and Technology and Society.

The head office is located in Trondheim. Sintef has its Norwegian offices in Oslo, Bergen and Ålesund. Around the world it has a laboratory in Hirtshals (Denmark) and offices in Houston (Texas), Rio de Janeiro (Brazil) and Chile.

About 2100 people are employed by this company which makes SINTEF the largest independent research organisation in Scandinavia. 1500 of the employees are working in Trondheim.

For more than 2000 clients of about 60 different countries SINTEF is carrying out more than 7000 projects in research per year. It is a non-commercial research organisation and applies its earnings in research.

2.1. SINTEF Energy Research

About 200 people work at the Energy Research institute of SINTEF. The disciplines of this institute are energy systems, electric power systems, electric power technology, energy efficiency, thermal energy and gas technology.

This internship was done in the research area of energy efficiency which is divided in six fields of research: Energy efficiency for buildings, energy production from waste heat, heat pump processes and systems, improving industrial energy efficiency and finally **food technology**.

3. Scope of the Work

Dry-cured ham is produced since centuries. At the beginning the purpose of curing and drying was to keep the meat durable as there was no possibility to cool it in summer. Nowadays dry-cured ham is not only produced due to the good durability anymore but also for the special taste this treating causes. Due to climatic situation, sanitary/hygienic reason and reliability industrial production nowadays takes place in climate chambers in which the product is held at constant temperature in a controlled atmosphere during ripening and drying.
In manufacturing of ham the drying process is the most time- and energy-consuming part, because of the size of the product and the drying related energy demand (latent heat of evaporation for water is high). Also the quality demand for the ripening increases the production time. In fact, the considered best quality dry-cured ham as production time of 2 years, during which the product temperature and the surrounding climate needs to be controlled. This poses a significant energy related production cost. In order to improve the drying process the knowledge of the influential factors is necessary.

To simulate the drying process, reliable drying rates and a physical model are needed. For this the product specific drying rate needs to be determined, which is only possible via experiments since general conclusions in food drying are difficult to obtain. Experiments with samples used in industrial production (approx. 9 kg per piece) would be too expensive and time-consuming. Hence small scale experiments are required in order to obtain qualitative drying characteristics for ham. The drying rate of small scale experiments was modelled and this model can be transferred to sizes of samples used in industrial production.

Since SINTEF is a research organisation there haven't been any operational boundary conditions.

4. State of the Art in Industrial Production of Dry-Cured Ham

To analyze the actual state an excursion was done to the production plant for dry-cured ham of Notura in Tynset. Notura produces two different kinds of ham: Standard ham with a producing time of 3 months as well as high-end hams with a producing time of 14 months and 24 months.
The meat used in this process is the back leg of pork with a weight of approx. 9 kg. It arrives frozen and is thawed up in the beginning where the weight is reduced by 3.4% due to loss of water.

In the production of standard ham, the meat is pressed after thawing up (for further loss of weight and opening of microstructure for better salt diffusion and water dehydration). Afterwards it is rubbed with nitrite salt which preserves the red colour of meat and stored in sea salt inside plastic bags (at 4-6°C). After two weeks the salt is washed away with water of 14°C and the hams are stored again for two weeks so that the salt content is balanced. Then they are immersed in 2.5% solution of kaliumsorbate/potassium sorbate (E202) for protection against microorganism. Now the main process starts where the hams are dried convectively in an arrangement as seen in Fig. 1.

Figure 1: Arrangement of hams in drying facility

The temperature in this facility is set on 13°C, the relative humidity on 68%. The air velocity is between 0.1 and 0.4m/s to ensure moisture transport.
The drying process is finished as soon as the average water activity is lower than 0.9 (after 8-9 weeks). When the water activity is under this value a safe product is guaranteed.
After drying the bones are removed and the ham is pressed in a shape *(Fig. 2)*.

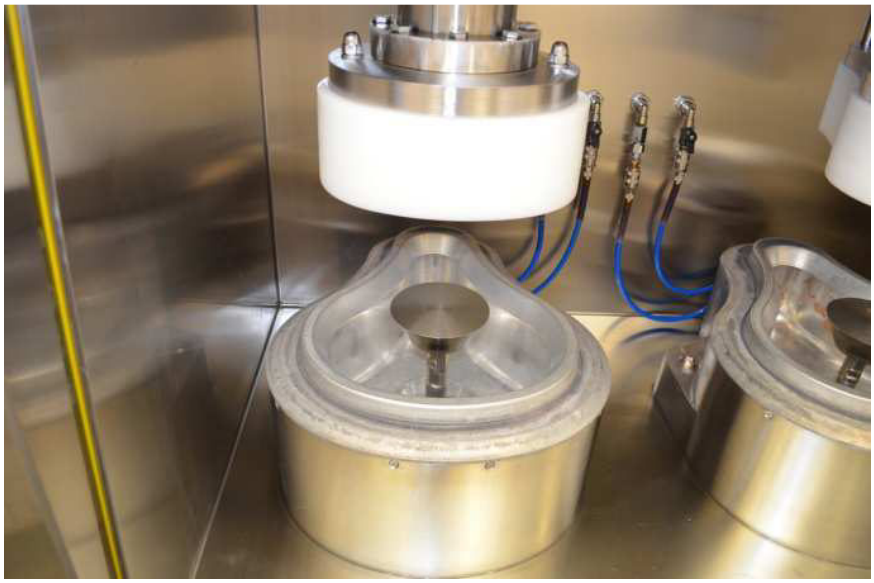

Figure 2: Pressing device for final shape of ham

At the end the final water content with regard to dry mass is about 130% and the salt content with regard to overall mass 9%.

5. Aim of the Investigation

The aim of the project work is to investigate the convective drying characteristics of dry-cured ham. The focus is hereby on the prediction of the drying rate and time with respect to the drying conditions (temperature and humidity).

With the knowledge about the drying behaviour of pork the industrial process can be improved in time- and energy-consuming aspects.

The following tasks were performed in the framework of this internship:

1. Evaluation of industrial production plant to figure out the drying parameters applied in the small scale experiments
2. Determination of Sorption isotherms for dry-cured and raw meat as they are product specific and cannot found in literature
3. Small scale experiments with dry-cured ham
    a. Influence of relative humidity on drying rate
    b. Influence of temperature on drying rate
    c. Influence of salt content on drying rate
4. Evaluation of different physical models in order to model the drying rate
5. Verifying of the applied model for alternating relative humidity
6. Literature research to obtain basic knowledge about the production process of dry-cured ham as well as literature values needed for modelling the process

This project is limited by the size of the experiments. Just experiments with small samples have been performed because drying of the whole pork back leg lasts too long (up to 24 months). Therefore the results of this work have to be projected to industrial dimensions.

6. Fundamental Theory[1]

The intention of a drying process is to reduce the initial water content X_0 of a substance to the final water content X_{end}. To achieve this, p_i, the partial pressure of water in the surrounding, has to be lower than p_ω°, the saturated vapour pressure of water on the surface of the substance.
In convective drying the substance is overflowed by a gas, mostly air, with a certain relative humidity (RH) and temperature (T). The partial pressure of water in the surrounding is directly connected to RH and p_ω° whereby p_ω° is dependent on T. Values for p_ω° at various temperatures are listed in vapour pressure tables.

$$RH = \frac{p_i}{p_\omega^\circ} \rightarrow p_i = RH * p_\omega^\circ \qquad \text{(Eq. 1)}$$

The driving force of the drying process is the difference between p_ω° and p_i. By replacing p_i with the relation of RH and p_ω° out of Eq.1 the driving force can be described as following:

$$p_\omega^\circ - p_i = p_\omega^\circ(1 - RH) \qquad \text{(Eq. 2)}$$

This shows that the condition of the overflowing air is significantly determining the drying process.

The drying process is divided in three parts. The first part is determined by surface evaporation and just dependent on the drying properties of water. The loss of water is linear to time in this part, the drying rate is constant. When the water content reaches the critical value the second drying part starts where the drying behaviour is also affected by the properties of the substance. This part is characterized by a falling drying rate. In the third part the remaining water like chemical bound water or capillary water is removed.

In the drying of cured meat the water content is first reduced by osmotic drying. Due to the low initial water content at the beginning of the convective drying only the second part of drying processes is considered.

Two different physical models are examined and compared. One model is for non-hygroscopic substances, the other one for hygroscopic substances.

[1] /4/ (Mersmann et al., 2005)

A substance is hygroscopic if a part of its moisture is bound by adsorption to the material whereas in non-hygroscopic substances moisture is not bound in this way.
Meat is a hygroscopic substance. To investigate if this property is negligible the following two models have been investigated.

6.1. Non-Hygroscopic Model

The model for non-hygroscopic substances is after /4/ and describes the drying rate of a product based on the similarity of heat and mass transfer. The amount of evaporated water depends on the temperature and humidity of the drying agent (air) as well as external and internal mass transfer resistance:

$$\dot{m}_\omega = \frac{1}{\frac{1}{\beta}+\frac{d(t)}{D_G}*\mu*(1-\frac{(p_i)m}{p})} * \frac{\overset{\circ}{p_\omega}-p_i}{R*T} \quad \text{(Eq. 3)}$$

β is the mass transfer coefficient on the surface and is calculated after /3/:

$$Sh = \frac{\beta * \frac{l}{2}}{D_G}$$

$$\rightarrow \beta = \frac{Sh*D_G}{\frac{l}{2}} \quad \text{(Eq. 4)}$$

$$Sh = \sqrt{{Sh_{lam}}^2 + {Sh_{turb}}^2} \quad \text{(Eq. 5)}$$

$$Sh_{lam} = 0.664 * Sc^{\frac{1}{3}} * Re^{\frac{1}{2}} \quad \text{(Eq. 6)}$$

$$Sh_{turb} = \frac{0{,}037*Re^{0.8}*Sc}{1+2.443*Re^{-0{,}1}*(Sc^{\frac{2}{3}}-1)} \quad \text{(Eq. 7)}$$

$$\eta_a = \upsilon_a * \rho_a \quad \text{(Eq. 8)}$$

$$Re = \frac{v_a*\frac{l}{2}*\rho_a}{\eta_a} \quad \text{(Eq. 9)}$$

(8) in (9)

$$Re = \frac{v_a*\frac{l}{2}}{\upsilon_a} \quad \text{(Eq. 10)}$$

$$Sc = \frac{\eta_a}{D_G*\rho_a} \quad \text{(Eq. 11)}$$

(8) in (11)

$$Sc = \frac{\upsilon_a}{D_G} \quad \text{(Eq. 12)}$$

$\frac{l}{2}$ is the characteristic length which corresponds to the half thickness of the slice in this experiments and was measured (A 4.7). v_a, the air velocity, was adjusted in the drying chamber.
D_G (diffusion coefficient of water in air), υ_a (kinematic viscosity) and ρ_a(density of air) are obtained from literature (A 1.1- A 1.3).

$d(t)$ is the dry layer thickness of the meat slice which increases with time due to the evaporated water. To simplify the calculation of d shrinkage is neglected, meat slices are assumed as cylindrical and no water is delivered from inside to the regions where water is evaporated. A 2-dimensional model is used to describe the development of the dry layer in radial and longitudinal direction.

The evaporated water creates a dry area in the meat. As the meat consists of water and dry mass following connection between evaporated volume of water ($V_{w,evap}$) and volume of dry layer (V_{dry}) exists:

$$V_{dry} = \frac{V_{w,evap}}{Y_{w,0}} \quad \text{(Eq. 13)}$$

$V_{w,evap}$ is the volume occupied by the evaporated amount of water

$$V_{w,evap} = \frac{\Delta m}{\rho_w} \quad \text{(Eq. 14)}$$

$Y_{w,0}$ is initial percent by volume of water in meat.

$$Y_{w,0} = \frac{V_{w,0}}{V_t} = \frac{m_{w,0} * \rho_w}{m_t * \rho_t} = X_{w,0} * \frac{\rho_w}{\rho_t} \quad \text{(Eq. 15)}$$

X_w (water content with regard to total mass) is determined in experiments (A 4.2). ρ_w (density of water) is obtained from literature (A 1.4), ρ_t (total density of meat) of unsalted slice is obtained from literature (A 1.5) and has to be calculated for the salted slices.

$$\rho_t = X_{w,0} * \rho_w + c_{s,t} * \rho_s + \left(1 - (X_{w,0} + c_{s,t})\right) * \rho_{dm}$$

$$\rightarrow \rho_{dm} = \frac{1}{1-(X_{w,0}+c_{s,t})} * (\rho_t - (X_{w,0} * \rho_w + c_{s,t} * \rho_s)) \quad \text{(Eq. 16)}$$

(14) & (15) in (13):

$$V_{dry} = \frac{1}{X_{w,0}} * \Delta m * \frac{\rho_t}{\rho_w{}^2} \quad \text{(Eq. 17)}$$

The meat slice is considered cylindrical with thickness l and radius R_{all} as shown in Fig. 3.

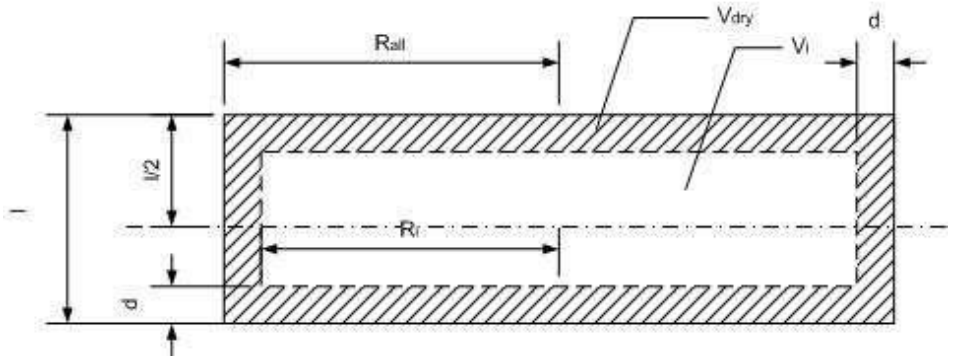

Figure 3: Sketch of meat slice

The evaporation of water results in a reduced inner volume of meat with initial water content (V_i).

$$V_i = V_t - V_{dry} \quad \text{(Eq. 18)}$$

V_t is the volume of the meat slices:

$$V_t = 0{,}5 * A_{meat} * l \quad \text{(Eq. 19)}$$

The area of the meat slices (A_{meat}) is measured with regard to mass (see A 4.7).

A dry layer of thickness d arises which leads to a reduction of the inner radius:

$$R_i = R_{all} - d \quad \text{(Eq. 20)}$$

R_{all} is calculated with the area of the slices:

$$0.5 * A_{meat} = \pi * R_{all}{}^2 \rightarrow R_{all} = \sqrt{\frac{0{,}5 * A_{meat}}{\pi}} \quad \text{(Eq. 21)}$$

The inner volume V_i is calculated with by d reduced l and R_{all}:

$$V_i = \pi * R_i{}^2 * l_i{}^2 = \pi * (R_{all} - d)^2 * (l - 2 * d) \quad \text{(Eq. 22)}$$

(21) in (22):

$$V_i = \pi * (\sqrt{\frac{0{,}5*A_{meat}}{\pi}} - d)^2 * (l - 2 * d) \quad \text{(Eq. 23)}$$

(23), (19) and (17) in (18):

$$\pi * (\sqrt{\frac{0.5 * A_{meat}}{\pi}} - d)^2 * (l - 2 * d) = 0.5 * A_{meat} * l - \frac{1}{X_{w,0}} * \Delta m * \frac{\rho_t}{{\rho_w}^2}$$

$$\rightarrow d^3 + d^2 * \left(-2 * \sqrt{\frac{0{,}5*A_{meat}}{\pi}} - \frac{l}{2}\right) + d * \left(\frac{0.5*A_{meat}}{\pi} + \sqrt{\frac{0{,}5*A_{meat}}{\pi}} * l\right) - \frac{1}{2*\pi} * \frac{1}{X_{w,0}} * \Delta m * \frac{\rho_t}{\rho_w^2} = 0 \quad \text{(Eq. 24)}$$

Additional Δm can be replaced by following equation:

$$\Delta m_{\%} = \frac{\Delta m}{m_0} \rightarrow \Delta m = \Delta m_{\%} * m_0 \quad \text{(Eq. 24*)}$$

(24*) in (24):

$$d^3 + d^2 * \left(-2 * \sqrt{\frac{0{,}5*A_{meat}}{\pi}} - \frac{l}{2}\right) + d * \left(\frac{0.5*A_{meat}}{\pi} + \sqrt{\frac{0{,}5*A_{meat}}{\pi}} * l\right) - \frac{1}{2*\pi} * \frac{1}{X_{w,0}} * \Delta m_{\%} * m_0 * \frac{\rho_t}{\rho_w^2} = 0$$

(Eq. 24**)

Eq. 24** is solved numerical.

μ is a diffusion resistance coefficient which is investigated experimentally.

p_i is the partial pressure of water at the applied temperature and $(p_i)_m$ is the logarithmical average of it at the inlet ($p_{i,in}$) and outlet ($p_{i,out}$) of the dryer. It is calculated as follows:

$$(p_i)_m = \frac{p_{i,out} - p_{i,in}}{\ln \frac{p_{i,out}}{p_{i,in}}} \quad \text{(Eq. 25)}$$

$$p_i = RH * p_\omega^\circ \quad \text{(Eq. 1)}$$

$$p_{i,in} = RH_{in} * p_\omega^\circ \quad \text{(Eq. 26)}$$

$$p_{i,out} = RH_{out} * p_\omega^\circ \quad \text{(Eq. 27)}$$

(26) & (27) in (25):

$$(p_i)_m = \frac{\overset{\circ}{p_\omega} * (RH_{out} - RH_{in})}{\ln \frac{RH_{out}}{RH_{in}}} \quad \text{(Eq. 28)}$$

p is the absolute surrounding pressure.

R is the special gas constant of water which can be calculated with the universal gas constant ($\tilde{R}$) and the molar mass of water (M_i):

$$R = \frac{\tilde{R}}{M_i} \quad \text{(Eq. 29)}$$

6.2. Hygroscopic Model

The model for hygroscopic substances is after /4/ and describes the drying rate as a function of an apparent or effective diffusion. Under constant external drying conditions (temperature, humidity, approach velocity) the drying rate can be described as:

$$\dot{m}_\omega = \pi^2 * \rho_{dm,s} * \frac{D_{eff}}{0.5 * l} * (X - X_e) \quad \text{(Eq. 30)}$$

$\rho_{dm,s}$ is the dry mass density including salt in the dry mass. It is calculated with the salt content regarding to dry mass, salt included ($c_{s,d,s}$), the density of salt (ρ_s) which is obtained from literature and the density of dry mass salt excluded (ρ_{dm}) which was already calculated in chapter 7.1 (Eq. 16):

$$\rho_{dm,s} = c_{s,dm,s} * \rho_s + \left(1 - c_{s,d,s}\right) * \rho_{dm} \quad \text{(Eq. 31)}$$

$c_{s,d,s}$ is calculated with the total salt content (c_s) and the water content with regard to total mass:

$$c_{s,dm,s} = c_{s,t} * \left(\frac{X_w}{1 - X_w} + 1\right) \quad \text{(Eq. 32)}$$

For calculation of $c_{s,d,s}$ see appendix A 1.1.

(32) in (31):

$$\rho_{dm,s} = c_{s,t} * \left(\frac{X_w}{1 - X_w} + 1\right) * \rho_s + \left(1 - c_{s,t} * \left(\frac{X_w}{1 - X_w} + 1\right)\right) * \rho_{dm} \quad \text{(Eq. 33)}$$

The effective diffusion coefficient (D_{eff}) is investigated experimentally.

l is like in 7.1 the characteristic length which corresponds to the thickness of the slice in this experiments and has to be measured.

X is the current water content with regard to dry mass and X_e the equilibrium water content (also with regard to dry mass) corresponding to the present air humidity and temperature. X is calculated with the loss of mass:

$$X = \frac{w(t)}{m_{dm,s}} = \frac{w_0 - \Delta m}{(1 - X_{w,0}) * m_0} = \frac{(X_{w,0} * m_0 - \Delta m)}{(1 - X_{w,0}) * m_0} \quad \text{(Eq. 34)}$$

X_e is a property of the substance and is determined in experiments.

7. Experimental Design, Measuring and Analysis Technology

The samples for the experiments were topside slices of pork with a mass between 50g and 200g.

7.1. Generation of Meat Slices with different Salt Content

To determine the influence of salt content on the drying behaviour meat slices were generated with different salt content at first. Thus, experiments were carried out on curing. Slices with salt content between 24% and 28% of dry mass were generated.
Three different approaches for curing are applied in the industrial manufacturing of dry-cured products: Dry curing (meat is rubbed with salt), wet curing (meat is immersed in brine) and fast curing (injection of brine in veins). In this project dry curing was applied as it is used in the industrial production of Notura and can be simply realized.
The slices were rubbed with nitrite salt (approx. 5g nitrite per 100g of meat), put in a plastic bag (each slice in one bag) and completely covered with sea salt. The bags were stored in a fridge at 4°C. To generate different salt contents the samples were stored for one hour, two hours and four hours. After that the salt was washed off with cold water and the slices were stored again for approx. one week thus the salt balanced within the slices.
The salt content was measured with a salt probe *(Fig. 4)* which was calibrated before. Therefore salted slices were measured with the probe which has values between 0 and 100. Afterwards the salt content was determined with a destructive method. A connection between the probe value and the salt content was identified (see appendix A 3.1).

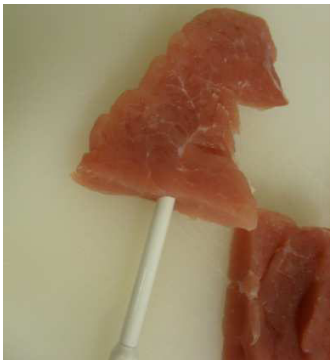

Figure 4: Measuring salt content with probe

7.2. Determination of Water Content

The water content (X) was determined by figuring out the amount of water in the substance. To approach this, a sample of the meat was heated in an oven at 104°C until the mass wasn't changing anymore. The loss of mass corresponds to the amount of water before drying, the remaining mass corresponds to the dry mass.

$$X = \frac{w}{m_{dm,s}} \qquad \text{(Eq. 34)}$$

The approach is in accordance with /2/.

The water content was measured for unsalted and different salted slices before drying to determine the initial water content which is necessary for calculating the sorption isotherms and also for calculating the present water content with loss of mass.

7.3. Measuring of Water Activity

The water activity (a_w) is the availability of "free" water in a substance. It corresponds to the relative humidity and reaches values between 0 (absolute dry) and 1 (condensing humidity). To get safe food the a_w has to be lower than 0.9 for dry-cured ham. The water activity was measured with the AquaLab (Decagon Devices Inc, Pullman, USA) *(Fig. 5)*.

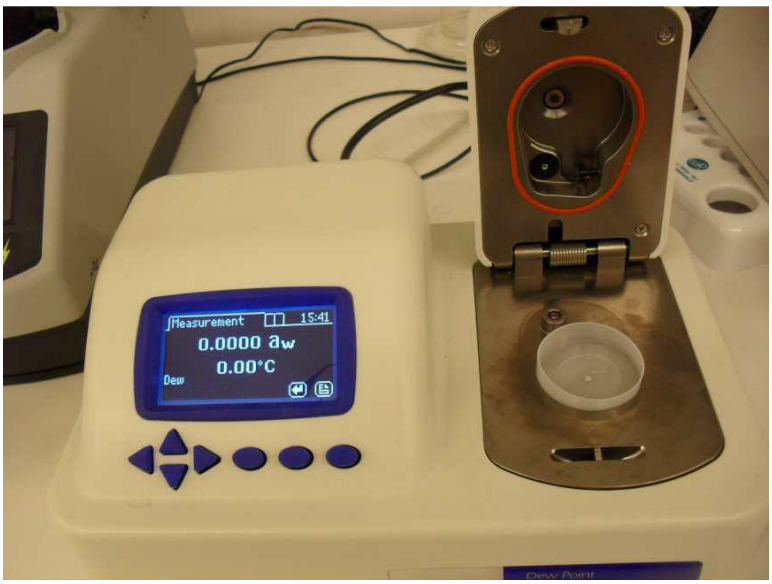

Figure 5: AquaLab

Before using the AquaLab a calibration was performed. Therefore two calibration standards in the range of the a_w which was going to be measured were chosen. The standard values in dependency of the measured values were shown in a diagram and the best fit line was determined. With this best fit line the measured values were corrected (see appendix A 3.2).

7.4. Determination of the Sorption Isotherms

Sorption isotherms show the equilibrium water content of a substance dependent on the water activity or relative humidiy at a certain temperature. To obtain this points the substance was subjected to a relative humidity and temperature until the water content wasn't changing anymore. This approach was repeated at various relative humidities at the same temperature.
Analyzes were done with the water sorption analyser CISorp (CI Precision, Salisbury, United Kingdom*) (Fig. 6).*

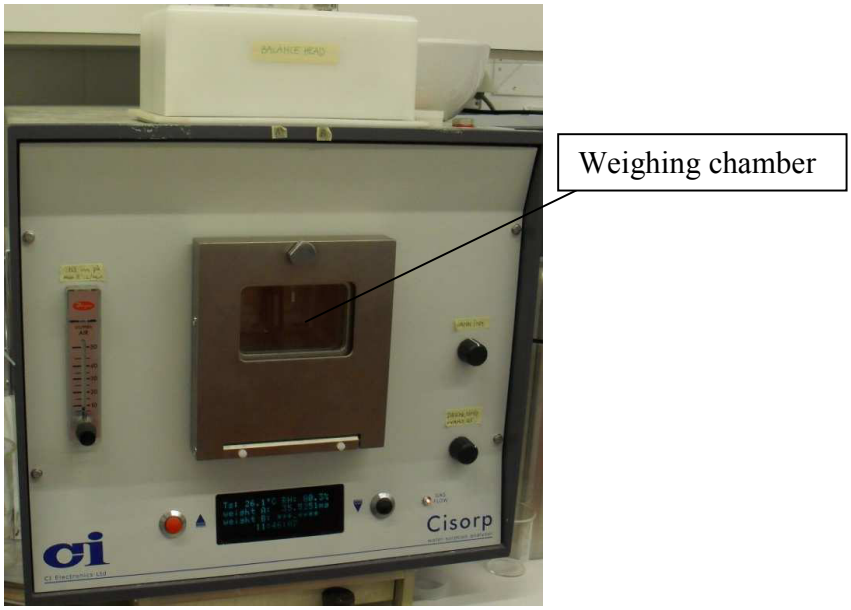

Figure 6: CISorp

A sample was put in the microbalance which is installed in a weighing chamber. In this chamber the relative humidity and the temperature were set. The weight of the sample was checked and saved continuously as well as the relative humidity and temperature. When the mass wasn't changing anymore the next lower relative humidity was set and the process was repeated until all points needed for the experiments were determined. With the initial mass, the loss of mass until equilibrium and the inital water content the equilibrium water content was calculated (Eq. 34, modified):

$$X_e = \frac{w_e}{m_{dm,s}} = \frac{w_0 - \Delta m_e}{(1 - X_{w,0}) * m_0} = \frac{(X_{w,0} * m_0 - \Delta m_e)}{(1 - X_{w,0}) * m_0}$$

7.5. Drying Experiments

Purpose of the drying experiments was to determine the influence of temperature, relative humidity and salt content on the drying behaviour. Therefore the reduction of mass was measured with time under different conditions. Slices with different salt content were hanged in the drying chamber *(Fig. 7)* where relative humidity, temperature and air velocity was set. The setted values are in accordance with the values used in industrial production of Notura in Tynset.

Figure 7: Arrangement of slices in chamber

For all experiments the air velocity was the same. In the first part of the experiments the temperature was always the same and the relative humidity variated in each experiment. In the second part the relative humidity was always the same and the temperature variated (Settings: Tab. 1).

Experiment	Temparature	Relative Humidity	Air velocity
1.1	13 °C	60%	0.4 m/s
1.2, 2.2	13 °C	68%	0.4 m/s
1.3	13 °C	80%	0.4 m/s
2.1	10 °C	68%	0.4 m/s
2.3	16 °C	68%	0.4 m/s

Table 1: Experiment settings

Additional, one experiment was carried out at 13°C with alternating relative humidity between 60% and 80% during one drying process.

In each experiment one of the slices was measured with an online measuring balance which saved the current mass every five minutes. The slice was hanged with a wire on the bottom of the balance. As there was just one of this balances available the mass of the other slices were checked manualy outside the drying chamber. No more measurements than necessary were done to avoid huge effects on the set temperature and air humidity.
The drying process in the beginning was faster. Thus, the first days the mass was checked two or three times a day and later just once a day. The experiments were finished when the average of water content reached the water content of industrial produced ham. The water content was calculated with the loss of mass, initial mass and initial water content (Eq. 34).
(Measured values: see A 4.5)

To determine the factors μ of the non-hygroscopic model and D_{eff} of the hygroscopic the drying rate ($\dot{m}_\omega$) was programmed in an excel sheet. For defined time steps ($\Delta t = 100s$) $\dot{m}_\omega$ was considered as constant. The factors were set that the curve of $\Delta m_\%$ fitted best. For calculation of $X\,(t)$ with programmed $\dot{m}_\omega$ see appendix A 2.6.

7.6. Used Devices

Device	Experiment	Accuracy	Calibration
Balance	7.1	n.a.	no
Salt probe	7.1	n.a.	yes
Drying oven VWR Dry-Line	7.2	$\pm\,0.4\,°C$	no
Balance	7.2	n.a.	no
AquaLab Dew Point Water Activity Meter 4TEV	7.3	$\pm 0.003 a_w$	yes
Cisorp Water Sorption Analyser	7.4	$\pm 1.0 \mu g$	no
Balance	7.5	n.a.	no
Drying chamber	7.5	n.a.	no

Table 2: List of used devices

8. Results and Discussion

8.1. Comparison of Models

In Fig. 8 the water content (X) as a function of time (t) for the non-hygroscopic and the hygroscopic model is shown exemplarily for the experiment at temperature $T = 13°C$; relative humidity $RH = 68\%$ and with high salted slices. In Fig. 9 the same is done for the experiment at temperature $T = 13°C$; relative humidity $RH = 80\%$ and with unsalted slices.

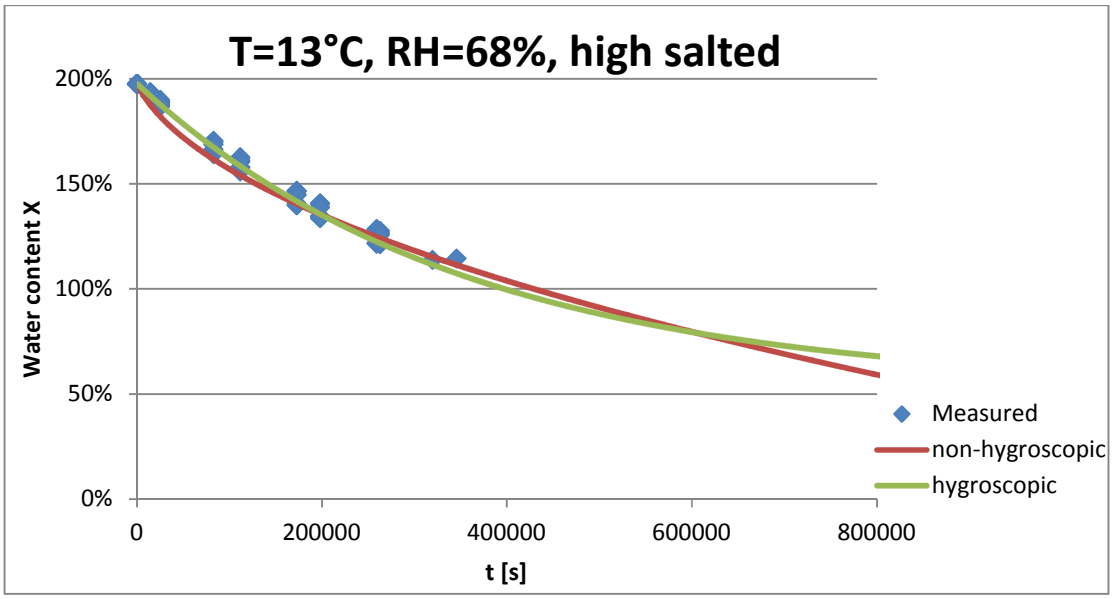

Figure 8: X(t) measured and of non-hygroscopic and hygroscopic model (high salted pork)

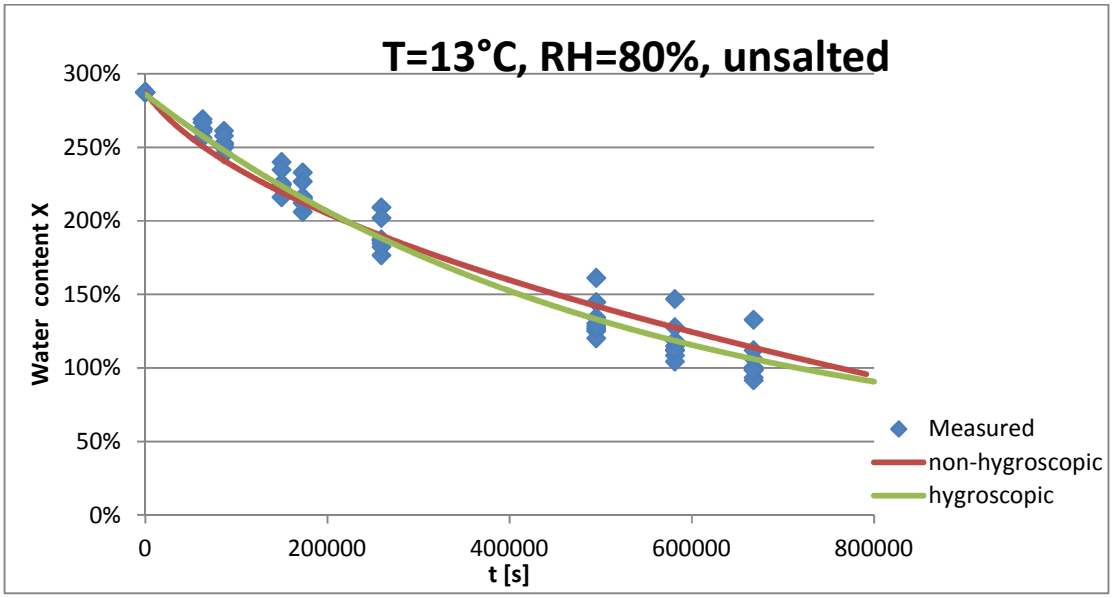

Figure 9: X(t) measured and of non-hygroscopic and hygroscopic model (unsalted pork)

The hygroscopic model fits better to the course of X. Especially, in the beginning the drying rate is overestimated by the non-hygroscopic model. In Tab. 3 and Tab. 4 the variances of the models (as percentage of the measured value) at the measured times are listed. In the experiment at $T = 13°C, RH = 80\%$ with unsalted slices the difference is significant. In average the variance of the hygroscopic model is 0.8% whereas the variance of the non-hygroscopic model is 4.3%. Furthermore the maximal variance of the hygroscopic model is 1.8%, of the non-hygroscopic model it is 9.2%.

Time [s]	Average	Model hy.	Variance	Model non-hy.	Variance
0	197.6%	197.6%	0.0%	197.6%	0.0%
14400	192.7%	191.8%	0.5%	186.0%	3.5%
25200	188.6%	187.7%	0.5%	180.3%	4.4%
82800	168.2%	167.4%	0.5%	159.9%	4.9%
111600	160.0%	158.5%	0.9%	152.5%	4.7%
172800	143.8%	141.7%	1.5%	139.2%	3.2%
198000	137.9%	135.6%	1.7%	132.3%	4.1%
259200	125.4%	122.5%	2.3%	124.0%	1.1%
Average			**1.0%**		**3.2%**
Max			**2.3%**		**4.9%**

Table 3: Variance of model values from average measured values (T=13°C; RH=68%; high salted)

Time [s]	Average	Model hy.	Variance	Model non-hy.	Variance
0	287.6%	287.6%	0.0%	287.6%	0.0%
63000	263.2%	258.9%	1.6%	250.8%	4.7%
86400	252.9%	249.1%	1.5%	241.1%	4.7%
149700	226.7%	224.7%	0.9%	219.5%	3.2%
172800	217.7%	216.5%	0.6%	212.6%	2.3%
259200	189.6%	188.9%	0.4%	190.1%	0.3%
495000	134.0%	133.5%	0.4%	142.2%	6.1%
581400	118.3%	118.7%	0.3%	127.6%	7.9%
667800	104.4%	106.3%	1.8%	114.0%	9.2%
Average			**0.8%**		**4.3%**
Max			**1.8%**		**9.2%**

Table 4: Variance of model values from average measured values (T=13°C; RH=80%; unsalted)

Fig. 10 and Fig. 11 show the drying rates ($\dot{m}_\omega$) (for the same experiments as in Fig. 8 and Fig. 9) as a function of t for both models. The measured values were obtained by a data saving balance.

$\dot{m}_\omega$ of the non-hygroscopic model is high in the beginning and decreases fast and the decreasing becomes slower with time whereas $\dot{m}_\omega$ of the hygroscopic model is lower at the beginning but decreases slower with time.

Compared with the values of the online measurement the non-hygroscopic model describes $\dot{m}_\omega$ too fast at the beginning. The hygroscopic model fits better however it describes the drying rate of the measurement a little bit too low. This is due to the fact that the model was applied on the average of all measurements. As there is a variance of salt content for the samples as well as the composition (for example of fat and muscles) of each sample varies the deviation of the measured sample is in an acceptable range. However, it can be clearly seen that the shape of the curve from the hygroscopic model fits better to the drying rate obtained by measurement.

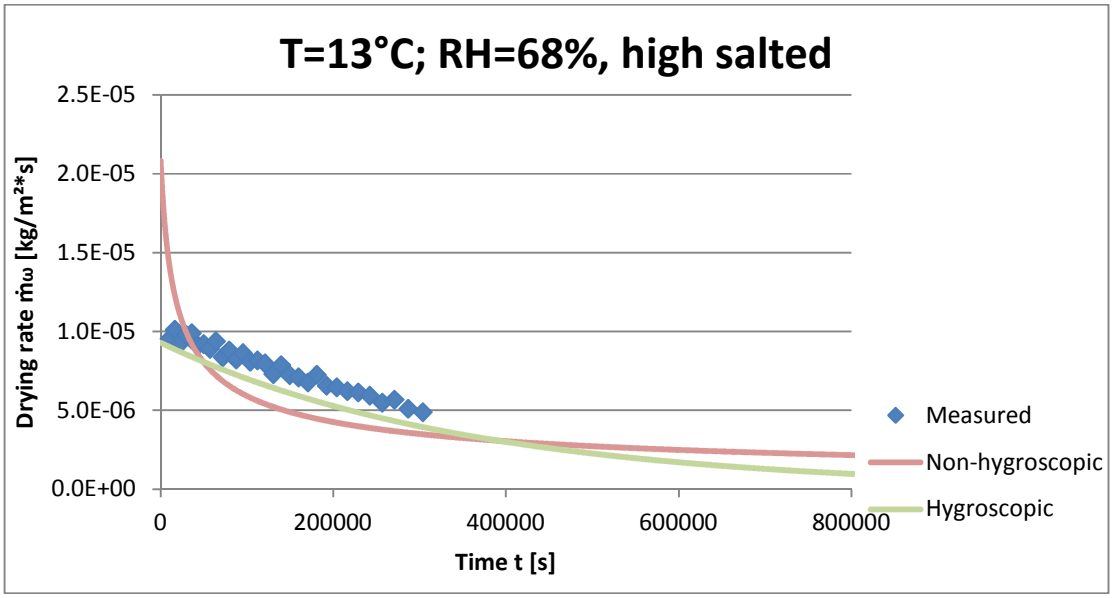

Figure 10: Drying rate measured and of non-hygroscopic and hygroscopic model (high salted pork)

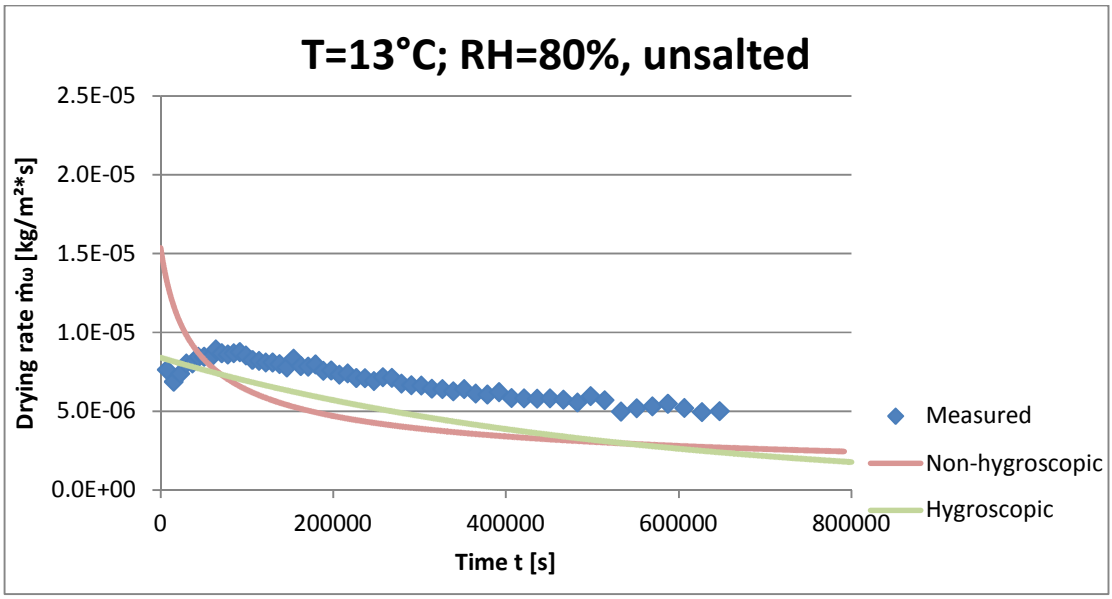

Figure 11: Drying rate measured and of non-hygroscopic and hygroscopic model (unsalted pork)

For further investigations just the hygroscopic model was considered. The influence of humidity (RH), temperature (T) and salt content ($c_{s,dm,s}$) were studied.

8.1. Effective Diffusion Coefficient

The effective diffusion coefficient (D_{eff}) was determined semi-empirically by matching the course of the model on the measured values (regression analyse). D_{eff} is dependent on RH and $c_{s,dm,s}$. For various RH the factors differ the most *(Fig. 18)*, for various T there is not a significant difference *(Fig. 20)*. A linear connection is recognizable between D_{eff} and RH as well as for D_{eff} and $c_{s,dm,s}$ *(Fig. 19)*.

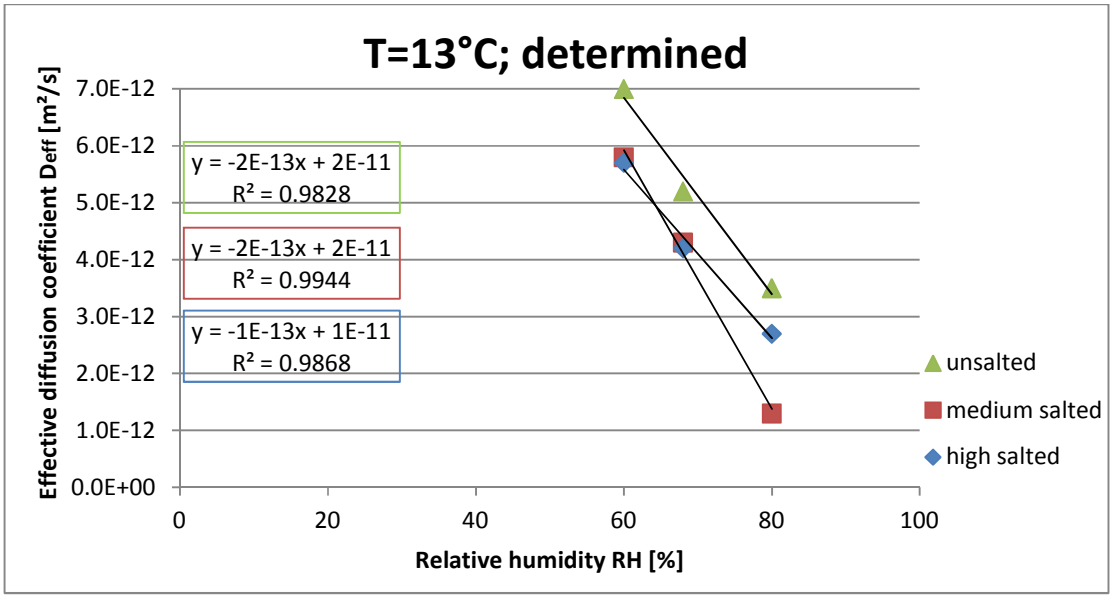

Figure 12: Influence of RH on effective diffusion coefficient at various salt contents

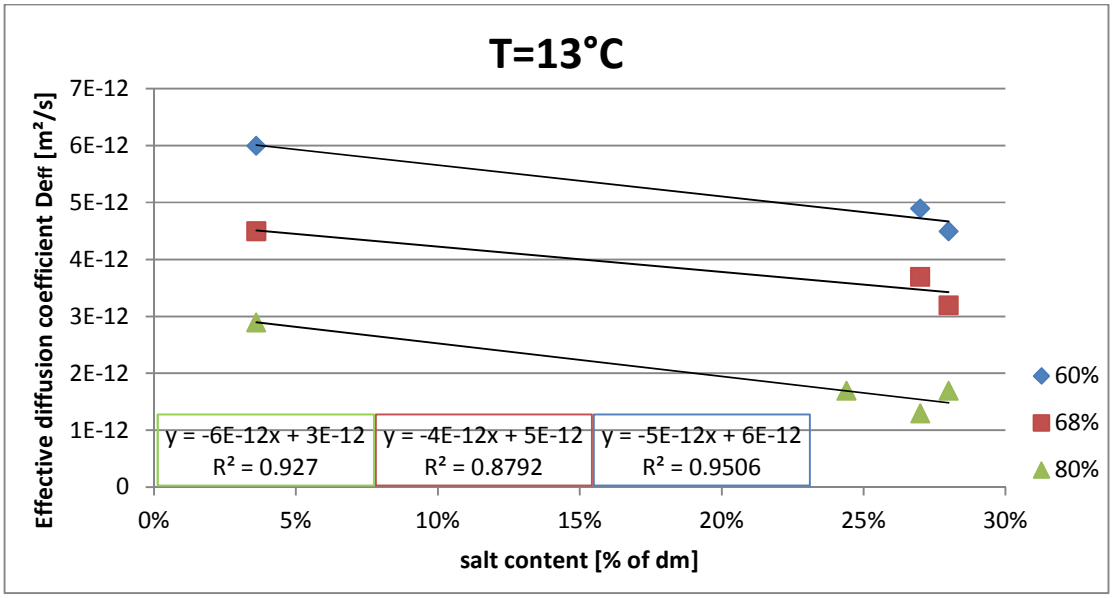

Figure 13: Influence of salt content on effective diffusion coefficient at various relative humidity

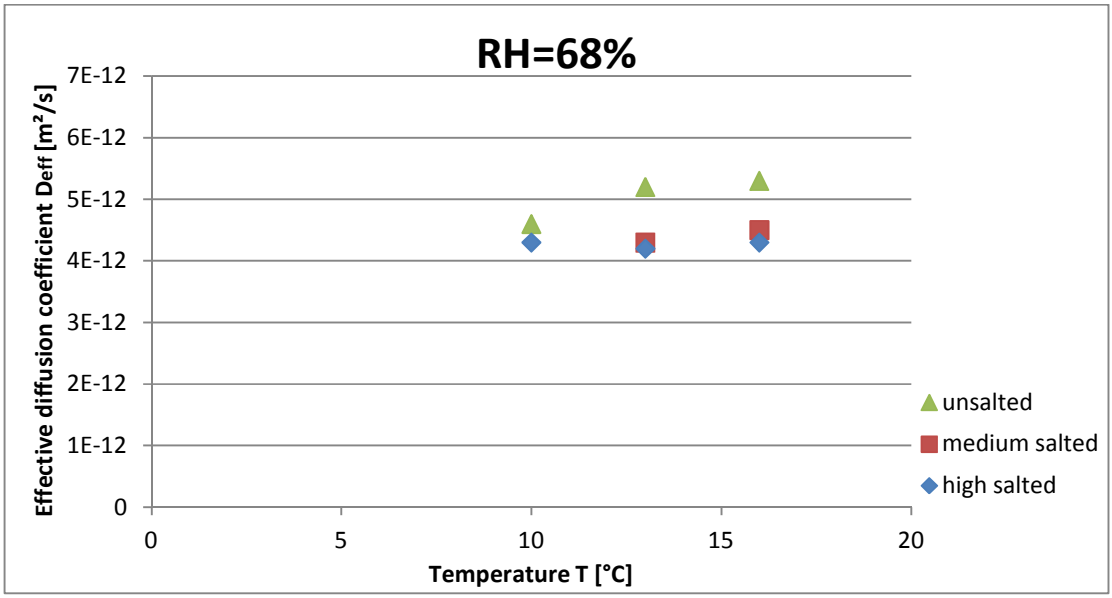

Figure 14: Influence of temperature on effective diffusion coefficient at various salt contents

Comparing D_{eff} of high salted samples at varying RH *(Fig. 18)* as well as D_{eff} at $RH = 80\%$ at varying $c_{s,dm,s}$ *(Fig.19)*, D_{eff} of high salted pork at 80% was determined to high.

A new diffusion coefficient of high salted pork at 80% has been adjusted *(Fig. 21 and Fig. 22)*. With this new value the equilibrium water content X_e was determined empirically so that the model was still fitting.

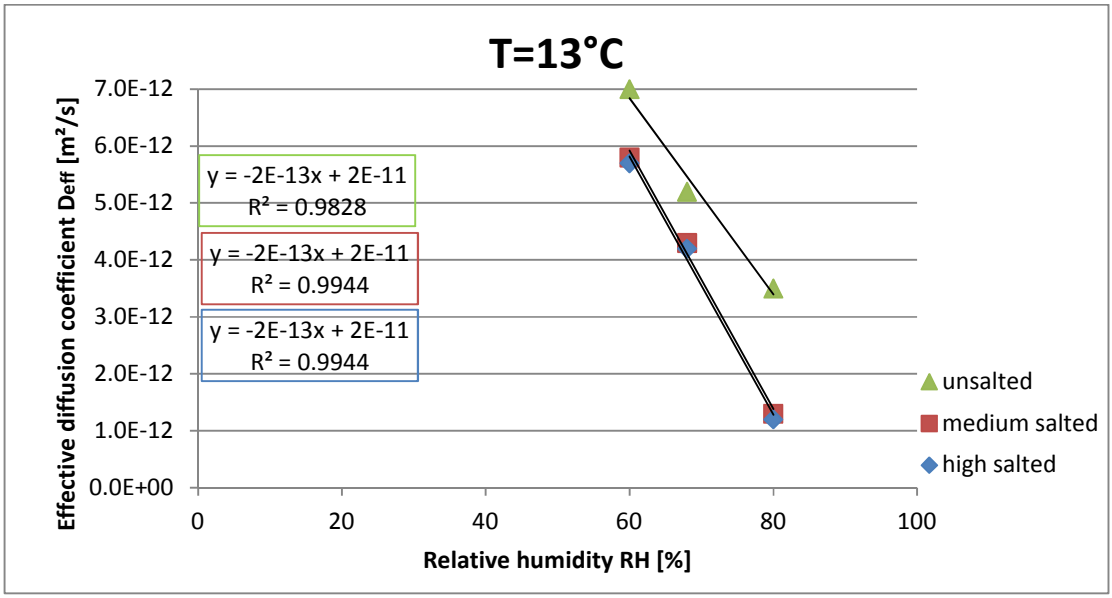

Figure 15: Influence of relative humidity on effective diffusion coefficient at various salt contents with adjusted Deff

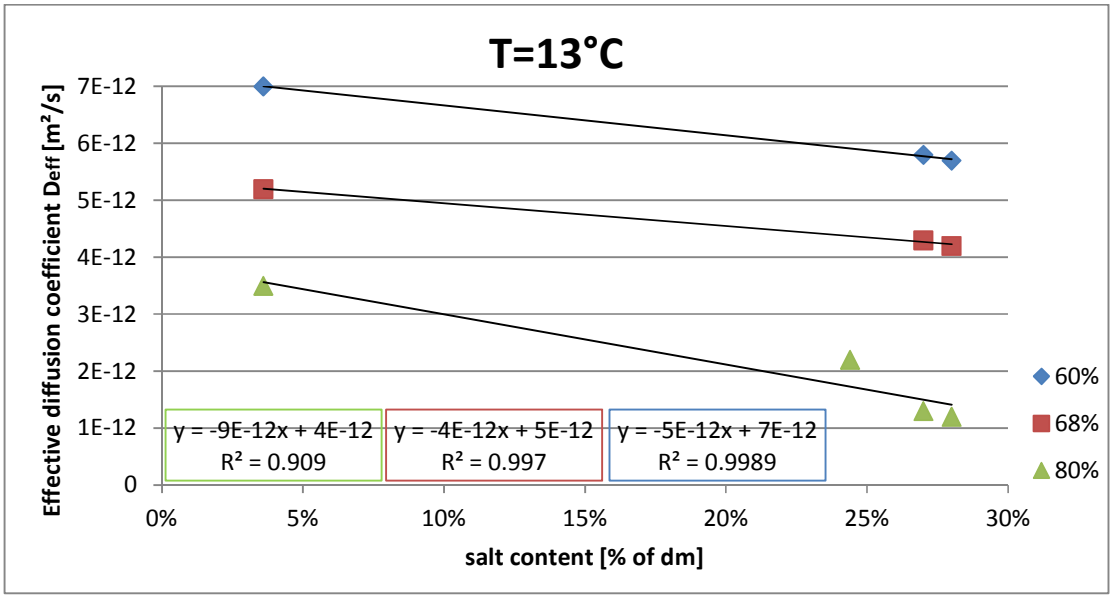

Figure 16: Influence of salt content on effective diffusion coefficient at various relative humidity with adjusted Deff

D_{eff} of high salted pork at 80% has been adjusted from $2.7e^{-12}\frac{m^2}{s}$ to $1.2e^{-12}\frac{m^2}{s}$. Therefore X_e decreases from 120% to 70%.

8.2. Influence of Relative Humidity

In Fig.12 the curves of the drying rate ($\dot{m}_\omega(X)$) for different relative humidity (RH) are clearly apart from each other. This shows that RH has a strong influence on $\dot{m}_\omega$ and thus on the course of $X(t)$ *(Fig. 13)*.

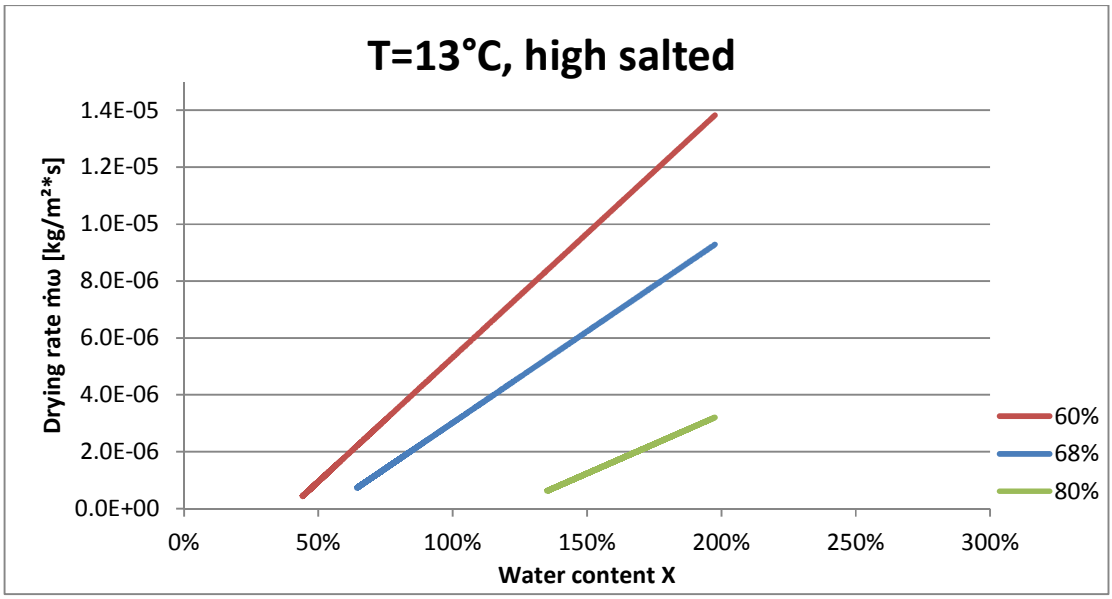

Figure 17: Influence of relative humidity on drying rate (high salted pork)

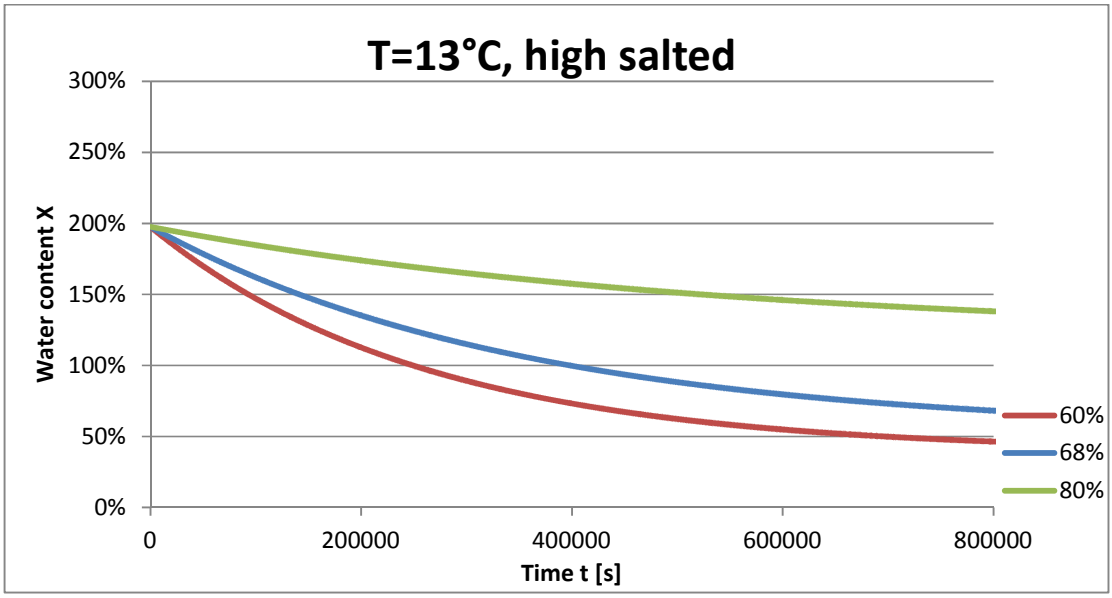

Figure 18: Influence of relative humidity on X(t) (high salted pork)

8.3. Influence of Temperature

The curves of $\dot{m}_\omega(X)$ *(Fig. 14)* and also of $X(t)$ *(Fig. 15)* are close together so that a difference is not recognizable. Thus, temperature (T) has no influence in the applied temperature range.

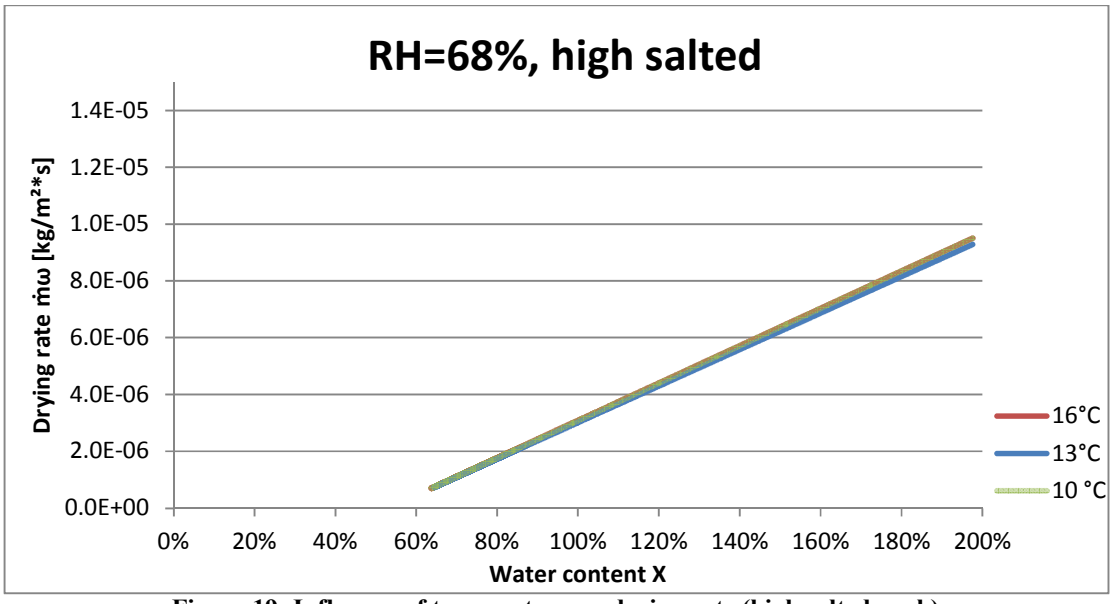

Figure 19: Influence of temperature on drying rate (high salted pork)

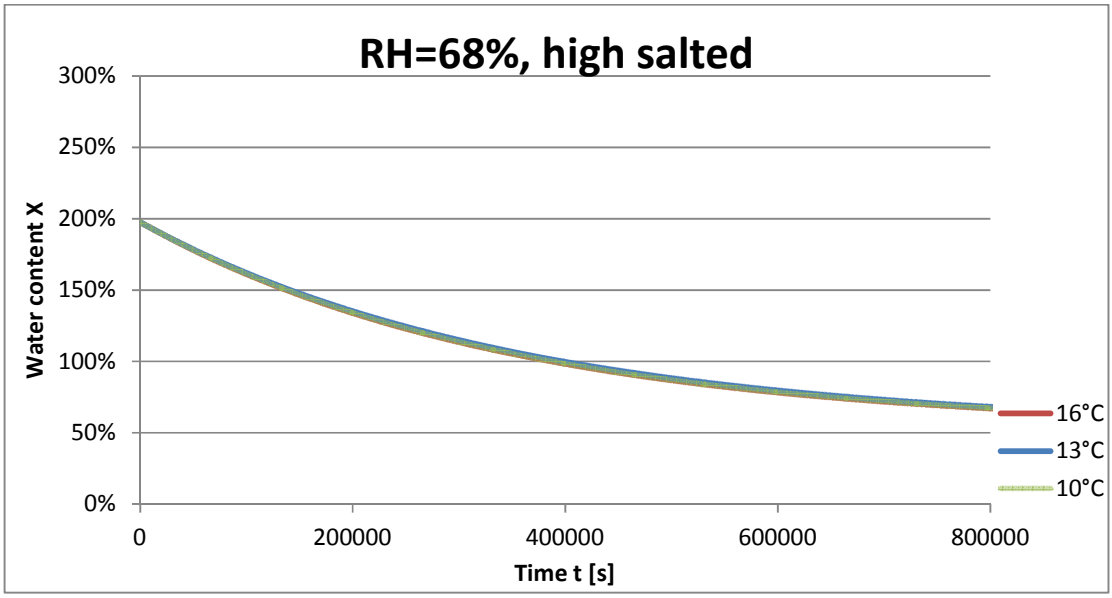

Figure 20: Influence of temperature on X(t) (high salted pork)

8.4. Influence of Salt Content

Comparing the curves of the drying rate for unsalted slices and slices with different salt content, Fig. 16 shows that the lower the salt content the higher is $\dot{m}_{\omega}(X)$.

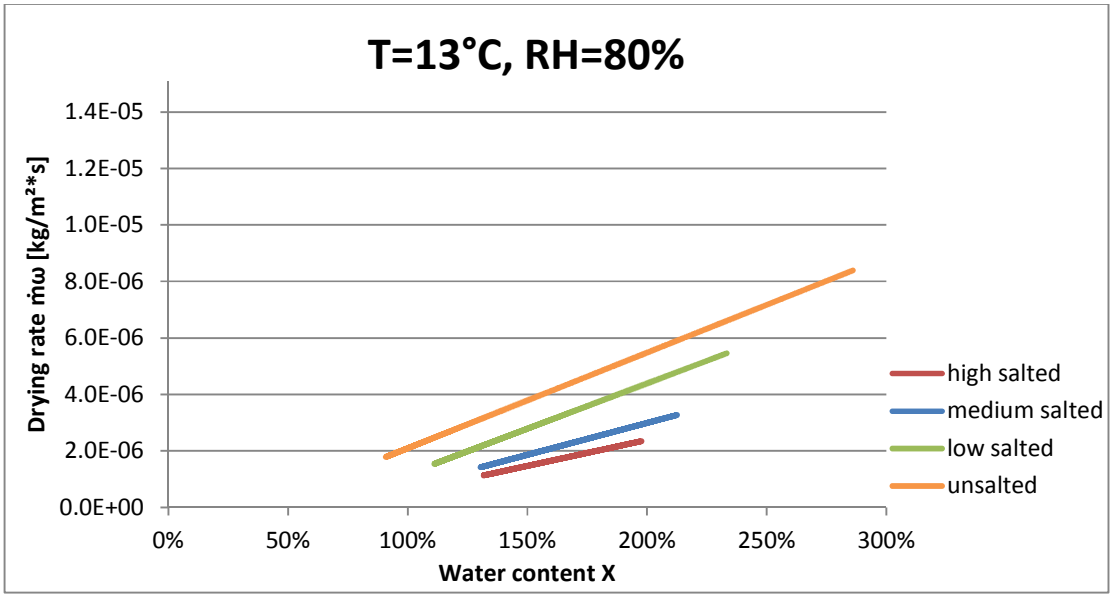

Figure 21: Influence of salt content on drying rate

Fig. 17 shows the decreasing of the water content with time. The higher the salt content the lower the initial water content (X_0). Therefore high salted pork has the lowest X at beginning, unsalted pork the highest. As the drying rate is higher for lower salt content X of unsalted pork is reduced the fastest and X of high salted pork the slowest. Thus there are intersection points in Fig. 17 where the $X(t)$-curves of different salted pork cut each other. After certain time high salted pork has highest X, unsalted pork lowest.

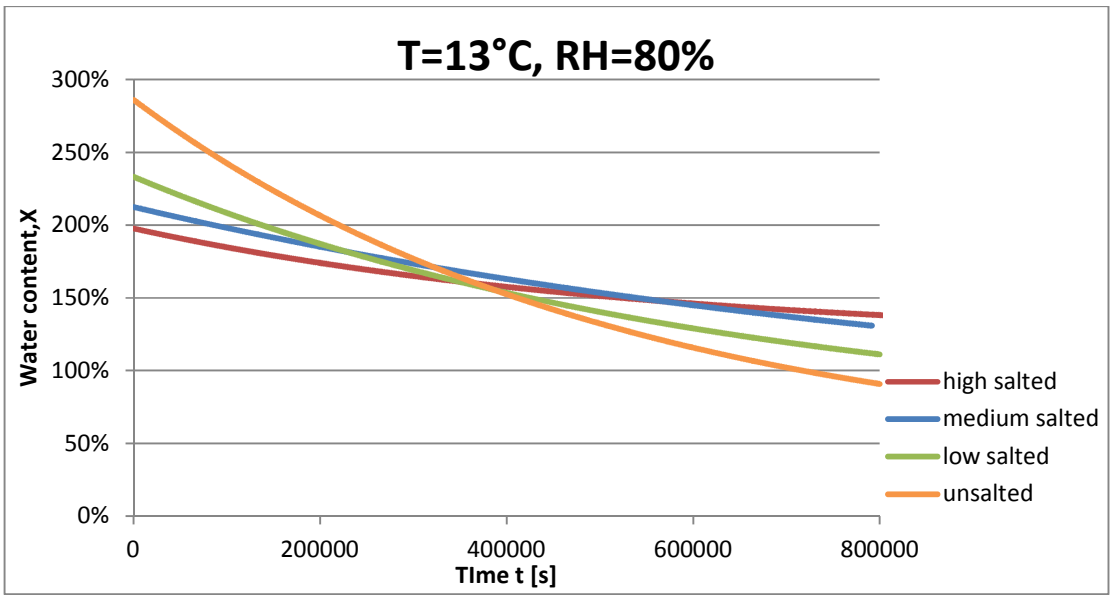

Figure 22: Influence of salt content on X(t)

8.5. Verifying of Model for Alternating Relative Humidity

To apply the model on alternating relative humidity the linear connection between D_{eff} and RH was used. Furthermore the connection between X_e and RH was simplified as linear. Fig. 24 and Fig. 25 show the measured values and the hygroscopic model for high and medium salted slices. In Tab. 3 and Tab. 4 the variances of the models (as percentage of the measured value) at the measured times are listed. In the beginning the model fits almost perfectly. With time the variance decreases but with a maximum of 7.2% for high salted slices and 8.7% for low salted slices. This can be explained with the thermal inertia of the drying product. Changes in temperature and humidity will in real physical systems have time-delayed effect on the drying rate. This is not considered by the model. However, as it can be seen in Fig. 24 the moisture content of the samples can be predicted with the semi-empirical relations from the hygroscopic model quite well.

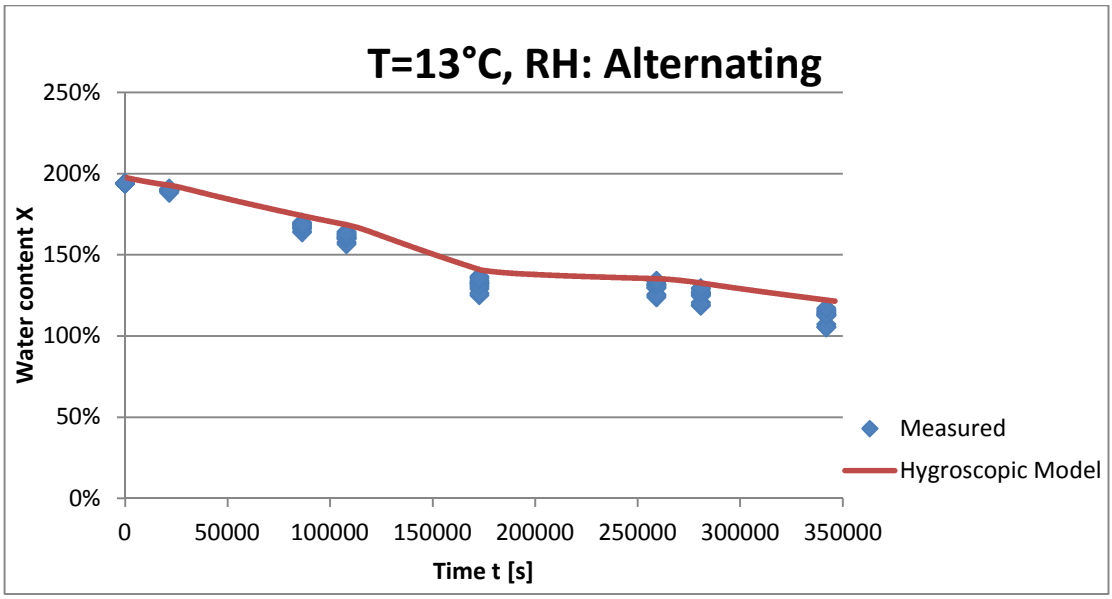

Figure 23: Measured values and hygroscopic model at alternating relative humidity (high salted pork)

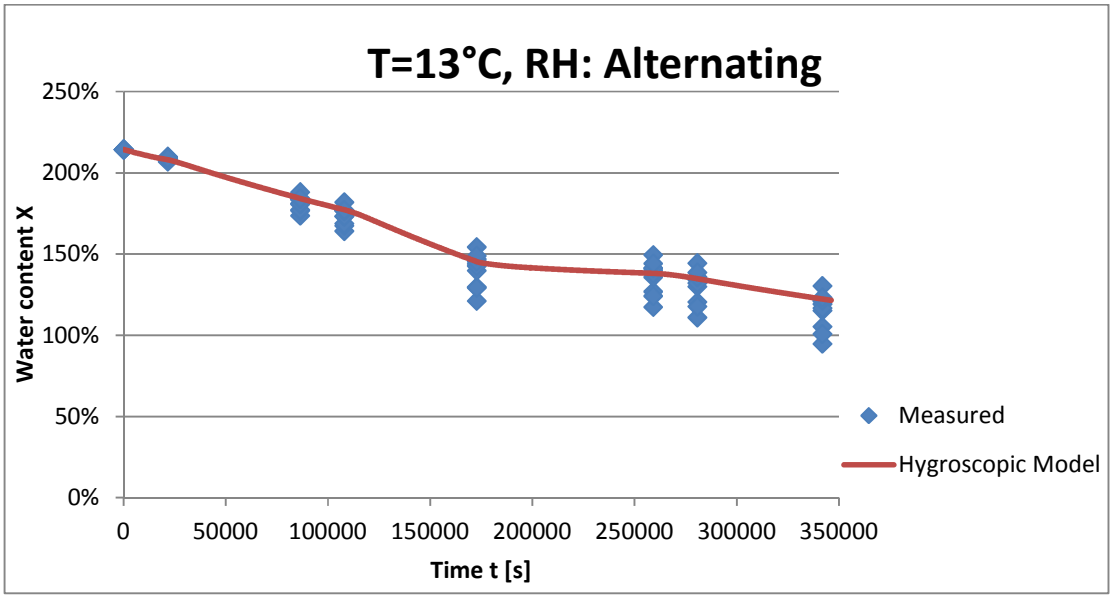

Figure 24: : Measured values and hygroscopic model at alternating relative humidity (unsalted pork)

Time [s]	Average	Model hy.	Variance
0	197.6%	197.6%	0.0%
21600	193.2%	192.8%	0.2%
86400	170.5%	174.0%	1.5%
108000	164.0%	168.5%	2.1%
172800	134.4%	141.0%	3.5%
259200	132.6%	135.3%	2.0%
280800	127.6%	132.7%	4.3%
342000	114.7%	122.2%	7.2%
Average			**2.6%**
Max			**7.2%**

Table 5: Variance of model values from average measured values (high salted pork)

Time [s]	Average	Model hy.	Variance
0	214.5%	214.5%	0.0%
21600	208.7%	208.3%	0.2%
86400	181.4%	185.1%	1.6%
108000	173.7%	178.3%	2.1%
172800	140.3%	146.5%	3.3%
259200	135.9%	139.3%	2.5%
280800	130.1%	136.0%	5.0%
342000	114.9%	124.0%	8.7%
Average			**2.9%**
Max			**8.7%**

Table 6: Variance of model values from average measured values (unsalted pork)

9. Summary of the Results

- The hygroscopic model was applied on the drying process

$$\dot{m}_{\omega} = \pi^2 * \rho_{dm,s} * \frac{D_{eff}}{0.5*l} * (X - X_e) \qquad \text{(Eq. 30)}$$

  The highest variance of this model from the average of the measured values is 8.7%.

- Effective diffusion coefficients:

$T\ [°C]$	RH	$D_{eff}\ [\frac{m^2}{s}]$
10	68%	$4.6 * 10^{-12}$
13	60%	$7.0 * 10^{-12}$
13	68%	$5.2 * 10^{-12}$
13	80%	$3.5 * 10^{-12}$
16	68%	$5.3 * 10^{-12}$

Table 7: Effective diffusion coefficient of unsalted meat for different conditions

$T\ [°C]$	RH	$D_{eff}\ [\frac{m^2}{s}]$
10	68%	$3.5 * 10^{-12}$
13	80%	$2.2 * 10^{-12}$

Table 8: Effective diffusion coefficient of low salted meat for different conditions

$T\ [°C]$	RH	$D_{eff}\ [\frac{m^2}{s}]$
13	60%	$5.8 * 10^{-12}$
13	68%	$4.3 * 10^{-12}$
13	80%	$1.5 * 10^{-12}$
16	68%	$4.5 * 10^{-12}$

Figure 25: Effective diffusion coefficient of medium salted meat for different conditions

$T\ [°C]$	RH	$D_{eff}\ [\frac{m^2}{s}]$
10	68%	$4.3 * 10^{-12}$
13	60%	$5.7 * 10^{-12}$
13	68%	$4.2 * 10^{-12}$
13	80%	$1.2 * 10^{-12}$
16	68%	$4.3 * 10^{-12}$

Figure 26: Effective diffusion coefficient of high salted meat for different conditions

- Salt content end equilibrium water content:

Sample	$c_{s,dm}$	$X_e(60\%)$	$X_e(68\%)$	$X_e(80\%)$
Unsalted	3.6%	23%	27%	38%
Low salted	24.4%	27%	43%	63%
Medium salted	26.6%	38%	57%	67%
High salted	28.4%	39%	53%	70%

Figure 27: Xe at 20°C with adjusted value of high salted meat at 80% RH

10. Conclusions and Suggestions for further Work

The drying behaviour of small slices of pork with different salt content was investigated at various relative humidity and temperature. For describing the drying rate a non-hygroscopic model and a hygroscopic Model have been evaluated and compared. The hygroscopic model resulted in a higher model accuracy. With this model even the drying behaviour at alternating relative humidity was described well, when the semi-empirical relations for the influence of temperature and humidity was considered.
A linear connection between relative humidity and effective diffusion coefficient as well as between salt content and effective diffusion coefficient was found. Temperature has no influence on the effective diffusion coefficient in the applied temperature range. This is an important finding for industrial production, where normally the focus is on the temperature during production and as quality controlling parameter. However, the humidity in the production as a much higher influence on the drying rate, and therefore also product quality. It can be expected that a minor temperature variation during production will not influence significantly the quality, but a minor variation in humidity will give a significant influence. Control system in the industry should therefore focus much more on maintaining the correct humidity.

By upscaling the obtained semi-empirical hygroscopic model, the drying process in industrial production of ham can be described in process simulations. However, upscaling of these kind of models need to be done under careful consideration of the boundary conditions. This aspect should be investigated further.

In this project the used sorption isotherms have been determined at approx. 20°C since the used device was not able to cool down. As there could be a significant variance of the equilibrium water content at 20°C compared to 10°C, 13°C and 16°C, isotherms at this temperatures should be determined. Therefore the used device can be installed in a room where the temperature is adjustable or it has to be used another device.

It is also important to know how the drying rate influences the properties of the meat. If the drying is too fast the surface layer is drying out, if it is to slow the meat could be contaminated by microorganism.

With the knowledge of the drying behaviour, the transferring on industrial scale and the influence to the properties the industrial drying process of ham can be

optimized in time- and energy-consumption while ensuring the quality of the product.

11. List of Literature

/1/ Baehr, H. D., Stephan, K., 2010, Wärme- und Stoffübertragung, Springer Berlin Heidelberg.

/2/ CODEX STAN 167-1989 (International Food Standard)

/3/ Gnielinski, V., Mersmann, A., Thurner, F.: "Verdampfung, Kristallisation, Trocknung" Vieweg Verlag

/4/ Mersmann, A., Kind, M., Stichlmair, J., 2005, Thermische Verfahrenstechnik: Grundlagen und Methoden, *in* Springer, ed., Berlin.

/5/ http://www.cambridge.org/us/engineering/author/nellisandklein/downloads/examples/EXAMPLE_9.2-1.pdf (11.02.2014)

/6/ http://go.key.net/rs/key/images/Bulk%20Density%20Averages%20100630.pdf (11.02.2014)

/7/ http://physics.nist.gov/cgi-bin/cuu/Value?r (11.02.2014)

/8/ http://www.seilnacht.com/Chemie/ch_nacl.htm (11.02.2014)

Appendix

A 1. Values used from Literature

A 1.1 Diffusion Coefficient Water in Air

Out of /5/

$$D_G = -2{,}775 * 10^{-6}\frac{m^2}{s} + 4{,}479 * 10^{-8}\frac{m^2}{s*K} * T + 1{,}656 * 10^{-10}\frac{m^2}{s*K^2} * T^2$$

$$D_G(283{,}15K) = 2{,}32 * 10^{-5}\frac{m^2}{s}$$
$$D_G(286{,}15K) = 2{,}36 * 10^{-5}\frac{m^2}{s}$$
$$D_G(289{,}15K) = 2{,}40 * 10^{-5}\frac{m^2}{s}$$

A 1.2 Kinematic Viscosity of Air

Out of /1/: Interpolation of values in Tab. B1

$$\upsilon_a\ (13°C) = 146{,}8 * 10^{-7}\frac{m^2}{s}$$
$$\upsilon_a\ (10°C) = 144{,}1 * 10^{-7}\frac{m^2}{s}$$
$$\upsilon_a\ (16°C) = 149{,}6 * 10^{-7}\frac{m^2}{s}$$

A 1.3 Density of Air

Out of /1/: Interpolation of values in Tab. B1

$$\rho_a(10°C) = 1{,}23\frac{kg}{m^3}$$
$$\rho_a(13°C) = 1{,}22\frac{kg}{m^3}$$
$$\rho_a(16°C) = 1{,}21\frac{kg}{m^3}$$

A 1.4 Density of Water

Out of /1/: Tab. B2

$$\rho_w = 1000\frac{kg}{m^3}$$

A 1.5 Total Density of Unsalted Meat

Out of /6/: Bulk density of ground meat

$\rho_{t,0,us} = 881 \frac{kg}{m^3}$

A 1.6 Universal Gas Constant

Out of /7/:

$\tilde{R} = 8{,}314 \ \frac{kJ}{kmol*K}$

A 1.7 Molar Mass of Water

Values out of Periodic Table of the Elements:

$M_H = 1 \frac{kg}{kmol}$
$M_O = 16 \frac{kg}{kmol}$
$M_{water}(H_2O) = 2 * M_H + M_O = 2 * 1 \frac{kg}{kmol} + 16 \frac{kg}{kmol} = 18 \frac{kg}{kmol}$

A 1.8 Density of Salt

Out of /8/:

$\rho_s = 2170 \frac{kg}{m^3}$

A 2. Calculations

A 2.1 Converse of salt content with regard to overall mass in salt content with regard to dry mass, salt included

$$c_{s,dm,s} = \frac{s}{m_{dm,s}} \quad \text{(Eq. A 2.1)}$$

$$s = c_{s,t}(t) * m(t) \quad \text{(Eq. A 2.2)}$$

$$m(t) = w(t) + m_{dm,s} \quad \text{(Eq. A 2.3)}$$

$$w(t) = X(t) * m_{dm,s} \quad \text{(Eq. A 2.4)}$$

$$X(t) = \frac{X_w(t)}{1-X_w(t)} \quad \text{(Eq. A 2.5)}$$

(Eq. A 2.3), (Eq. A 2.4), and (Eq. A 2.5) in (Eq. A 2.2):

$$s = c_{s,t}(t) * m_{dm,s} * \left(\frac{X_w(t)}{1-X_w(t)} + 1\right) \quad \text{(Eq. A 2.6)}$$

(Eq. A 2.6) in (Eq. A 2.1):

$$c_{s,dm,s} = c_{s,t}(t) * \left(\frac{X_w(t)}{1-X_w(t)} + 1\right) = c_{s,t}(t) * \left(\frac{1}{1-X_w(t)}\right) \quad \text{(Eq. A 2.7)}$$

A 2.2 Converse of salt content with regard to dry mass, salt excluded in salt content with regard to overall mass

$$c_{s,t}(t) = \frac{s(t)}{m(t)} \quad \text{(Eq. A 2.7)}$$

$$c_{s,d}(t) = \frac{s(t)}{m_{dm}} \rightarrow s(t) = c_{s,d}(t) * m_{dm} \quad \text{(Eq. A 2.9)}$$

$$m(t) = s(t) + w(t) + m_{dm}$$

$$\rightarrow m_{dm} = m(t) - (s(t) + w(t)) \quad \text{(Eq. A 2.10)}$$

$$w(t) = X_w(t) * m(t) \quad \text{(Eq. A 2.11)}$$

(Eq. A 2.9) and (Eq. A 2.11) in (Eq. A 2.10):

$$m_{dm} = m(t) - (c_{s,d}(t) * m_{dm} + X_w(t) * m(t))$$

$$\rightarrow m_{dm} = m(t) * \frac{1-X_W(t)}{1+c_{s,d}(t)} \quad \text{(Eq. A 2.12)}$$

(Eq. A 2.12) in (Eq. A 2.9):

$$s(t) = c_{s,d}(t) * m(t) * \frac{1-X_W(t)}{1+c_{s,d}(t)} = m(t) * (1 - X_w(t)) * \frac{c_{s,d}(t)}{1+c_{s,d}(t)} \quad \text{(Eq. A 2.13)}$$

(A 2.13) in (A 2.7)

$$c_{s,t}(t) = \frac{1}{m(t)} * m(t) * \left(1 - X_w(t)\right) * \frac{c_{s,d}(t)}{1+c_{s,d}(t)} = \left(1 - X_w(t)\right) * \frac{c_{s,d}(t)}{1+c_{s,d}(t)} \quad \text{(Eq. A 2.14)}$$

A 2.3 Mass Transfer Coefficient

With (Eq.4) – (Eq.12) (Chapter 6.1); literature values A 1.1 – A 1.3 and calculated value of thickness l (A 4.6):

$\beta(10°C) = 9.5 * 10^{-3} \frac{m}{s}$
$\beta(13°C) = 9.5 * 10^{-3} \frac{m}{s}$
$\beta(16°C) = 9.6 * 10^{-3} \frac{m}{s}$

A 2.4 Calculation of Dry Mass Density (Salt Included)

The dry mass density is calculated with the density of the components. The components are salt (density: ρ_s; share on dry mass salt included: $c_{s,dm,s}$) and the dry mass without salt (density: ρ_{dm}; share on dry mass salt included: $(1 - c_{s,dm,s})$).

$$\rho_{dm,s,us} = c_{s,dm,s} * \rho_s + \left(1 - c_{s,dm,s}\right) * \rho_{dm} \quad \text{(Eq. A 2.15)}$$

The dry mass density is calculated with Eq. 16:

$$\rho_{dm} = \frac{1}{1-(X_w+c_{s,t})} * (\rho_t - (X_w * \rho_w + c_{s,t} * \rho_s))$$

$$c_{s,t} = (1 - X_w) * \frac{c_{s,d}}{1+c_{s,d}} \quad \text{(Eq. A 2.14)}$$

(Eq. A 2.14) in (Eq. 15):

$$\rho_{dm} = \frac{1}{1-(X_w+(1-X_w)*\frac{c_{s,d}}{1+c_{s,d}})} * (\rho_t - (X_w * \rho_w + (1 - X_w) * \frac{c_{s,d}}{1+c_{s,d}} * \rho_s))$$

(Eq. A 2.16)

Where X_w is the water content with regard to overall mass, $c_{s,t}$ is the salt content with regard to overall mass, ρ_t is the total density of unsalted meat, ρ_w is the density of water and ρ_s is the density of salt. As ρ_t of unsalted meat can be found in literature ρ_{dm} is calculated with the values of unsalted meat:

$\rho_w = 1000\frac{kg}{m^3}, \rho_{t,us} = 881\frac{kg}{m^3}, \rho_s = 2170\frac{kg}{m^3}$ (See A 1.)

$c_{s,d,us} = 3.6\%$; (A 4.1), $X_{w,us} = 74.2\%$ (A 4.2)

Insert values in Eq. A 2.16:

$$\rho_{dm} = 480.0\frac{kg}{m^3}$$

$$c_{s,dm,s} = c_{s,t}(t) * (\frac{1}{1-X_w(t)}) \quad \text{(Eq. A 2.7)}$$

(Eq. A 2.14) in (Eq. A 2.7):

$$\rightarrow c_{s,dm,s} = \frac{c_{s,d}(t)}{1+c_{s,d}(t)} \quad \text{(Eq. A 2.17)}$$

(Eq. A 2.17) in (Eq. A 2.15)

$$\rho_{dm,s} = \frac{c_{s,d}(t)}{1+c_{s,d}(t)} * \rho_s + \left(1 - \frac{c_{s,d}(t)}{1+c_{s,d}(t)}\right) * \rho_{dm} \quad \text{(Eq. A 2.18)}$$

Salt content with regard to dry mass, salt excluded for different salting times (See A 4.1):

$c_{s,d,0.us} = 3.6\%;\ c_{s,d,ls} = 24.4\%;\ c_{s,d,ms} = 26.6\%;\ c_{s,d,hs} = 28.4\%$

Insert values in Eq. A 2.18:

$\rightarrow \rho_{dm,s,us} = 538.7\frac{kg}{m^3};\ \rho_{dm,s,ls} = 811.5\frac{kg}{m^3};\ \rho_{dm,s,ms} = 835.1\frac{kg}{m^3};\ \rho_{dm,s,hs} = 853.8\frac{kg}{m^3}$

A 2.5 Calculation of $\Delta m_{\%}$

$$\dot{m}_{\omega} \triangleq \frac{\dot{m}}{A} \approx \frac{\Delta m}{\Delta t * A} \quad \text{(Eq. A 2.19)}$$

Mass specific area ($\frac{A}{m}$) of slices was measured (A 4.7)

$$A = \frac{A}{m} * m \quad \text{(Eq. A 2.20)}$$

The vaporized amount of water for a small period of time follows by inserting (Eq. A 2.20) in (Eq. A 2.19):

$$\Delta m_{t_n - t_{n+1}} = \dot{m}_{\omega,t_n} * \Delta t * (\frac{A}{m})_{t_n} * m(t) \quad \text{(Eq. A 2.21)}$$

$$m(t) = m_0 - \Delta m(t) = m_0 - \frac{\Delta m(t_n) + \Delta m(t_{n+1})}{2} \quad \text{(Eq. A 2.22)}$$

Simplified with $\frac{\Delta m(t_n) + \Delta m(t_{n+1})}{2} \approx \Delta m(t_{n+1})$:

$$m(t) = m_0 - \Delta m(t) = m_0 - \Delta m(t_{n+1}) \quad \text{(Eq. A 2.22*)}$$

(Eq. A 2.22*) in (Eq. A 2.21):

$$\Delta m_{t_n - t_{n+1}} = \dot{m}_{\omega,t_n} * \Delta t * (\frac{A}{m})_{t_n} * (m_0 - \Delta m(t_{n+1})) \text{(Eq. A 2.23)}$$

For small, similar periods of time it can be calculated:

$$\rightarrow \Delta m(t_{n+1}) = \Delta m(t_n) + \Delta m_{t_n - t_{n+1}} \quad \text{(Eq. A 2.24)}$$

(Eq. A 2.23) in (Eq. A 2.24):

$$\Delta m(t_{n+1}) = \Delta m(t_n) + \dot{m}_{\omega,t_n} * \Delta t * (\frac{A}{m})_{t_n} * (m_0 - \Delta m(t_{n+1})) \quad \text{(Eq. A 2.25)}$$

$$\Delta m_{\%}(t_{n+1}) = \frac{\Delta m(t_{n+1})}{m_0} \quad \text{(Eq. A 2.26)}$$

(Eq. A 2.25) in (Eq. A 2.26):

$$\Delta m_{\%}(t_{n+1}) = \frac{\Delta m(t_n) + \dot{m}_{\omega,t_n} * \Delta t * (\frac{A}{m})_{t_n} * (m_0 - \Delta m(t_{n+1}))}{m_0} = \Delta m_{\%}(t_n) + \dot{m}_{\omega,t_n} * \Delta t * (\frac{A}{m})_{t_n} * (1 - \Delta m_{\%}(t_{n+1}))$$

$$\rightarrow \Delta m_{\%}(t_{n+1}) = \Delta m_{\%}(t_n) + \frac{\dot{m}_{\omega,t_n} * \Delta t * \frac{A}{m}}{1 + \dot{m}_{\omega,t_n} * \Delta t * \frac{A}{m}} \quad \text{(Eq. A 2.27)}$$

A 2.6 Calculation of $X(t)$ for Programming

For programming $X(t)$ has to be calculated with $\Delta m_{\%}$ (calculation of $\Delta m_{\%}$: A 2.5).

$$X(t) = \frac{(X_{w,0} * m_0 - \Delta m)}{(1 - X_{w,0}) * m_0} = \frac{X_{w,0} - \Delta m_{\%}(t)}{1 - X_{w,0}} \quad \text{(Eq. 34; Chapter 6.2)}$$

$$X_w = \frac{X}{1 + X} \quad \text{(Eq. A 2.28)}$$

(Eq. A 2.27) in (Eq.34):

$$X(t) = \frac{\frac{X_0}{1 + X_0} - \Delta m_{\%}(t)}{1 - \frac{X_0}{1 + X_0}} \quad \text{(Eq. A 2.28)}$$

A 3. Calibrations

A 3.1 Salt probe

Probe value	$c_{s,t}$	$c_{s,dm}$	X_w	X
77	7.4%	20.7%	56.8%	131.5%
71	7.4%	17.4%	50.0%	100.0%
79	8.2%	28.9%	63.4%	173.2%
84	8.8%	31.0%	62.8%	168.8%
80	7.2%	25.4%	64.4%	180.9%
81	8.0%	28.3%	63.7%	175.5%
84	8.1%	28.2%	63.2%	171.7%

Table 9: Measured values with probe and chemical method for calibration of salt probe

Comparing the coefficient of determination the probe values are regarded as corresponding to the salt content with regard to dry mass (salt excluded of dry mass).

$$c_{s,dm} = 0.0085 * e^{0.0426 * probe\ value}$$

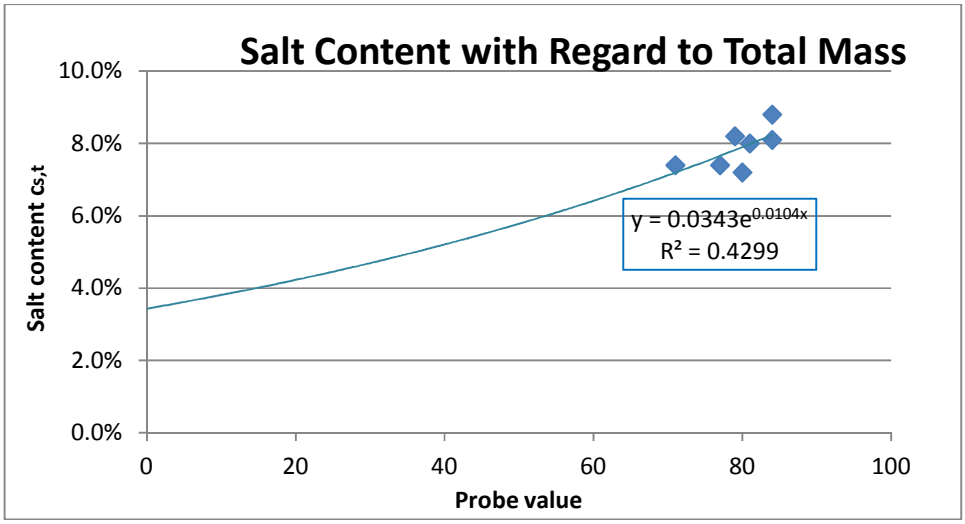

Figure 28: Calibration curve of salt probe with measured salt content (salt content with regard to total mass)

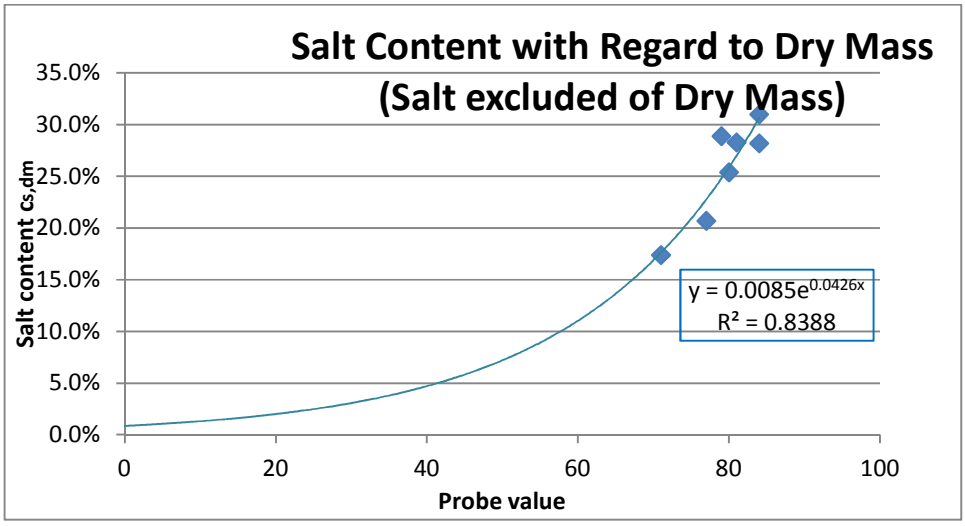

Figure 29: Calibration curve of salt probe with measured salt content (salt content with regard dry mass, salt excluded)

A 3.2 Aqualab

Set value	Measured value
0.984	0.978
0.760	0.757

Table 10: Set values (fluid for calibration) and measured values of Aqualab

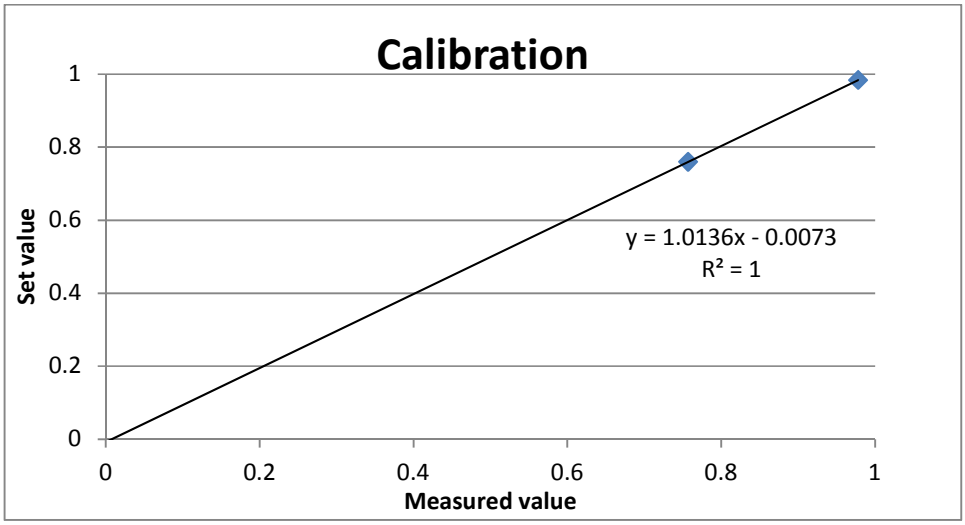

Figure 30: Calibration curve of Aqualab

$$a_w(real) = 1.0136 * a_w(measured) - 0.0073$$

A 4. Measurements
A 4.1 Salt Content with Regard to Dry Mass (Salt excluded)

Sample	Probe Value	$c_{s,dm}$
1	43	5%
2	42	5%
3	37	4%
4	35	4%
5	42	5%
6	37	4%
7	40	5%
8	33	3%
9	40	5%
10	31	3%
11	39	5%
12	41	5%
13	39	5%
14	38	4%
15	32	3%
16	28	3%
17	23	2%
18	26	3%
19	26	3%
20	23	2%
21	33	3%
22	42	5%
23	30	3%
24	18	2%
25	32	3%
26	33	3%
27	32	3%
28	19	2%
29	15	2%
∅	**32.7**	**3.62%**
SD	**7.7**	**1.07%**
u	**1.4299**	**0.1987%**
U	**3.0**	**0.4%**

Table 11: Salt content unsalted samples

$$c_{s,dm,us} = (3.6 \pm 0.4)\%$$

Sample	Probe	$c_{s,dm,s}$
1	79	25%
2	76	22%
3	80	26%
4	79	25%
5	78	24%
6	80	26%
7	79	25%
8	77	23%
9	79	25%
10	78	24%
11	79	25%
12	79	25%
13	81	27%
14	77	23%
∅	**78.64**	**24.40%**
$\boldsymbol{SD}$	**1.29**	**1.33%**
$\boldsymbol{u}$	**0.3448**	**0.3555%**
$\boldsymbol{U}$	**0.7447**	**0.8%**

Table 12: Salt content low salted samples

$$c_{s,dm,ls} = (24.4 \pm 0.8)\%$$

Sample	Probe	$c_{s,dm,s}$
1	82	28%
2	83	29%
3	83	29%
4	82	28%
5	83	29%
6	83	29%
7	82	28%
8	82	28%
9	79	25%
10	83	29%
11	79	25%
12	81	27%
13	85	32%
14	81	27%
15	79	25%
16	77	23%
17	81	27%
18	82	28%
19	88	36%
20	84	31%
21	80	26%

22	83	29%
23	79	25%
24	82	28%
25	83	29%
26	83	29%
27	85	32%
28	84	31%
29	77	23%
30	79	25%
31	81	27%
32	83	29%
33	79	25%
34	81	27%
35	80	26%
36	84	31%
37	53	8%
38	75	21%
39	68	15%
40	79	25%
41	73	19%
42	77	23%
∅	**80.2**	**26.6%**
SD	**5.5**	**4.6%**
u	**0.8487**	**0.7098%**
U	**1.8**	**1.5%**

Table 13: Salt content medium salted samples

$$c_{s,dm,ms} = (26.6 \pm 1.5)\%$$

Sample	Probe	$c_{s,dm,s}$
1	83	29%
2	79	25%
3	82	28%
4	84	31%
5	84	31%
6	83	29%
7	84	31%
8	84	31%
9	84	31%
10	80	26%
11	83	29%
12	82	28%
13	80	26%

14	74	20%
15	84	31%
16	85	32%
17	87	35%
18	83	29%
19	85	32%
20	84	31%
21	80	26%
22	86	33%
23	82	28%
24	85	32%
25	86	33%
26	82	28%
27	88	36%
28	79	25%
29	87	35%
30	87	35%
31	83	29%
32	83	29%
33	84	31%
34	82	28%
35	81	27%
36	83	29%
37	83	29%
38	82	28%
39	85	32%
40	83	29%
41	77	23%
42	78	24%
43	70	17%
44	72	18%
45	79	25%
46	77	23%
47	76	22%
∅	**82.0**	**28.4%**
SD	**3.8**	**4.2%**
u	**0.5543**	**0.6126%**
U	**1.11**	**1.3%**

Table 14: Salt content high salted samples

$$c_{s,dm,hs} = (28.4 \pm 1.3)\%$$

A 4.2 Water Content before Drying

Sample	Pan [g]	m_0 + pan[g]	m_0 [g]	m_{dm} + pan [g]	m_{dm} [g]	w [g]	X_w	X
1	2.608	10.754	8.146	4.727	2.119	6.027	74.0%	284.4
2	2.607	10.978	8.371	4.759	2.152	6.219	74.3%	289.0
3	2.616	10.974	8.358	4.761	2.145	6.213	74.3%	289.7
4	2.579	11.447	8.868	4.824	2.245	6.623	74.7%	295.0
5	2.578	15.649	13.071	5.940	3.362	9.709	74.3%	288.8
6	2.575	13.228	10.653	5.316	2.741	7.912	74.3%	288.7
7	2.584	9.531	6.947	4.374	1.790	5.157	74.2%	288.1
8	2.581	9.938	7.357	4.504	1.923	5.434	73.9%	282.6
9	2.575	11.846	9.271	5.540	2.965	6.306	68.0%	212.7
10	2.591	13.580	10.989	5.514	2.923	8.066	73.4%	275.9
11	2.585	15.651	13.066	5.915	3.330	9.736	74.5%	292.4
12	2.583	14.545	11.962	5.772	3.189	8.773	73.3%	275.1
13	2.587	13.803	11.216	5.434	2.847	8.369	74.6%	294.0
∅							**74.2%**	**281.3**
SD							**1.7%**	**20.65**
u							**0.5%**	**5.7%**
U							**1.1%**	**12.5%**

Table 15: Water content unsalted samples

$$X_{w,0,us} = (74.2 \pm 1.1)\%$$

$$X_{0,us} = (281 \pm 13)\%$$

Sample	m_0 [g]	m_{dm} [g]	w [g]	X_w	X
1	5.365	1.586	3.779	70.4%	238.3%
2	6.496	1.943	4.553	70.1%	234.3%
3	4.853	1.476	3.377	69.6%	228.8%
∅				**70.0%**	**233.8%**
SD				**0.4%**	**3. 9%**
u				**0.2%**	**2.2%**
U				**0.9%**	**9.7%**

Table 16: Water content low salted samples

$$X_{w,0,ls} = (70.0 \pm 0.9)\%$$

$$X_{0,ls} = (234 \pm 10)\%$$

Sample	m_0 [g]	m_{dm} [g]	w [g]	X_w	X
1	5.687	1.800	3.887	68.3%	215.9%
2	5.714	1.833	3.881	67.9%	211.7%
3	5.393	1.703	3.690	68.4%	216.7%
Ø				**68.2%**	**214.8%**
SD				**0.2%**	**2.2%**
u				**0.1%**	**1.3%**
U				**0.6%**	**5.4%**

Table 17: Water content medium salted samples

$$X_{w,0,ms} = (68.2 \pm 0.6)\%$$

$$X_{0,ms} = (215 \pm 6)\%$$

Sample	m_0 [g]	m_{dm} [g]	w [g]	X_w	X
1	3.487	1.158	2.329	66.8%	201.1%
2	4.827	1.588	3.239	67.1%	204.0%
3	5.143	1.791	3.352	65.2%	187.2%
Ø				**66.4%**	**197.4%**
SD				**0.8%**	**7.4%**
u				**0.5%**	**4.2%**
U				**2.1%**	**18.2%**

Table 18: Water content high salted samples

$$X_{w,0,hs} = (66.4 \pm 2.1)\%$$

$$X_{0,hs} = (197 \pm 19)\%$$

A 4.3 Water Activity before drying

Calibration of Aqualab see A 3.2

$$a_w(calibrated) = 1.0136 * a_w(measured) - 0.0073$$

Sample	a_w measured	T [°C]	a_w calibrated
1	0.985	25.0	0.991
2	0.986	24.9	0.992
3	0.984	25.3	0.990
∅	**0.985**		**0.991**
$\boldsymbol{SD}$			**0.00083**
$\boldsymbol{u}$			**0.00048**
$\boldsymbol{U}$			**0.00205**

Table 19: Water activity unsalted samples

$$a_{w,0,us} = 0.9910 \pm 0.0021$$

Sample	a_w measured	T [°C]	a_w calibrated
1	0.957	24.9	0.963
2	0.961	24.9	0.967
∅	**0.959**		**0.965**
$\boldsymbol{SD}$			**0.00203**
$\boldsymbol{u}$			**0.00143**
$\boldsymbol{U}$			**0.02**

Table 20: Water activity low salted samples

$$a_{w,0,ls} = 0.97 \pm 0.02$$

Sample	a_w measured	T [°C]	a_w calibrated
1	0.947	18.5	0.953
2	0.930	21.5	0.935
3	0.925	20.7	0.930
∅	**0.933**		**0.939**
$\boldsymbol{SD}$			**0.00988**
$\boldsymbol{u}$			**0.00570**
$\boldsymbol{U}$			**0.025**

Table 21: Water activity medium salted samples

$$a_{w,0,ms} = 0.939 \pm 0.025$$

Sample	a_w measured	$T\ [°C]$	a_w calibrated
1	0.934	21.5	0.939
2	0.936	22.6	0.941
3	0.930	18.9	0.935
∅	**0.934**		**0.939**
SD			**0.00249**
u			**0.00144**
U			**0.007**

Table 22: Water activity high salted samples

$$a_{w,0,hs} = 0.939 \pm 0.007$$

A 4.4 Sorption Isotherms

Equilibrium Water Content

$c_{s,dm,s}$	$X_e(60\%)$	$X_e(68\%)$	$X_e(80\%)$
3.6%	23%	27%	38%
24.4%	27%	43%	63%
26.6%	38%	57%	67%
28.4%	39%	53%	120%

Table 23: Equilibrium water content of different salted samples

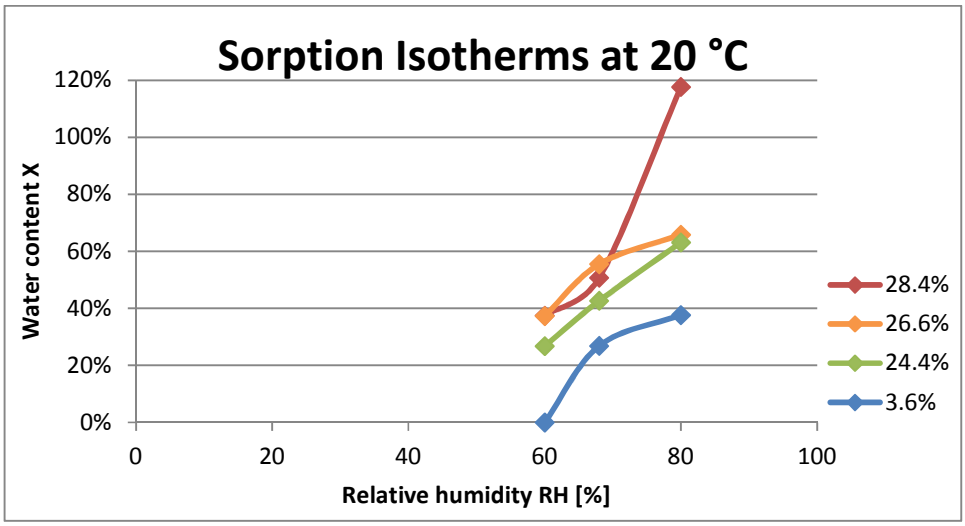

Figure 31: Sorption isotherms at 20°C of pork with 3.6%, 24.4%, 26.6% and 28.4% salt content (of total mass, salt excluded)

A 4.5 Loss of mass during Drying

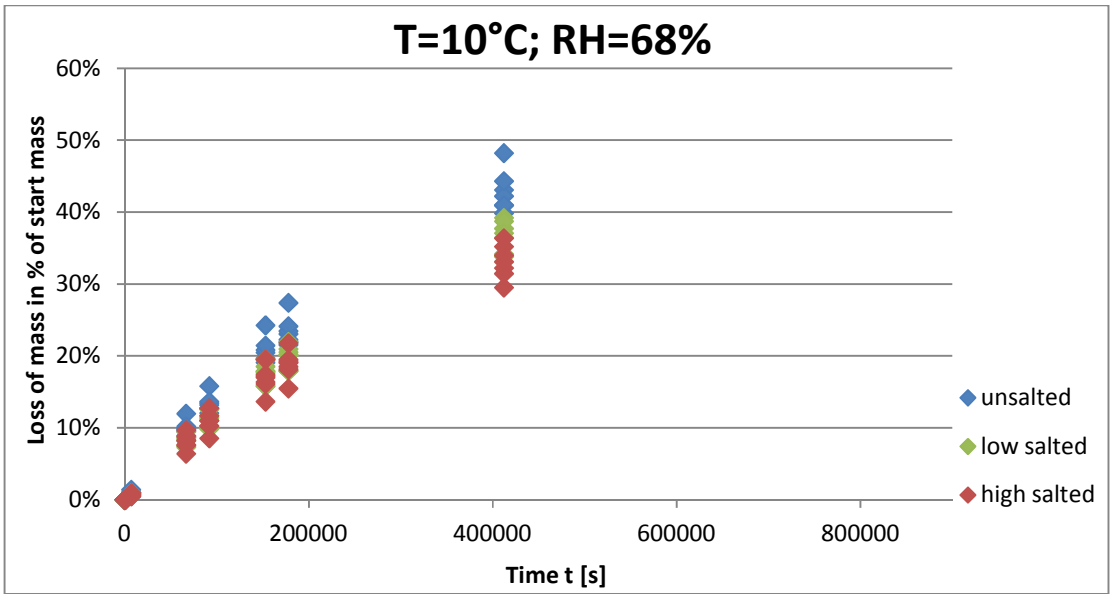

Figure 32: Loss of mass with time at T=10 °C; RH=68%

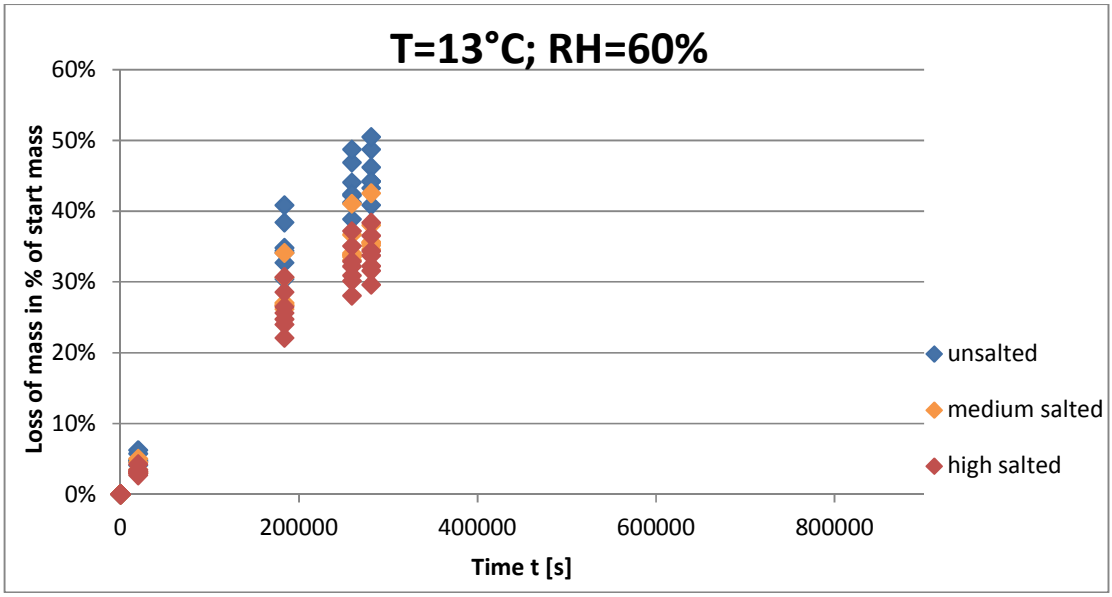

Figure 33: Loss of mass with time at T=13 °C; RH=60%

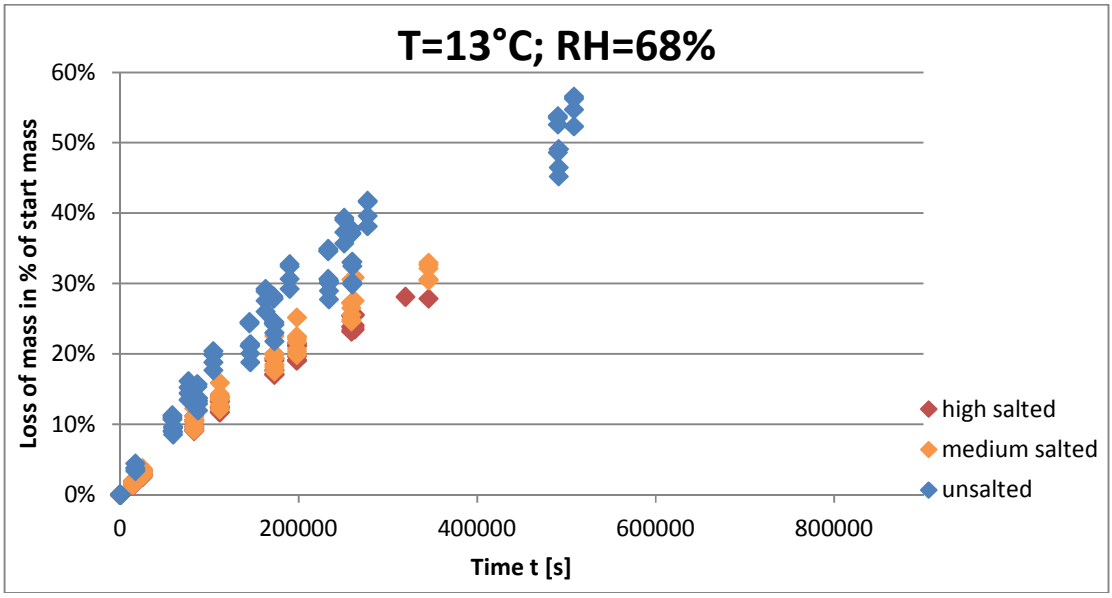

Figure 34: Loss of mass with time at T=13 °C; RH=68%

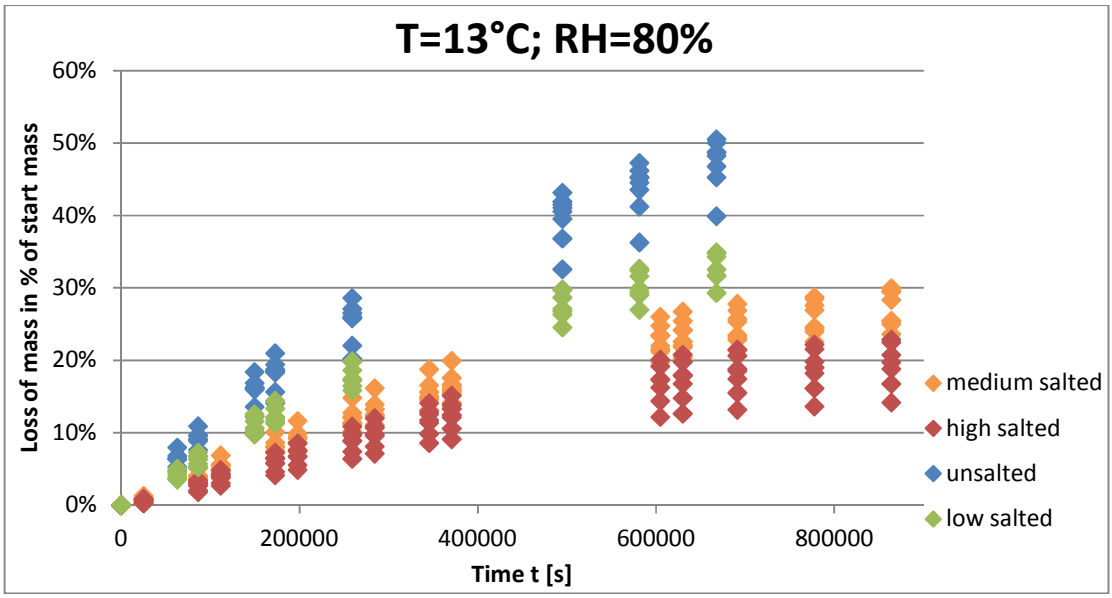

Figure 35: Loss of mass with time at T=13 °C; RH=80%

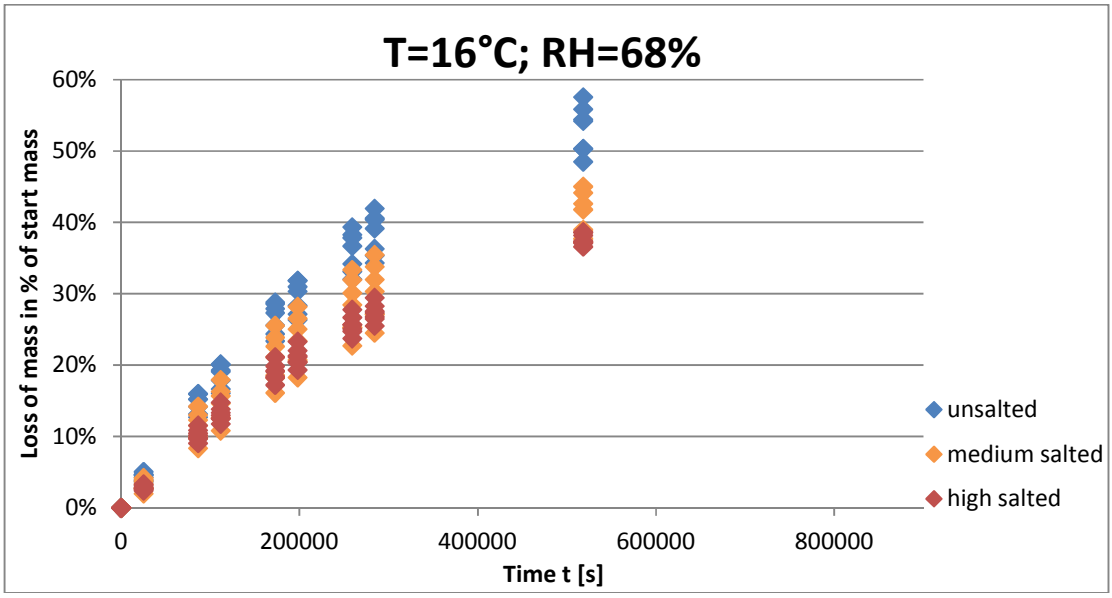

Figure 36: Loss of mass with time at T=16 °C; RH=68%

A 4.6 Thickness of slices

Sample	$l\ [m]$
1	0.009
2	0.008
3	0.008
4	0.012
5	0.012
6	0.010
7	0.008
8	0.015
9	0.009
10	0.013
11	0.012
12	0.011
13	0.013
14	0.012
15	0.011
16	0.014
17	0.014
18	0.008
19	0.010
20	0.011
∅	**0.0110**
$\boldsymbol{SD}$	**0.00214476**
$\boldsymbol{u}$	**0.00047958**
$\boldsymbol{U}$	**0.0010**

Table 24: Thickness of unsalted and salted slices

$$l = (0.011 \pm 0.001)m$$

A 4.7 Mass specific area

Sample	$\frac{A}{m}\left[\frac{m^2}{kg}\right]$
1	0.213
2	0.177
3	0.146
4	0.174
5	0.157
6	0.160
7	0.168
8	0.158
9	0.156
10	0.152
11	0.163
12	0.158
13	0.191
14	0.175
15	0.099
16	0.088
17	0.107
18	0.103
19	0.113
20	0.108
21	0.135
22	0.125
23	0.168
24	0.143
25	0.153
26	0.155
∅	**0.148**
$\boldsymbol{SD}$	**0.0305**
$\boldsymbol{u}$	**0.0032**
$\boldsymbol{U}$	**0.0066**

Table 25: Mass specific area of unsalted and salted slices before and after drying

$$\frac{A}{m} = (0.148 \pm 0.007)\frac{m^2}{kg}$$

A 4.8 Dry Layer Thickness

$d_{us} = 0.005452m * \Delta m_{\%}$

$R^2 = 0.9753$

$d_{ls} = 0.0091912m * \Delta m_{\%}$

$R^2 = 0.9724$

$d_{ms} = 0.0097516m * \Delta m_{\%}$

$R^2 = 0.9733$

$d_{hs} = 0.010264m * \Delta m_{\%}$

$R^2 = 0.9705$