# DYNAMIC MODEL AND KINETICS FOR CONVECTIVE DRYING OF HAM WITH DIFFERENT SALT CONTENTS

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*Abstract*: A number of experiments have been carried out to identify the influence of air humidity and salt content on the drying kinetics of pork. Small scale experiments with unsalted, low-salted and high-salted ham muscles Semimembranosus were carried out under different drying conditions. Average drying rates for the different drying conditions are presented and their kinetics is discussed. With the obtained drying kinetics a physical and a semi-empirical model were verified and evaluated under different drying conditions. The semi-empirical model shows better accuracy even at alternating relative humidity. The model can be implemented in process simulation with respect to energy efficiency.

*Keywords*: Process simulation, Object-oriented modelling, Dry-cured ham, Energy efficiency.

## INTRODUCTION

Drying is the process of water removing from a product by evaporation. Drying meat under natural temperatures, humidity and circulation of the air, including direct influence of sun rays, is the oldest method of meat preservation[1]. Due to climatic situation, sanitary reason and reliability, industrial drying nowadays takes place in ventilated climate chambers in which the product is held at constant temperature in a controlled atmosphere during ripening and drying.

Dry-cured meat is a popular product worldwide and one of the most valuable meat products. As a raw material for producing dry-cured ham the two main muscles of pork leg are used – Semimembranosus and Biceps femoris[2].

The main processes during the production of dry-cured ham are salting, drying and ripening. During salting some moisture is moved out from the product and salt moves to the tissues. Slow drying with ripening provides losses of moisture and redistribution of salt and moisture in the product, achieving high quality taste and sensory appearance of the final product. So, the biochemical reactions which are taking place during the manufacture of dry-cured ham are controlled by the dehydration process of meat due to moisture diffusivity which depends on water content and composition of raw material as well as on process parameters such as salt content, air temperature and relative humidity. Process parameters also directly affect the microstructure and various other properties of dried meat due to the microstructural changes may affect the path through which heat and mass must transfer[3]. The kinetics of these reactions is affected by moisture content, as a consequence, the rate of water losses influence the extent of those reactions.

During the process, some physical, microbiological and biochemical phenomena responsible for the appearance, flavor and aroma, typical of these products as well as of its conservation and sanitary safety take place[4], [5]. The ripening process is an important step in the manufacture of meat products. Chemical and sensory changes occurring through the process are strongly dependent on the duration of the ripening process which has been demonstrated in different dry-cured meat products[6], [7], [8]. Furthermore, dehydration during ripening contributes to stabilizing the product by decreasing the water activity value ($a_w$)[9]. To achieve the high-quality of dry-cured ham it is 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. Internal and external diffusions are to be the same to achieve efficient and uniform drying process.

NaCl absorption considered together with dehydration is one of the fundamental processes contributing to the stability of dry cured ham[10]. Salt content influences on the drying kinetics and as a consequence on total time of the process and therefore is of great interest for understanding the drying rates. The effect of air relative humidity on the ripening process is accounted for the influence of relative humidity on weight losses and $a_w$[11], [12], [9]. As a factor influencing on the drying rates of the process air relative humidity ought to be evaluated for process optimization and achieving economic benefits.

Since a lot of processes occurring during the production the industrial manufacturing of dry-cured ham is energy and time consuming, the whole production time for the standard ham is around 4 months but in fact the best quality of dry-cured ham is achieved after two years of controlled processing. To control and predict drying kinetics simulation of the process is of special interest for the evaluation of the process without expensive and long experiments.

To simulate the drying process, reliable drying rates and a physical model are needed. It was also tested if the suitable model is still valid under alternating conditions within one drying process. Experiments with samples used in industrial production (approx. 9 kg per piece) would 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 should be transferable to industrial sized samples.

The focus of the article is to obtain the knowledge on the prediction of the drying rate and time with respect to the drying conditions (temperature and relative humidity) and salt content. Two different models are examined and compared – one physical model is normally used for non-hygroscopic substances, the second model is based on the effective diffusion approach and used for hygroscopic substances to investigate if the hygroscopic property is negligible during the drying process of dry-cured ham or not.

## MATERIALS AND METHODS

*Drying system*

The drying system used for this investigation was a heat pump based dryer, as described in[13]. The air was dehumidified at the evaporator of the heat pump and heated to its initial drying temperature at the system's condenser. By adjusting the temperature in both heat exchangers the conditions of the drying air could be well controlled (temperature+/-0.2K, relative humidity +/-2%). Weight reduction was determined after certain time steps continuously by a weight scale (CPA 32000, Sartorius, Göttingen, Germany) for one sample, while the weight reduction for the other samples in the parallels was determined manually by interrupting the drying process after certain time steps and placing the sample on a weight scale outside the drying chamber. The system was calibrated and the weight reduction was determined with an accuracy of 0.01%. The weight reduction obtained was used to calculate the moisture content of the product during the drying. The velocity of the drying air was controlled by a fan (0.4 m/sec +/- 0.05). The temperature, relative humidity and velocity of the drying air, as well as the weight reduction and temperature of the product were recorded (NI cDAQ9172, National Instruments). Test series with a 0.4 m/sec air velocity, drying air temperature of 10°C, 13°C and 16°C and humidity of 60%, 68% and 80% were performed with 15 parallels. The bone dry mass of the product, before and after drying, was determined by grinding a sample, placing it at 130ºC (drying oven DryLine, VWR, Oslo Norway), and measuring the weight reduction when it reached equilibrium, according to (International Food Standard, 1989). Slices with a thickness of 1 cm from the Semimembranosus muscle from fresh slaughtered pork were provided from a local supplier. The samples were salted for a certain time in order to reach the desired salt content and stored for 3 days for salt balancing. Unsalted samples (initial salt content < 3.6%$_{\text{dry matter}}$ +/- 0.4%), low salted (initial salt content 24.4%$_{\text{dry matter}}$ +/- 0.8%) and high salted (initial salt content 28.4%$_{\text{dry matter}}$ +/- 1.3%) were used for the drying experiments. Initial water content of the samples before drying was 74.2% +/- 1.1%, 70.0% +/- 0.9% and 66.4% +/- 2.1% for unsalted, low salted and high salted samples respectively.

*Models*

Two models were considered in order to calculate the drying rate from the different experiments[14]. First a physical approach based on the similarity between coupled heat and mass transfer was evaluated and secondly a semi-empirical model based on the effective diffusion ($D_{eff}$) is considered.

*Physical model*

Mass transfer in convective drying is driven by partial pressure gradient between the water vapor in the product and the ambient air. This gives the drying rate

$$\dot{m}_{water} = \beta_{total} \frac{p_w^0 - p_i}{R * T} \quad (1)$$

where $\beta_{total}$ is the overall mass transfer, $p_w^0$ is the saturation vapor pressure, $p_i$ partial vapor pressure of the product, R is the gas constant and T the temperature of the drying air. The overall mass transfer is summed up from the mass transfer coefficient ß and the diffusion through the product:

$$\beta_{total} = \frac{1}{\beta} + \frac{s}{D_g} \mu \left(1 - \frac{(p_i)_m}{p}\right) \quad (2)$$

where $D_g$ is the diffusion coefficient of water vapor in air, s is the thickness of the dry layer, μ is the diffusion resistance which states how much the diffusion is slowed down by the product structure, $(p_i)_m$ is the average partial vapor pressure of the product and p is the ambient partial vapor pressure. The mass transfer coefficient ß can be calculated with the geometry of the product and the dimensionless Sherwood, respectively Nusselt, number, according to standard text books.

The drying rate in this model depends on several physical factors, which are influencing the drying behavior. The conditions outside (heat and mass transfer coefficients) the product are influencing the process as well as the properties of the drying media, especially the temperature and the humidity. Additionally the "internal" properties of the product, like the size of the dry layer and the physical properties of the product are considered by the model (thermal conductivity, diffusion, diffusion resistance), are considered. The drying velocity, according to this model, is high when the approach velocity is increased and the size of the drying product is decreased.

*Semi-empirical model*

For hygroscopic drying products the drying process is controlled by internal diffusion mechanism and the drying rate is so small that heat transport mechanisms are not influencing the process. The moisture is removed from the product by non-stationary diffusion. The driving potential is the difference between the moisture content X and equilibrium moisture content $X^*$.The drying process can therefore be described by the partial differential equation from the non-stationary diffusion:

$$\frac{\partial(X-X^*)}{\partial t} = D_{eff}\frac{\partial^2(X-X^*)}{\partial y^2} \tag{3}$$

Hereby an effective diffusion inside the drying product is assumed. The mathematical solution for this approach can be found in several textbook drying literatures for known geometries. For long drying times the average moisture content $\bar{X}$ can be used in the solution und the assumption of an uniform moisture distribution in the beginning of the process (t=0):

$$\frac{\bar{X}-X^*}{X_{t=0}-X^*} = \frac{8}{\pi^2}\exp\left[-D_{eff}\,\tau\left(\frac{\pi}{s}\right)^2\right] \qquad 4)$$

where τ is the drying time. The drying rate is consequently obtained by the derivation of the above equation:

$$\dot{m}_{water} = -\rho_s s\frac{dX}{dt} = \frac{\pi^2\rho_s D_{eff}}{s}(X-X^*) \tag{5}$$

where $\rho_s$ is the density of the dried product. This approach must be considered as semi-empirical, since the effective diffusion must be determined empirical by experiments for different drying conditions and defined geometries.

## RESULTS AND DISCUSSION

*Model*

The drying rates ($\dot{m}_\omega$) determined with the two proposed model was compared with experimentally obtained drying rates. The drying conditions (temperature, humidity and velocity) of the air where hereby kept constant. The empirical model, based on the effective diffusion approach, resulted in general in a better accuracy than the proposed physical model. The variance for the semi-empirical model was in average 2.6%, while the physical model showed a variance of 2.9%. Fig shows one example of the drying rates obtained from the proposed models and the experimentally obtained drying rate. Similar graphs can be obtained for all performed experiments. It can be seen that the physical model overestimates the initial drying rate significantly, while the semi-empirical model models the general fall of the drying rate more accurate.

The drying rate of the physical model is high in the beginning and decreases fast; the decreasing becomes slower with time whereas $\dot{m}_\omega$ of the semi-empirical model is lower at the beginning but decreases slower with time. Compared with the values of the online measurement the physical model describes $\dot{m}_\omega$ too fast at the beginning. The semi-empirical model fits the measured values in general better.

Physical models cover normally a wider range of drying situations, where e.g. the initial moisture content can be varied as well as the drying conditions. This makes it easier to upscale the model to different sized processes. Semi-empirical models are normally limited in its application, since the initial conditions like moisture content and drying conditions must be kept constant. Especially the up-scaling of semi-empirical models can be challenging in daily engineering practice. However, for the further investigations just the semi-empirical model was considered, since it is more accurate and models the fall of the drying rate more precious.

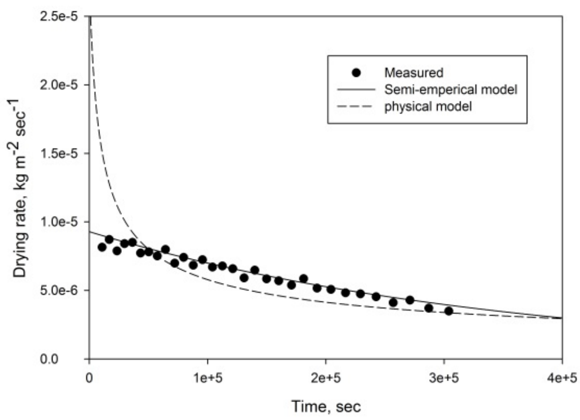


Fig. 1. Example of the measured drying rate compared to the proposed models (high salted meat, 13°C, 68% humidity).

*Drying experiments*

With the performed experiments the influence of the drying temperature and the humidity was investigated in more details. Table 1 is summing up the determined effective diffusions for all performed experiments. The influence of the approach velocity was not studied, since it was considered negligible for drying rate. The drying behaviour was studied at a drying temperature of 10°C, 13°C and 16°C, while the humidity was kept constant at 68%. However the obtained drying rates differed only minor from each other and were statistically not relevant. The focus in industrial production is very often on the maintenance of the temperature in the drying system. Based on the performed experiments one can conclude that a certain variation (between 10°C and 16°C) will not have an visible influence on the drying rate. However, since the product undergoes also a certain ripening during drying the strictly maintained temperature could be necessary for quality reasons, which are based on temperature depending biochemical reactions.

Table 1. Effective diffusion for meat at a temperature of 13°C with varying air humidity.

| *RH* | *Deff,* $m^2\ sec^{-1}$ | *Deff,* $m^2\ sec^{-1}$ | *Deff,* $m^2\ sec^{-1}$ |
|---|---|---|---|
| 60 % | $7.0 * 10^{-12}$ | n.a. | $5.7 * 10^{-12}$ |
| 68 % | $5.2 * 10^{-12}$ | $3.5 * 10^{-12}$ | $4.2 * 10^{-12}$ |
| 80 % | $3.5 * 10^{-12}$ | $2.2 * 10^{-12}$ | $1.2 * 10^{-12}$ |

In Fig  the drying rate for different humidity at a constant temperature (13°C) are given depending on the moisture content. It can be seen that the humidity has high influence on the actual drying rate. As lower the humidity as faster the determined drying rate. This result is according the general drying theory in which an increased vapour pressure difference will also increase the drying rate. This is also illustrated in the drying curves in Fig. Industrial production of dry-cured ham should therefore especially maintain the humidity of the drying air, since minor changes will give a significant influence on the dehydration rate.

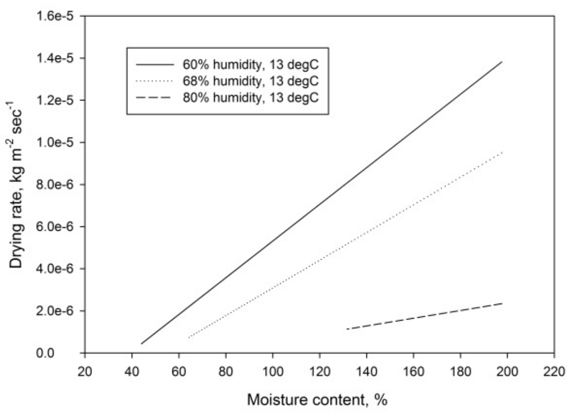


Fig. 2. Influence of relative humidity on drying rate (low salted pork).

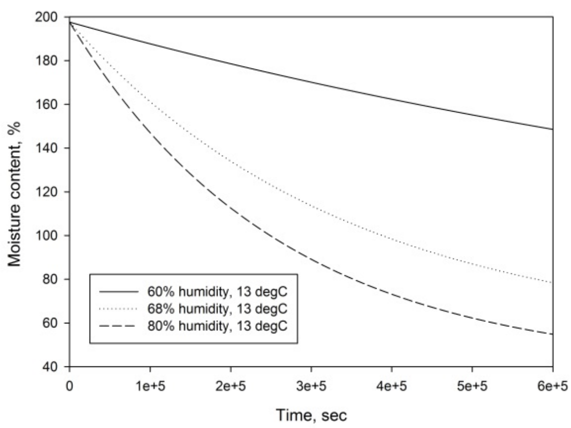


Fig. 3.  Influence of relative humidity on X(t) (low salted pork).

Comparing the curves of the drying rate for unsalted slices and slices with different salt content, Figure 4 shows that the salt content is influencing the overall drying rate. Unsalted meat shows the fastest dehydration, while it is clear that the increasing salt content is decreasing the drying rate. It should be noted that NaCl is the most important ingredient used in dry-cured meat products to achieve both suppression of microorganisms and good organoleptic characteristics but could also decrease the drying rate values as it is shown in the graph. This effect can be explained with the water binding character of the salt.

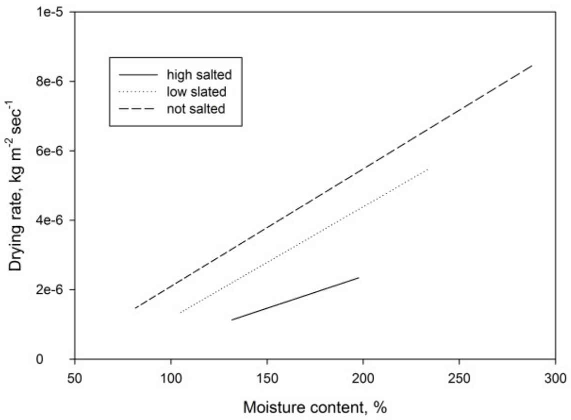


Fig. 4. Influence of salt content on drying rate.

The reduced drying rate is directly influencing the drying curve for the meat, as shown in Fig. Un-salted meat has the highest water content in the beginning for drying, while the initial water content is decreased in the presence of salt. This is due to the osmotic dehydration which occurs during the salting process. However, the salt presence is reducing the drying rate and the salted meat is drying slower than meat with lower salt content. It is interesting to observe the unsalted meat is more dehydrated after a certain time than the salted meat. With respect to processing time an optimum needs to be found between faster dehydration and increased salt content. It should be also noted that a low salt content is normally demanded by the consumer in order reduce health risks.

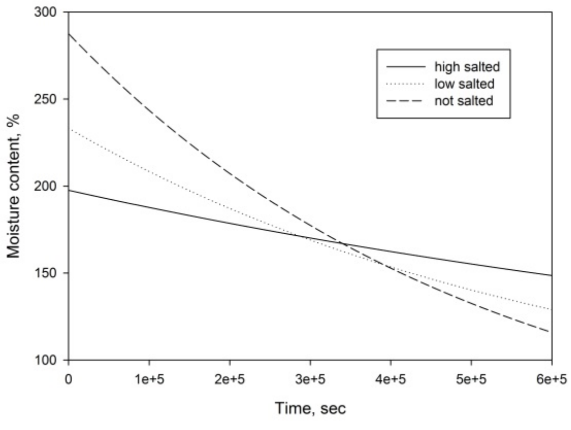


Fig. 5. Drying curve for meat with different salt contents.

*Variation of drying conditions*

The suggested semi-empirical model and the determined effective diffusion were used to model a drying curve under varying drying conditions. Hereby the drying temperature was kept constant at 13°C, since the investigated temperature variation did no influence the drying behaviour. The humidity of the air was varied from 68% to 60% to 80% and back to 68% after certain time intervals as shown in Fig. The modelled drying rate was compared with 10 parallels to get a certain statistical certainty of the result.

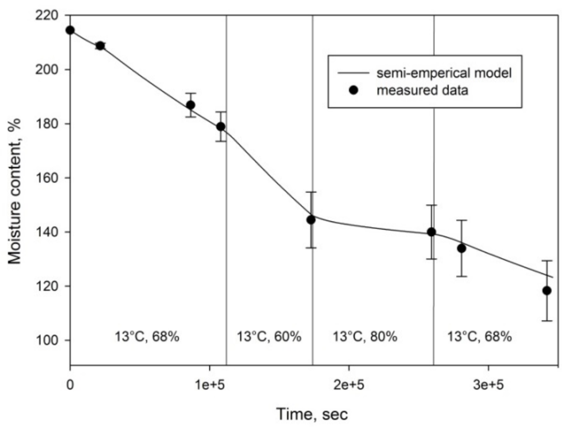


Fig. 6. Modelled and measured drying curve for meat at constant temperature and varying humidity.

It can be seen that the suggested semi-empirical model and the obtained effective diffusions (Table 1) predicted the experimentally obtained drying curve quite well. However, towards the end of the experiment the standard deviation increased and also the accuracy of the model is decreased. This could be explained with experimental uncertainty or the limitation of the semi-empirical models in general. However it is visible that the drying dynamic can be modelled also for varying humidity with the proposed model.

## CONCLUSION

Two models were evaluated for the prediction of the drying rate for dry-cured meat at different drying conditions. The semi-empirical model gave the best accuracy, while the physical model overestimated the drying rate especially during the first hours of drying. The semi-empirical model is based on the effective diffusion approach and was used further to evaluate the experimental drying behaviour.

The investigated drying temperature of 10°C, 13°C and 16°C resulted in similar drying rates and curves where the difference was negligible. The humidity of the drying air influenced the drying rate significantly and the dehydration increased with decreasing humidity. The influence of the approach velocity was not investigated. The investigation showed further that salted meat is drying significantly slow than unsalted meat. The obtained effective diffusions are given in Table 1 for different humidity and salt content.

The semi-empirical model was used to predict the drying curve under varying humidity and predicted the moisture content with satisfying accuracy. However, the usual limitations for semi-empirical models also apply here and up-scaling or different drying conditions can only be applied under careful consideration.

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