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REVIEW PAPER

Manufacture of dry-cured ham: A review. Part 2. Drying kinetics, modeling and equipment

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Abstract Dehydration in foodstuff manufacture is a process when a product loses the weight by reduction in water content. Regarding the production of dry-cured ham, dehydration mainly takes place during the drying stage. However, during the salting and the resting steps, water content of the hams also reduces by 3–4 %, which should be taken into account in order to adjust the necessary rate of the further drying. In addition, such parameters as pH of the raw material and salt content of being dried hams also influence the drying rate and the quality of the final product. The present paper is devoted to highlighting processes and parameters influencing the dehydration of dry-cured ham during the manufacture. Industrial drying systems used for the manufacture of dry-cured ham are described for the comparison of construction and energy consumption. Mathematical models mostly used to predict the drying behavior of dry-cured ham are described.

Keywords Dry-cured ham · Drying kinetics · Modeling · Industrial drying systems

Introduction

Dry-cured ham is a popular meat product worldwide, highly appreciated by consumers. The oldest drying method is a technique which uses natural conditions—the sun and air—for product dehydration. Due to the great influence of weather conditions and not less due to safety reasons, nowadays a drying process takes place in ventilated climate chambers in which the product is held at constant temperature in a controlled atmosphere.

The process of dry-cured ham manufacture is long and consists generally of salting followed by a long drying period. During the salting stage, the product is affected by the action of salt (NaCl) which penetrates and distributes uniformly during the resting step. Consequently, the part of moisture is removed from the product by the action of osmotic dehydration. It helps to prepare the product for the further drying step by reducing the energy costs by partial water removal.

Drying is the main process of dry-cured ham production and consists of water removal from the product by evaporation which is driven by a concentration gradient between the drying air and the being dried product. Drying is the most energy- and time-consuming process and that is why optimization of this step is of special interest [1]. Latent heat of vaporization for water is 2257 kJ kg^{-1} water at temperature 100 °C and pressure in 1 atm [2]. It means that for the vaporization of one kilogram water, the energy input which should be applied to the product is 0.63 kWh kg^{-1}. It is an ideal case, and real energy costs can approach 3500–6000 kWh kg^{-1}. Thus, maintenance of the atmosphere at certain parameters requires sufficient energy expenses; therefore, it is crucial to achieve the maximally efficient drying process with a certain drying rate. At the same time, the quality of the product needs to be kept at a high level in order to be accepted by consumers. Along with environmental parameters, such product properties as salt content of being dried ham and pH value of the raw material are the

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parameters also influencing water activity level and drying kinetics of the product.

Considering the complexity of drying kinetics of dry-cured ham, for the process optimization, adequate modeling of water losses must be considered. There are two general approaches used to describe the drying kinetics: physical and empirical (semi-empirical). According to the physical approach, the drying rate is governed by the rate of the two processes—heat and mass transfers [3]. Balance between these two processes is crucial; otherwise, the quality of the product drops; for example, in the case when heat transfer is bigger than mass transfer, the effect called case hardening can appear [4]. It leads to restricted water transfer in the product, and microbial spoilage can occur under the hardening case. In the empirical approach, for hygroscopic 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 [3, 5].

The process of drying hams is normally followed by the ripening process, and the total time when the product loses the weight by dehydration and obtains the necessary textural and flavor characteristics by enzymatic activity can be also called drying–ripening. Dehydration during the drying–ripening contributes to stabilizing the product by decreasing water content and, consequently, the water activity value [6].

This article is a second part of the review paper on dry-cured ham manufacture. In this part, the main processes and product parameters influencing the dehydration of dry-cured ham through the manufacture will be considered along with process modeling used to predict and optimize the drying process. Modern industrial drying systems are represented for overall understanding of the construction, the principals of work performance and the energy consumption parameters.

Dehydration of dry-cured ham during the manufacture

Dehydration in the process of dry-cured ham manufacture mainly takes place during three time-consuming stages: the salting period, the following resting stage and the drying–ripening step.

Generally, the dehydration processes during dry-cured ham production can be described using material (internal) and environmental (external) properties [7, 8]. The most affecting environmental factors are air temperature and air relative humidity. Air velocity is an important parameter in food drying processes, but in the production of dry-cured ham, air speed values are kept small (generally around 0.1–0.5 m s^{-1}) and are supposed to have a little influence on the drying–ripening process. In addition, such material parameter as pH of the raw material and salt content of the being dried ham mainly contribute to the dehydration rates [3, 8–11]. There is still a lack of the information about the influence of initial moisture content on dehydration rate for dry-cured ham. However, [12] reported significant variations of initial water content for *Biceps femoris*, *Semimembranosus* and *Semitendinosus* pork muscles that could be a factor influencing the drying rates of the product. In the work, fifty-two hams from three different producers were used and the water content was reported as follows: 58.3–69.2 % w.b. for *Biceps femoris* muscle, 48.6–66.5 % w.b. for *Semimembranosus* muscle and 53.0–69.5 % w.b. for *Semitendinosus* muscle. As hams are salted and rested before to be dried, the fluctuations in water content can be even bigger due to different salt uptake by different muscles and, as a consequence, different moisture losses during the salting and the resting stages.

External parameters influencing the dehydration of dry-cured ham

Temperature

Temperature regimes during the salting, the resting and the drying–ripening stages of dry-cured ham influence both dehydration rate and the product's final quality and should be adjusted carefully [13]. Protease activity rises with temperature during the dry-cured ham manufacture [14, 15] and affects dry-cured ham softness [16, 17] and pastiness [18]. Lipase activities also increase with the temperature [19, 20] along with lipid oxidation [21]. Generally, lipid oxidation processes at moderate temperatures have good influence on the final product and promote the generation of desirable chemical compounds which are responsible for the distinctive final flavor of dry-cured ham [22–24]. But with the increase in temperature, lipid oxidation is bigger that leads to the formation of unwanted rancid flavor of the final product.

The most common temperature interval for the salting of dry-cured ham is 0–4 °C, and for the resting step, it is 1–6 °C [13]. The temperature modes are maintained within this diapason to reduce the possibility of microbial spoilage and at the same time to avoid freezing [25]. Temperature regimes during the drying–ripening stage vary significantly from the beginning of the process to the end; thus, for Iberian ham, the drying–ripening is split into three time intervals: the first phase is maintained at 6–16 °C, the second at 16–26 °C and the third at 12–22 °C [13]. This temperature range with the adjusted air relative humidity provides necessary moisture diffusivity and allows the adequate activity of meat enzymes that leads to the formation of distinctive quality of the final product.

Salting and resting stages In spite of the fact that temperature conditions are straightly defined for the salting and the resting stage of the dry-cured ham manufacture, there is still a lack of information on the influence of different temperatures on moisture losses during the salting and the resting step. Garcia-Gil et al. [25] studied the temperature influence on salt uptake during the salting stage for *Biceps femoris* muscle of pork. The authors used three different temperatures suitable for the salting step: −1, 0.5 and 4 °C. The work showed that at the highest salting temperature, the hams absorbed slightly more salt (salt content at the end of the salting step is 12.2 % d.b.) than at the lower temperatures (salt content at the end of the salting stage for salting temperatures −1 and 0.5 °C is 11.3 and 11.2 % d.b., respectively); it means that at higher temperatures, salt diffusion is bigger. According to the theory of mass transfer, it is possible to claim that the more the salt is taken by ham, the more the water is going out the tissues. Correlating with the dehydration of the tissues, that means the higher water losses with the rise of temperature during the salting stage. It generally matches up with the common diffusion theory of the influence of temperature on water removal kinetics [3, 26]. Sabadini et al. [27] supported this theory for trapezius muscle of beef. The authors reported that the increase in temperature provokes the rise in water losses for the two types of salting: dry and wet.

There is not much information in the literature on the influence of temperature regimes on moisture losses during the resting step of dry-cured ham manufacture; however, during the resting stage, expected moisture losses are even bigger than during the salting (4–6 % for the salting stage compared to 3–4 % for the resting step) [28] that can be a background for the further investigation.

Drying–ripening stage The dependence of water diffusivity from temperature during the drying–ripening stage has been investigated thoroughly [11, 29, 30]. This correlation can be described by Arrhenius equation for most food products (Eq. 1) [29, 31–33].

$$D = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (1)$$

where D is the diffusion coefficient (m^2 s^{-1}), D_0 is the maximum diffusion coefficient at infinite temperature (m^2 s^{-1}), E_a is the activation energy for diffusion (J mol^{-1}), T is the temperature (K), and R is the universal gas constant (J K^{-1} mol^{-1}).

Gou et al. [11] showed for pork *Gluteus medius* muscle that water diffusivity increases with the temperature growth from 5 to 26 °C during drying. Clemente et al. [29] showed the same tendency of increasing moisture diffusivity with the temperature growth from 5 up to 20 °C for pork *Biceps femoris* muscle. However, based on the performed experiments held by [30] with *Semimembranosus* muscle of pork, a certain variation (13 ± 3 °C) will only have a minor influence on the drying rate. However, one should be careful with temperature increasing due to the possibility of microbiological spoilage since the product undergoes also a certain ripening during drying. The straightly maintained temperature is necessary for quality reasons, which are based on temperature-dependent biochemical reactions.

Relative humidity

The information on the influence of air relative humidity on dehydration kinetics comes down to the claimed general increase in water losses and drop in water activity values with the decrease in relative humidity of the air that is in an agreement with the general drying theory: an increased vapor pressure difference will promote the rise of drying rate [3]. High values of relative humidity can promote such undesirable effects as microbial contamination or mold growth; low values can lead to the case hardening. The most used diapason is 75–95 % for the salting step and 65–80 % for the drying–ripening stage [13]. During the drying–ripening, air relative humidity values are varied throughout the process along with temperature alterations; thus, for Iberian dry-cured ham, the first phase is maintained at 60–80 %, the second at 55–85 % and the third at 60–90 % [13]. Air relative humidity is a crucial parameter, especially during the drying–ripening of dry-cured ham; even minor alterations influence significantly the dehydration rate [30].

Salting and resting stages There is a small amount of information on the influence of relative humidity on the weight losses by osmotic dehydration during the salting and the resting stages. The relative humidity is kept high during the salting step to ensure bigger salt uptake by the meat tissues. However, some researchers claim that high values of relative humidity are undesirable during the resting period of dry-cured ham manufacture since under these conditions the formation of slime [34], mites [35] and molds [36] is possible. A certain reduction in relative humidity is also recommended to avoid phosphate crystallization in the external parts of the ham [37]. At the same time, low values of relative humidity can lead to crustiness [38]. For many high-quality dry-cured hams, relative humidity is forcedly decreased from the salting to the resting step and can be decreased even bigger to the end of the resting [13].

Arnau et al. [38] evaluated the effect of relative humidity of the drying air among other parameters on weight losses and water content and activity during the resting period of dry-cured ham manufacture for *Semimembranosus* muscle. The work was carried out at 4 °C and three different relative humidities (52, 78 and 85 %) during 40 days. The study showed that the weight losses gradually decrease with the rise in relative humidity. The highest water content as well as the highest water activity was observed in the samples at 85 % air relative humidity, and the lowest values were in the samples at 52 %. Comaposada et al. [39] showed the same tendency in their work for pork *Gluteus medius* muscle. The hams were held at three different relative humidities during the resting stage of dry-cured ham manufacture: 70–75, 75–80 and 80–85 % at 4 °C. The hams kept at higher relative humidity showed lower water losses and higher water content and water activity.

Thus, the lower the relative humidity during the resting stage, the lower the moisture content after this period. This tendency is well explained by different drying kinetic equations [39]. Low relative humidities help to avoid microbial spoilage, but there is also a possibility to suppress proteolytic activity since the reduction in water content along with water activity happens together with the increase in salt content [40].

Drying–ripening stage The influence of air relative humidity on drying kinetics has been investigated for meat-based products by many authors [6, 30, 41, 42].

Simal et al. [6] carried out a set of drying experiments at constant drying air temperature (14 °C) and several air relative humidities (70, 75, 80 and 85 %) for a meat-based product (sobrassada). Moisture content of the final product decreased progressively with time, but the authors claimed that there is no significant influence of air relative humidity on the moisture content: A drop of relative humidity only contributed to a slight increase in water losses.

Lykova et al. [41] also investigated the influence of air relative humidity on water losses and water activity for sausage-type meat products. The authors also reported a small rise in the water losses with the drop of air relative humidity—from 18.4 at 88 % relative humidity up to 20.5 at 78 % relative humidity. The same tendency was observed with water activity value—with the decrease in air relative humidity, water activity also slightly dropped. Stiebing and Roedel [42] also studied weight losses for meat-based product (salami) and obtained similar results.

However, [30] claimed that relative humidity of the drying air influences the drying rate significantly. The work was carried out at three different humidities (60, 68 and 80 %) at 13 °C. The authors reported a significant increase in the drying rate with the drop of humidity and suggested to maintain air relative humidity thoroughly since even small alterations influence significantly the dehydration rate.

Air velocity influence on the drying–ripening

Clemente [1] studied the drying behavior of *Biceps femoris* and *Semimembranosus* muscles of pork under different air velocities (0.6, 2.0, 2.8 m s^{-1}) at 25 °C. The authors reported that drying kinetics was influenced by the air velocity and the moisture diffusivity coefficient was higher at higher speeds of the air for the both muscles. The influence was stronger for low air velocities; for air velocities over 2 m s^{-1}, the authors suggested that the increase in air velocity did not influence the drying kinetics and the drying process was mostly governed by the internal resistance to mass transfer. However, since during the drying–ripening stage air velocity is maintained very low, it is believed that in the dry-cured ham manufacture, the influence of air velocity is negligible for the drying rate [30]. In the process of drying–ripening, the most important changes are biochemical; moisture losses during this period should be kept low enough to enable proteolytic and lipolytic enzymes to work effectively. But a certain value ought to be adjusted to allow the air to flow freely between the hams to prevent molds and yeasts growth or microbial spoilage [13]. At the same time, the speed of the air should be kept low enough to prevent undesirable acceleration of drying rate or case hardening. Furthermore, the increase in air speed will not only cause undesirable moisture losses but also give the rise to energy consumption that should be avoided.

Internal parameters influencing the drying rate of dry-cured ham

Salt content

Each type of dry-cured ham has characteristic salt content which varies significantly from type to type. So, for Parma ham, the final salt content ought to be 4.2–6.2 % [43]; for Iberian ham, 6.5 % [13]; and for Bayonne ham, 7.7 % [44]. But there are several species which have even higher salt content including Toscano and Juinhua hams with 8.3 % [45] and 8–15 % of salt concentration, respectively [46].

It has been reported by several authors that salt content influences the drying kinetics of dry-cured ham during the drying–ripening stage [11, 30]. Gou et al. [11] reported the difference in moisture diffusivity depending on NaCl content for *Gluteus medius* muscle of pork salted by wet salting. The authors investigated unsalted meat and meat salted using three different salt solutions (2, 5 and 8 kg NaCl/100 kg H_2O). Moisture diffusion coefficient predictively decreased with the increasing salt content in the samples (from 6.2 × 10^{-11} m^2 s^{-1} for unsalted meat to 2.2 × 10^{-11} m^2 s^{-1} for the meat with salt content 30.1 kg NaCl/100 kg H_2O) at the drying temperature 13 °C and the air relative humidity 80 %. Bantle et al. [30] investigated the influence of salt concentration on drying kinetics of *Semimembranosus* muscle of pork using unsalted (<3.6 % dry matter), low salted (<24.4 % dry matter) and high salted (28.4 % dry matter) samples salted by dry salt.

The drying was also held at 13 °C and 80 % air relative humidity. The effective diffusion coefficient dropped from 3.5×10^{-11} m^2 s^{-1} to 1.2×10^{-11} m^2 s^{-1} for the unsalted and the high salted samples correspondingly. The main tendency is clear observed from the discussed works: the higher the salt content of the samples, the lower the water diffusivity during drying.

In general, the final quality of dry-cured ham is positively influenced by salt. Water activity of the product is reduced with time that gives better product stability. Moreover, there are solubilization and cohesiveness of myofibrillar proteins that give the final product its specific taste and texture [47]. At the same time, as it was mentioned above, some dry-cured ham species such as Italian Toscano, French Bayonne or Chinese Jinhua contain unnecessarily high salt content. In some countries such as Australia and the USA, the recommended salt consumption level is limited up to 6 g/day per person [48]. Extended salt intake can lead to hypertension, cardiovascular disease and stroke [49–51]. With the rising awareness about the need of salt reduction, there are some attempts to reduce salt content in dry-cured ham [33, 52]. However, the potential of salt reduction is restricted due to the high proteolysis rate of the dry-cured ham with low salt content and, consequently, high softness and the possibility of spoilage the product [16, 53].

pH value

pH values of pork meat have significant influence on the quality of dry-cured ham [54]; it is one of the parameters which allow us to classify the raw hams according to the suitability to use them for the dry-cured ham manufacture [13]. pH level of the raw meat influences both water holding capacity, microbial and proteolytic activity of the ham during the manufacture and organoleptic quality of the final product [53–55]. He et al. [56] investigated the hams separated on two groups according to the pH value in *Semimembranosus* muscle at 24-h postmortem: with low (<5.55) and with normal (>5.55) pH. For the low-pH hams, moisture content of the final product determined in *Biceps femoris* muscle was lower than for the normal-pH counterparts. Guerrero et al. [57] studied the influence of high pH (>6.2) and normal pH (<5.8) in *Semimembranosus* muscle of raw hams at 24-h postmortem and reported that the dry-cured hams produced from the hams with high pH value had higher moisture content than the hams produced from the hams with normal pH (measured in *Biceps femoris* muscle). But, the high-pH hams after the dry-curing process were pastier, softer, more crumbly and adhesive which are the drawbacks of the final quality.

According to [13], hams should be checked according to pH values at 1- or 24-h postmortem. Only hams with pH at 1-h postmortem above 6.0 and/or hams with pH at 24-h postmortem 5.6–6.1 should be chosen due to higher moisture content and lower salt diffusivity than the hams with neutral pH. This range of pH values provide high economic effect and allow us to avoid microbial spoilage or high water loses.

Modeling

The main aim of the models which describe the drying process is to provide the information about moisture loss throughout the process without expensive and long experiments. Since dry-cured ham producing is the longest step in the dry-cured manufacture (the duration varies from several months up to 48 months for the highest quality ham), modeling is a useful tool to control and predict drying kinetics for evaluation the process.

It is difficult to find a general model which will suit for all food products, and normally research works are focused on the idea to find a certain drying model for a defined product. The two modeling approaches that will be discussed and compared in the paper are a physical approach based on the similarity between coupled heat and mass transfer and an empirical (semi-empirical) approach based on diffusion coefficient. Semi-empirical models are mostly used in drying technology due to their simplicity and rather high accuracy.

Using an appropriate model, it is possible to establish efficient mass transfer analysis and achieve reproducibility of the quality of the controlled products [58].

Empirical and semi-empirical models

Fick's second law of diffusion

Fick's second law of diffusion is a common dependence between the concentration field and the diffusive flux under the consumption of steady state conditions. In the case of convective drying, mass transfer is driven by the concentration gradient. The correlation basically depends only on one parameter (diffusion). Equation 2 describes the concentration influenced by diffusion with time [5].

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \tag{2}$$

where C is the concentration of diffusing substance (amount of substance) (length)$^{-3}$, x is the space coordinate measured normal to the section (length), D is the diffusion coefficient (length^2 time^{-1}), and t is the time (s).

One-dimensional mass transfer is therefore described by Eq. (3).

$$\frac{\partial M}{\partial t} = D_{\mathrm{eff}}\frac{\partial^2 M}{\partial x^2} \tag{3}$$

Under the assumption of uniform initial moisture content, one-dimensional moisture movement, moisture transport which is controlled by internal diffusion and no shrinkage, Eq. (3) can be solved for known geometric shapes. The solutions of Fick's second law regarding mass transfer for a sphere, cylinder and infinite slab are described by Eqs. (4, 5 and 6), respectively [5, 59].

$$MR = \frac{6}{\pi^2} \sum_{n=1}^{\inf} \frac{1}{n^2} \exp\left[-n^2 \frac{\pi^2 D_{\mathrm{eff}} t}{r_{\mathrm{sphere}}^2}\right] \quad (4)$$

$$MR = \sum_{n=1}^{\inf} \frac{4}{\mathrm{Be}_n^2} \exp\left[-\frac{b_n^2 D_{\mathrm{eff}} t}{r_{\mathrm{cylinder}}^2}\right] \quad (5)$$

$$MR = \frac{8}{\pi^2} \sum_{n=1}^{\inf} \frac{1}{(2n-1)^2} \exp\left[-(2n-1)^2 \frac{\pi^2 D_{\mathrm{eff}} t}{L^2}\right] \quad (6)$$

where MR is the moisture ratio (dimensionless), n is the positive integer (dimensionless), Be is the root of the Bessel function (dimensionless), r is the radius (m), and L is the slab thickness (m).

For long duration of drying when t is big, but geometric factor r or L is small, only the first term of the series can be taken for calculation [5] (Eqs. 7, 8, 9).

$$MR = \frac{6}{\pi^2} \exp\left[-\frac{\pi^2 D_{\mathrm{eff}} t}{r_{\mathrm{sphere}}^2}\right] \quad (7)$$

$$MR = \frac{4}{B_1^2} \exp\left[-\frac{\mathrm{Be}_1^2 D_{\mathrm{eff}} t}{r_{\mathrm{cylinder}}^2}\right] \quad (8)$$

$$MR = \frac{8}{\pi^2} \exp\left[-\frac{\pi^2 D_{\mathrm{eff}} t}{L^2}\right] \quad (9)$$

These solutions can be rewritten in logarithmic form (Eq. 10) [31, 59, 60].

$$\ln(MR) = A - Bt \quad (10)$$

where constant B for sphere, cylinder and an infinite slab is as follows (Eqs. 11, 12, 13).

$$B = \frac{\pi^2 D_{\mathrm{eff}}}{r_{\mathrm{sphere}}^2} \quad (11)$$

$$B = \frac{\beta_1^2 D_{\mathrm{eff}}}{r_{\mathrm{cylinder}}^2} \quad (12)$$

$$B = \frac{\pi^2 D_{\mathrm{eff}}}{L^2} \quad (13)$$

The slope (B) is derived by plotting ln (MR) versus time using Eq. (10). Moisture ratio is generally obtained from experiments of a suitable comparable length. The effective diffusivity coefficient is derived from the slope.

Weibull model

The modified Weibull model depends on two parameters: scale parameter α (s) and shape parameter β (dimensionless) and can be represented as follows (Eq. 14) [61].

$$\frac{X_{\mathrm{w}} - X_{\mathrm{we}}}{X_{\mathrm{w0}} - X_{\mathrm{we}}} = MR = \exp\left(-\left[\frac{t}{\alpha}\right]^{\beta}\right) \quad (14)$$

where X_{w0} is the initial moisture content (kg/kg dry basis), X_{w} is the moisture content at time t (kg/kg dry basis), X_{we} is the equilibrium moisture content (kg/kg dry basis), and t is the time (s).

Parameter α represents the time needed to accomplish 63 % of the process; the rate of the process can be described by this value [62]. Mass transfer rate at the beginning is related to parameter β: the faster the drying rate, the lower the β [62]. Regarding dehydration, when $\beta > 1$, the product loses weight and the drying process continues; when $\beta = 1$, the Weibull model reduces to first-order kinetics [62].

To take into account diffusion occurring during drying, the Weibull model can be rewritten in the form of the modified Weibull model by replacing scale parameter α by (Eq. 15) [58, 62, 63].

$$\alpha = \frac{L^2}{D_{\mathrm{calc}}} \quad (15)$$

where D_{calc} ($m^2\ s^{-1}$) is the calculated apparent water diffusion coefficient, and L(m) is the half-thickness of the matter dried.

Thus, a modified Weibull model has the form of (Eq. 16).

$$MR = \exp\left(-\left[\frac{D_{\mathrm{calc}} t}{L^2}\right]^{\beta}\right) \quad (16)$$

D_{eff} can be then calculated from (Eq. 17).

$$D_{\mathrm{eff}} = \frac{D_{\mathrm{calc}}}{R_g} \quad (17)$$

where R_g is the geometric factor.

The analytical solution of the Fick and the Weibull models is quite similar. The only difference is the beta parameter, which implements a shape correction. The β parameter is considered for all non-ideality of the assumptions (non-uniform moisture distribution, shrinkage, etc.). The α or D_{calc} parameter basically includes all the other influencing parameters from Cranks analytical solution.

Physical models

The knowledge of heat and moisture transport is crucial for the process design, energy savings and product quality. But moisture transport during drying is described with difficulties by a physical model due to the complexity to find and fit product-specific properties as a function of process parameters. Bantle et al. [30] made an attempt to use a physical model to describe drying process, but it overestimated the drying rate, especially at the beginning comparing with the experimental results obtained at the same process parameters. Further effort should be applied to find physical correlations which will be able to fit the drying rates.

Industrial drying systems

The production of dry-cured ham is ancient preservation technique which improved food security centuries before the process was industrialized. The industrialization of the process improved food security, process stability and product quality, while at the same time the production is no longer depended on the local climate. Most producers have developed their own process parameters over the years, which give their product its characteristic appearance and taste. However, the process equipment used for the production is similar, since the main controlled parameters are temperature and humidity of the drying air.

Every drying process depends on the availability of a drying agent (mostly air) which removes the evaporated water from the product and at the same time supplies the necessary latent heat for water evaporation. Therefore, drying is a combined heat and mass transfer process. The design of a drying chamber ensures a good contact between the drying air and the being dried product and is therefore important for the drying rate, production time and product quality. A supply system for the drying agent provides the necessary amount of drying air with a certain temperature and humidity. The economy of the drying process depends on the design of the supply system, while the product quality is among other parameters defined by the construction of the drying chamber. In the following, the different characteristic drying systems which are used in the industrial productions are summed up.

Drying chamber

There are a large number of possible constructive solutions of drying chambers for dry-cured hams [64]. The size of industrial drying chambers is determined by the production rate, time for drying as well as minimum requirements for air flow. In most cases, the drying chamber is a room equipped with racks where the product is placed. The hams are normally hanged by the feet. For high-quality hams, it is not uncommon that the drying chambers can hold several thousands of hams at the same time. However, lager chambers are difficult to construct with respect to uniform air flow distribution, which can cause problems with the drying rate in places where too much or too little air is ventilated. It is therefore advisable to separate large chambers into smaller units where the air flow distribution as well as the drying progress can be better controlled.

The mass flow of the drying air must be enough to ventilate the whole drying chamber and to remove the evaporated water from the product. Since the drying air is generally the only energy supply into the drying chamber, the heat losses of the process must be also taken into account. In most cases, the local velocity in drying chambers for dry-cured ham is quite small in comparison with drying systems for other products due to the specific drying rate of hams. The size of the ventilation system is depending on the correct determination of the necessary mass flow of the drying air. An over-dimensioned ventilation system can result in a sufficient air flow and uniform air distribution, but causes also higher operation costs since more air than necessary is moved around in the system.

Heated ambient air drying (HAAD)

Traditionally, the ambient air was used for the production of dry-cured ham and a large amount of facilities still use the ambient air as a drying agent, especially in regions where the local climate is similar to the drying conditions of the production. A drying system based on the ambient air has a relatively simple configuration and has therefore low investment costs (Fig. 1) [65]. This might be one reason for the popularity of this system. The temperature of the ambient air in the most cases is not equal to the necessary drying temperature;

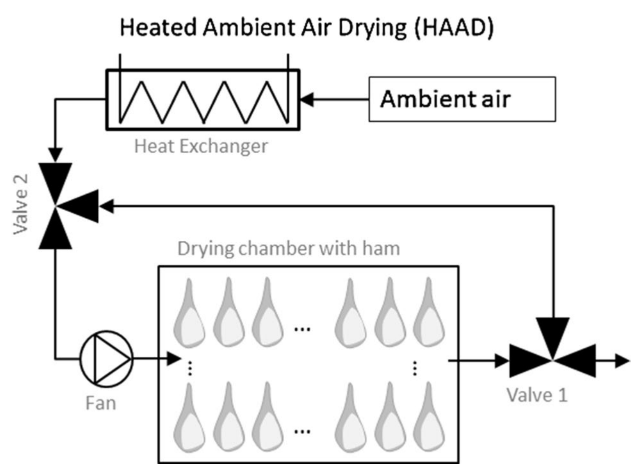

Fig. 1 Drying of ham using ambient air as drying agent

hence, the air is first heated in a heat exchanger before it is directly ventilated into the drying chamber. For hygienic reason, it is generally recommended to install a filter element before the ambient air is used in the process. In the cases when the ambient temperature is higher than the drying temperature, it is also possible to cool it down with the same heat exchanger when secondary heating/cooling media are used. Alternatively, the air is bypassing the heat exchanger for heating and a separate heat exchanger connected to a cooling loop is installed. Using the heat exchangers, it is possible to maintain the correct drying temperature. The humidity of the drying air can be adjusted by mixing a part of the wet air at the outlet of the drying chamber with the fresh drying air; the mixture is supplied back to the drying chamber. By adjusting the mass flow of a heating or cooling medium through the exchanger and the degree of mixing between fresh and moist drying air, it is possible to obtain the necessary parameters of the drying air. The regulation of the system needs to adjust these parameters continuously depending on the ambient conditions. HAAD systems depend on the seasonal variation of the ambient air, and problematic operation points might occur when the ambient humidity is too high. The economics of the process depends consequently on the amount of required heating and cooling and the seasonal variation of the ambient air parameters. If the heating or cooling energy can be supplied by excess energy from other operations of the production plant, the process can be quite economic. However, if a primary energy source for the heating and cooling operation of the HAAD system is necessary, the drying efficiency (which equals to the latent heat of evaporation divided by supplied energy to the system) can be low. This is especially true in regions where a large discrepancy between the conditions of drying air and ambient air is present.

Closed looped drying system

When the drying air is circulated through the process in a closed loop, there will be no influence or disturbance with the ambient air and the process is more stable and needs less regulation after initial adjustments (Fig. 2) [65]. Still, the evaporated water which was taken up from the product needs to be removed from the drying air. Commonly, this is done by cooling the air down below its dew point, so that the moisture is condensed out. The dehumidified air needs then to be heated up again in a second heat exchanger to its desired drying temperature. The heat exchangers for cooling use a cooling medium which is tempered by a separate cooling system. The same principle can be also used for the heat exchanger for re-heating of the drying air; however, in some cases also direct heating is used here in order to avoid another heating system and to minimize heat transfer losses. The regulation of a closed loop system is done by controlling the mass flow of the heating or cooling media

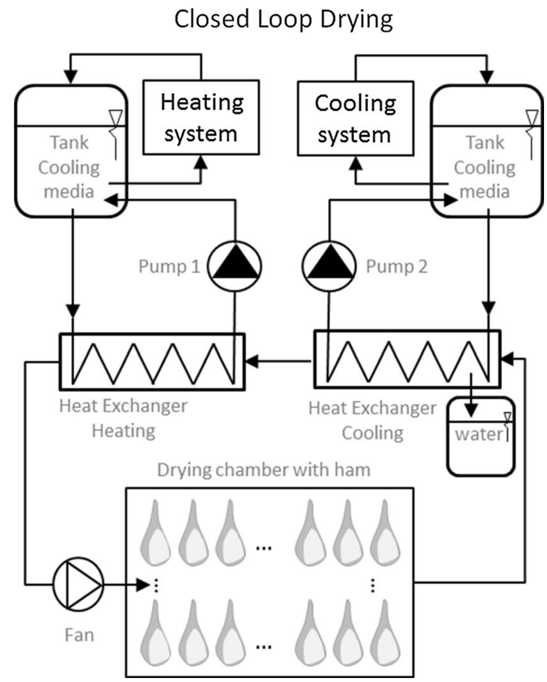

Fig. 2 Closed loop drying system with conditioning of drying air through heating and cooling loop

by their respective pumps. It is also possible to use excess heat from other processes in the production plant for re-heating of the drying air; however, for cooling normally a refrigeration cycle is necessary. The investment costs for a closed loop drying system are moderate but can be high due to the need of two different thermal operations (cooling followed by heating) or when more sub-systems are needed. The drying efficiency of such system is therefore quite often lower than 30 %. However, the operation is easy to control and the process is stable, which is why this system is very common in industrial applications.

Heat pump drying

In a closed loop cycle, it is necessary to cool the air in order to dehumidify it so that the drying air can be used again. Heat pumps are characterized by the possibility to produce cooling energy at the evaporator and heating energy at the condenser [66]. For the case of closed loop drying, this combined heat and cool load can be used to recover the drying energy (basically the latent heat of evaporation) and deliver this energy back into the drying process in the form of dehumidified and re-heated drying air. Heat pump drying consists of two loops: one closed loop for the drying air and one closed loop for the refrigerant of the heat pump (Fig. 3) [67, 68]. At the evaporator of the heat pump, the drying air is cooled down and the moisture from the air is condensed. Energy is hereby transferred to the refrigerant,

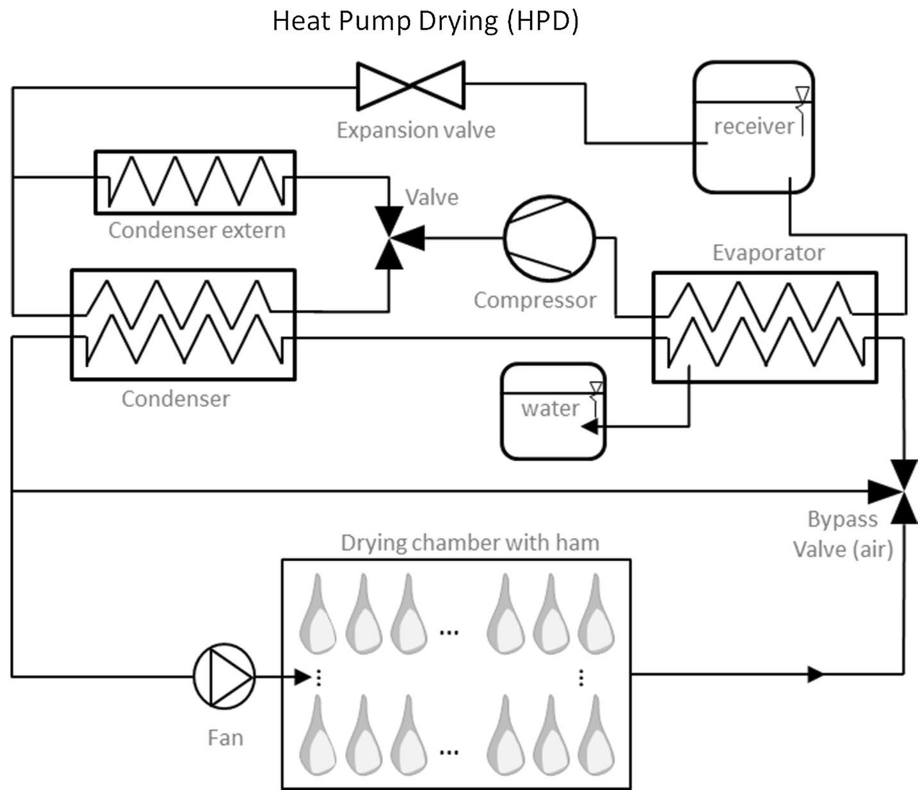

Fig. 3 Heat pump drying of ham with bypass

which is evaporated. The evaporated refrigerant is then compressed and can now be condensed back to the condenser at higher temperature. Hereby, the formally transferred energy is given back to the drying air which is then re-heated to its initial desired condition. Since both loops are closed, it is necessary to install a second, external condenser in order to transfer the excess heat out of the system. The external condenser is normally installed parallel to the main condenser, and the mass flow is controlled by a three-way valve. The main source for the excess energy is the compressor, which also should be equipped with a rotation speed control in order to ensure optimum working conditions at varying heat and cooling loads. It is also recommended to install a bypass valve for the drying air, so that only the necessary amount of drying air is cooled and re-heated; this makes the operation more efficient.

The drying efficiency of heat pump drying is normally between 80 and 90 % and therefore significantly higher compared to conventional HAAD or closed loop drying [69]. Correctly designed and operated heat pump driers can save up to 80 % of the drying energy from conventional driers [70]. However, installation costs are higher and the energy price for the primary energy can reduce the economic benefit. In Nordic countries, heat pump driers are widely used in dry-cured fish production since the 1980s, which kept the industry competitive on international markets. Some commercial household cloth driers are also equipped with heat pumps in order to fulfill energy requirements. It is expected that energy prices as well as political regulations will force the industry to implement this technology in larger numbers.

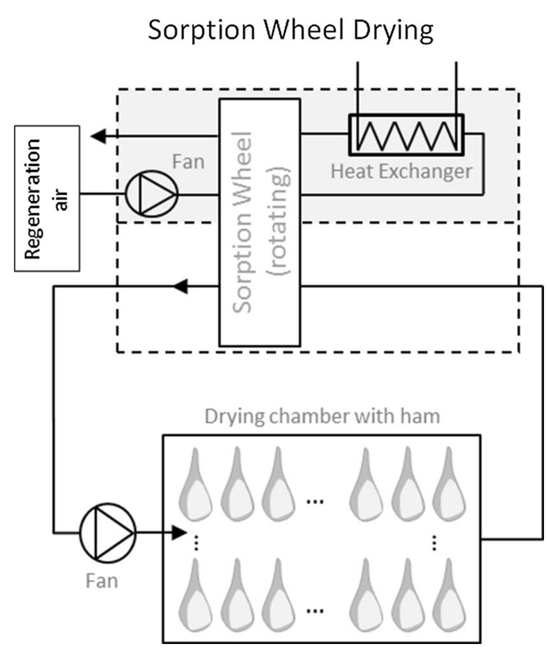

Fig. 4 Regeneration of drying air through sorption wheel

Table 1 Comparison of relative costs, efficiencies and operation complexity for different system solution for drying of dry-cured ham

Type	Installation costs	Operational costs	Drying efficiency (%)	Operational complexity
HAAD	Low	Moderate–high	30–40	Low
Closed loop	Moderate–high	High	20–35	Low
HPD	High	Low	80–90	Moderate
Sorption wheel	Moderate	Moderate–high	~30	Low

Sorption drying

Certain materials (e.g., silica gel) have very good sorption characteristics toward air humidity, which can be used for dehumidification of drying air. Still, the sorption material can only take up a limited amount of water from moist air and the regeneration of the sorption material is therefore of a key requirement for closed loop drying cycles with sorption-based dehumidification. Most often, this technology is implemented as a slowly rotating sorption wheel, where one part of the wheel is dehumidifying the drying air, while the other part is regenerated by a separate regeneration cycle (Fig. 4). The regeneration cycle uses also the air, but at significantly higher temperatures, so that the water is desorbed from the sorption material and leaves the system. The only energy supply to the system is a heat exchanger in order to heat the regeneration air. Different available heat sources can be used as an energy source including the excess energy from other operations of the plants. Operational conditions of sorption wheels require low temperatures, high humidity of the drying air and moderate air flow rates, which confirms well with process parameter in dry-cured ham production. The drying efficiency of sorption drying is similar to closed loop drying or HAAD. The operational costs can be low, if excess heat from other process in the production facility is available as a heat source. The operation of a sorption wheel is not complicated, and the system can be controlled through the amount of ventilated drying and regeneration air as well as the capacity of the heat exchanger.

Comparison of different drying systems according to energy efficiency is presented in Table 1.

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Conflict of interest None.

Compliance with Ethics Requirements This article does not contain any studies with human or alive animal subjects.

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