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Drying model for small tumbled beef pieces (*biltong*) at ambient and mild air temperatures

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Abstract

The literature on the modelling of meat drying mainly focuses on large pieces of pork with very few studies on small pieces of beef, particularly when previously tumbled with salt and vinegar. In this study, the drying kinetics of tumbled small pieces of beef (*biltong*) were investigated experimentally using a pilot dryer that allowed precise control of the air conditions. The kinetics were then modelled using a 2-compartment model that mimicked the diffusion model. Results showed that two experimental drying kinetics were enough to identify model parameters and to mimic the drying behaviour of *biltong* of different sizes subjected to a wide range of drying conditions [25 – 55°C, 30 – 40%RH]. The model also produced acceptable results (mean error on moisture content < 0.1 *d.b.* and $r^2 > 0.99$) for simulating *biltong* drying in industrial conditions. This model can be used as a sizing tool for small and medium drying plants in southern Africa.

Keywords: meat drying, convective drying, salted beef, compartmental model, drying kinetics

Running title

Drying model for small beef pieces

Practical application

Drying is widely used to process traditional meat products such as the salted/dried *biltong* in South Africa. The final product and the manufacturing process used to produce *biltong* are well described by ?. *Biltong* is original because it is made of strips of meat while up to now, modelling studies have mainly dealt with large meat muscles, like dried cured ham. *Biltong*, on the other hand, resembles to many other salted/dried products made from small meat muscles all over the world or meat strips mainly in developing countries but not only, for example jerky in the USA. The model developed will be useful for the prediction of drying time by processors who wants to ensure their end product remain stable and have to cope with variations in the size of the meat strips and in the temperature of the drying air.

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1. Introduction

Meat preservation is a major challenge in developing countries due to high perishability and the prevailing climatic and environmental conditions that lead to its rapid deterioration. In countries where refrigeration facilities are not available, if meat is not intended to be consumed immediately, it is processed using a wide range of traditional techniques such as salting, drying, smoking, cooking and fermentation used individually or in combination. The use of small muscles or muscles cut into strips allows the processing time to be reduced. A wide range of these popular traditional meat products are *kilishi* in the Sahel (?), *charque and carne do sol* in Brazil (?), *boucané* in Reunion Island (?), *pastirma* in Turkey (?), *kitoza* in Madagascar (?), *kaddid* or *gueddid* in North Africa (?) and *biltong* in South Africa (?). Biltong has an original feature which makes it different from other salted and dried meats in that it is frequently acidified with vinegar during processing. In addition, the final product is ready-to-eat meaning it requires no further preparation before consumption. The processing of biltong includes trimming, salting and acidification, spicing and drying. Thanks to its popularity in South Africa, biltong has become an everyday consumer product. Biltong can be made of different meats, but the best one is made from the meat of herbivorous animals (beef, antelope, etc.). In the last decade, biltong manufacturing has been industrialized which makes it available in supermarkets in South Africa and abroad, for example in Australia, United Kingdom, Netherlands, France, southern Africa, USA). The product is commonly sold in different forms including the whole muscle ('tongues'), as 'sticks' or slices, cubes, ground or pulverized. Different processes are used to prepare both modern and traditional biltong. Usually, two steps are involved. The first one is with wet or dry curing (typically 2.5% of salt and 5% of vinegar including spices –pepper and clove) in static mode or in a tumbler. The second one is drying at ambient temperature for one or two weeks at the artisanal scale and between 1 and 3 days at the industrial scale (?). Biltong is a shelf-stable product considered as an intermediate-moisture food (?) because of its moisture content (20–50%), water activity (0.60–0.90) and salt content (4–8%). However, the traditional process has been transferred at the industrial scale with no technological advances and processing has remained empirical, long and poorly-controlled. Today's consumers are increasingly concerned about healthy food and want less salty products with limited processing, which induces the shelf life of the product is shorter than that of the traditional biltong (??). In this context, processing needs to be strictly controlled to prevent problems with end-product stability. A recent study focussed on the first step of curing and demonstrated the advantages of tumbling and, using modelling tools, showed the impact of the main variables on the mass transfers of salt, acid, and water and on solutes profiles (?).

To date, modelling of meat drying have mainly focused on large pieces of pork. Only a few studies have modelled the drying of small muscles or strips, mainly of fresh meat (??) and salted meat (??). It is well known that the salt content of the meat affects the desorption isotherm and consequently drying kinetics (?), but only one recent study (?) showed that beef drying kinetics were closely linked with salt content. To our knowledge, very little literature is available on the modelling of drying of previously formulated small pieces of meat and none on beef that has undergone salting and acidification. The

objective of this study was consequently to analyse and model the drying kinetics of a biltong type meat previously salted and acidified to design a tool to help size the installations and optimize the drying conditions for small and medium-sized production units.

2. Materials and methods

2.1. Raw material

Beef muscles (*semitendinosus*) were sourced from a local supplier. External fat was removed and the meat cut into parallelepiped pieces, 20 mm thick, 65 mm wide and 200 mm long in the case of large pieces; the complete list of sizes is presented in table ???. The pieces of meat were vacuum packed, rapidly frozen and stored at -18°C until use. Before use, they were thawed for about 15 h at 4°C then for 1 h at 10°C . This procedure allowed the whole study to be carried out on the same batch of meat and thus limited this source of variability. This pre-treatment is widely used in laboratory studies and has no impact on the drying behavior of the product (?).

2.2. Tumbling

The pieces of meat were individually tumbled with 2.5% weight-per-weight basis (w/w) fine salt and 5% (w/w) white vinegar of a 10% weight-per-volume basis (w/v) acidity for 60 min at 10 rpm at 10°C in a laboratory-made Plexiglas tumbling device described by ?. At the end of tumbling, the pieces of meat were blotted dried, vacuum packed and stored at 4°C for about 15 ± 3 h before drying.

2.3. Drying

Drying kinetics were obtained using a pilot dryer (figure ??) i.e., a loop of circulating air comprising (i) an electric heater, (ii) a steam generator, (iii) a fan and (iv) a vertical drying chamber (30 cm x 30 cm x 100 cm) where the pieces of meat were hung parallel to the air flow. An automatic system controls the steam generator, the electric heater and the vent outlet to continuously maintain air conditions (temperature, relative humidity, velocity) at the desired values. The pieces of meat hung on the racks were automatically weighed with a *PM16* balance (Mettler Toledo, France) and the weight was recorded by on-line computer. The experimental conditions and the specific conditions of (?) are listed in table ??. Temperature was set at 35, 45 or 55°C . Relative humidity was set at 30% or 40% and air velocity at $1.8 \text{ m} \cdot \text{s}^{-1}$ in all the drying experiments. Moisture contents during drying were calculated from the initial experimental moisture content and periodic on-line weighing of all the pieces of meat (at 30 s intervals for the first 30 min or 15 min –depending on the temperature–, and then at 60 s intervals).

2.4. Sampling and sample preparation

Raw material was sampled from off-cuts of the pieces of meat and vacuum packed and stored at 4°C for less than 24 h before sample preparation. Some tumbled meat pieces were sampled after storage at 4°C for 24 h. Dried meat pieces were vacuum packed and stored at 4°C for 24 h. For sample preparation, the meat was cut into small cubes and then ground at 5,000 rpm using a *GM200* (Grindomix, France).

2.5. Physico-chemical analyses

Moisture content determination was adapted from French standard NF V04-401 (?) by placing a 10 g sample at 103°C and under atmospheric pressure for 24 h. Water activity was measured at 25°C using an *AquaLab 4TE water activity meter* (Meter group, France). Salt content was determined with a *Model 926 Chloride Analyzer* (Sherwood Scientific, UK) after 2 h of cold extraction in 0.3 N nitric acid. For pH analysis, 3 g of sample was mixed with 27 ml of dH_2O using a magnetic stirrer for 30 min. pH was then measured under continuous stirring using a *Titroline easy titrator* (SI Analytics GmbH, Germany). All analyses were performed in duplicates.

2.6. Experimental uncertainties

Using a set of three repetitions with the same drying kinetic (large size) at 35°C and 30% of relative humidity, it was possible to estimate the standard deviation σ of the error between the three measured product moisture contents at each sampling time. According to our experimental observations, σ is constant (maximum value of 0.06 *d.b.*) at low moisture content X then decreases with higher moisture contents, according to the following empirical equation:

$$\sigma \approx \min(0.060, 0.105 - 0.040 \cdot X) \quad (1)$$

In the rest of this paper, each vertical error bar is assumed to be equal to $\pm 2 \cdot \sigma$ (with a 95% probability). It should be noted that similar uncertainties applied to the simulated kinetics but are not shown in this paper to avoid overlapping data on figures.

2.7. Computer implementation

The model, composed of ordinary differential equations (ODE), was numerically solved using Backward Differentiation Formulas (BDF) implemented in *solve_ivp* in SciPy open source library. The program was written in Python 3.7 and takes less than 10 seconds to simulate 10 drying kinetics on a *HP EliteBook Folio 1040 G3* (Hewlett-Packard, USA) with an i7-6600U CPU at 2.60GHz and 16GB of RAM and running the Linux Debian 64bit operating system. The numerical identification of the transfer coefficients was obtained with the same Python program using *minimize* function from SciPy set for the Nelder & Mead robust method. The search was set to minimize the sum of squared relative errors, each experimental kinetic being weighed by its number of points. It usually took about 15 minutes to converge.

3. Model description

In the model, the beef pieces are considered as two compartments in series (figure ??). The internal one (noted #1) represents most of the volume while the outer one (noted #2) represents the surface volume. As stated by ? and ?, for a simple geometry (*i.e.* slab, cylinder, sphere), using a 2 or 3-compartment model can mimic a diffusion model with far less computational effort very well. The authors recommended choosing the volume of compartment #1 (noted V_1) as 73% of the total volume V_p , hence $V_1 = 0.73 \cdot V_p$ and $V_2 = 0.27 \cdot V_p$.

Shrinkage was neglected in order to assess the relevance of a modelling approach as parsimonious as possible. Moreover, taking shrinkage into consideration would lead to mathematical complications due to partial derivatives related to the non constant volume and surface and increased computation time.

At the interface between the surface of the biltong and the surrounding air, the convective mass flux density (ϕ_m in $kg \cdot s^{-1} \cdot m^{-2}$), which accounts for the vaporization of water at the surface, can be expressed as:

$$\phi_m = k_{2 \leftrightarrow a} \cdot (Pv_a - Pv_2) \quad (2)$$

where $k_{2 \leftrightarrow a}$ is the mass (water) transfer between the outer compartment and the surrounding air and

$$Pv_2 = a_w(X_2, T_p) \cdot Pv_{sat}(T_p) \quad (3)$$

where Pv_a is the partial pressure of vapour in the air, (Pv_2 is the partial pressure of vapour in equilibrium with compartment #2), X_2 is the moisture content (*d.b.*) of compartment #2, T_a is the drying temperature and T_p is the bulk temperature of the product.

Similarly, the convective heat flux density (ϕ_h in $W \cdot m^{-2}$) between compartment #2 and the surrounding air can be expressed as:

$$\phi_h = h_{2 \leftrightarrow a} \cdot (T_a - T_p) \quad (4)$$

where $h_{2 \leftrightarrow a}$ is the convective heat transfer coefficient between compartment #2 and the surrounding air.

It should be noted that in equations ??-??, Pv_2 is assumed to be equal to the partial pressure of vapour at the surface, and T_p is assumed to be equal to the temperature of the biltong at its surface. This is arguable since the product and its compartment #2 have non-negligible volumes, hence it is a biased estimate of what actually happens at the true surface. This simplification leads to slightly different transfer coefficients ($h_{2 \leftrightarrow a}$ and $k_{2 \leftrightarrow a}$) from what they truly are, when it comes to parameter identification.

Using the Chilton-Colburn analogy (??), $k_{2 \leftrightarrow a}$ and $h_{2 \leftrightarrow a}$ can be related as follows:

$$k_{2 \leftrightarrow a} \approx \frac{h_{2 \leftrightarrow a}}{65 \cdot Lv} \quad (5)$$

where Lv is the specific latent heat of water vaporization, in $J \cdot kg^{-1}$.

3.1. Mass balances

The water flux between compartments #1 and #2 is proportional to the difference in their moisture contents (X_1 and X_2). Neglecting shrinkage, one can write:

$$\rho_{dm} \cdot V_1 \cdot \frac{dX_1}{dt} = k_{1 \leftrightarrow 2} \cdot A_{1 \leftrightarrow 2} \cdot (X_2 - X_1) \quad (6)$$

and

$$\rho_{dm} \cdot V_2 \cdot \frac{dX_2}{dt} = A_{2 \leftrightarrow a} \cdot \phi_m - k_{1 \leftrightarrow 2} \cdot A_{1 \leftrightarrow 2} \cdot (X_2 - X_1) \quad (7)$$

where ρ_{dm} is the mass of the dry matter over the total volume (in $kg \cdot m^{-3}$), the total product volume is $V_p = V_1 + V_2$ (in m^3), $A_{1 \leftrightarrow 2}$ is the interfacial area between compartments #1 and #2 and $A_{2 \leftrightarrow a}$ is the interfacial area between compartment #2 and surrounding (drying) air (in m^2).

Since the global moisture content X_p of the sample can be expressed as:

$$X_p = \frac{V_1 \cdot X_1 + V_2 \cdot X_2}{V_1 + V_2} = \frac{V_1 \cdot X_1 + V_2 \cdot X_2}{V_p} \quad (8)$$

one can write:

$$\rho_{dm} \cdot V_p \cdot \frac{dX_p}{dt} = \rho_{dm} \cdot V_1 \cdot \frac{dX_1}{dt} + \rho_{dm} \cdot V_2 \cdot \frac{dX_2}{dt} = A_{2 \leftrightarrow a} \cdot \phi_m \quad (9)$$

3.2. Heat balances

Given the low thickness of biltong products, the temperature gradient inside the sample was neglected. Hence, only one -bulk- temperature T_p was considered:

$$\rho_p \cdot V_p \cdot \frac{d(Cp_p \cdot T_p)}{dt} = A_{2 \leftrightarrow a} \cdot \phi_h + A_{2 \leftrightarrow a} \cdot \phi_m \cdot (Lv + Cp_w \cdot T_p) \quad (10)$$

where the term $(Lv + Cp_w \cdot T_p)$ accounts for enthalpy loss due to water loss (Lv is the specific latent heat of water vaporisation, in $J \cdot kg^{-1}$, at T_p).

In addition, it is important to note that Cp_p decreases during the drying according to following equation:

$$\rho_p \cdot V_p \cdot Cp_p = \rho_{dm} \cdot V_p \cdot Cp_{dm} + \rho_{dm} \cdot V_p \cdot X_p \cdot Cp_w \quad (11)$$

Hence, equation ?? can be simplified as:

$$\rho_{dm} \cdot V_p \cdot (Cp_{dm} + X_p \cdot Cp_w) \cdot \frac{dT_p}{dt} = A_{2 \leftrightarrow a} \cdot \phi_h + A_{2 \leftrightarrow a} \cdot \phi_m \cdot Lv \quad (12)$$

Note: a summary of all equations is provided in appendix (section ??).

3.3. Required biltong properties

To be able to compute a simulation, the above-mentioned model requires several biltong properties. Apart from the dimensions and its initial moisture content and temperature, it also needs an equation for the sorption isotherms at different temperatures, the density ρ_{dm} and the specific heat capacity Cp_{dm} of the dry matter.

Using the well-known approach based on the composition, proposed by ?, we calculated $Cp_{dm} = 1650.0 J \cdot K^{-1} \cdot kg^{-1}$. The mass of the dry matter over the total (constant) volume of the biltong was estimated from density and moisture content measurements by ? and ?, was taken as $\rho_{dm} = 263.0 kg \cdot m^{-3}$.

Using data extracted from ?, valid for the 5–25°C temperature range, we calculated Arrhenius parameters for their Halsey equation for non-acidified salted (2.5%) beef meat (in contrast to our work, these authors did not use vinegar). The modified Halsey equation became:

$$a_w = \exp \left(\frac{-k_C \cdot \exp \left(\frac{Ea_C}{R \cdot (T_p + 273)} \right)}{X_2 \cdot \frac{k_n \cdot \exp \left(\frac{Ea_n}{R \cdot (T_p + 273)} \right)}{X_2}} \right) \quad (13)$$

where $k_C = 0.0000015847$, $Ea_C = 26226.04 \text{ J} \cdot \text{mol}^{-1}$, $k_n = 3.4628$ and $Ea_n = -2815.2 \text{ J} \cdot \text{mol}^{-1}$ and $R = 8.31 \text{ J} \cdot \text{K}^{-1} \cdot \text{mol}^{-1}$ (T_p in Celsius and X_2 in kg of water per kg of dry matter). Since we extrapolated results from ? to a temperature range of 35–55°C and used vinegar, we conducted a comparison to check the consistency of this approach. As shown on figure ??, our lab measurements (using vinegar) are of the same order of magnitude as both experimental measurements and the Halsey equation taken from ? and measurements reported by other authors (??). In addition, the observed slight effect of the temperature is acceptable even though impossible to truly validate because of the lack of corresponding data in the literature. A simple sensitivity analysis, not shown in this paper, confirmed the negligible influence of equation ?? on the simulations, apart from the exact location of the asymptote at the end of the drying kinetics.

4. Results & discussion

Table ?? summarises the different volumes and exchange areas (for the 2 compartments) of the pieces of meat. In each following figure, the mean error observed between experimental and simulated biltong moisture contents (*d.b.*) is displayed next to the experimental conditions. Similarly, the root mean square error (RMSE) and the determination coefficient (r^2) are presented. Error bars are shown only for experimental kinetics and only one out of five points to ensure the graph is easy to read.

4.1. Parameter identification of the 2-compartment model

The two experimental drying kinetics (figure ??) used to build the 2-compartment model corresponded to temperatures of 35°C and 55°C. This makes it possible on the one hand to cover the range of temperatures commonly used for biltong drying and on the other hand, by raising the temperature to 55°C, a slightly high temperature for biltong, to avoid too long experiments. In fact, by increasing the temperature from 35°C to 55°C, the drying time to reach the desired final moisture content of 0.5 dry basis ($X = 0.5$) was halved (from 5.5 days to 2.8 days).

The values of the 2-compartment model identified are listed in table ?. The parameter values of h_1 and h_2 were used to calculate the heat transfer coefficient h of the external compartment, which varied between 7.32 and 11.36 $\text{W} \cdot \text{m}^2 \cdot \text{K}^{-1}$. These values are close to low values of the convection transfer coefficient during forced-convection drying. This is logical as the external compartment largely accounts for transfers at the interface. The Chilton-Colburn analogy (equation ??) was used to calculate

the mass transfer coefficient of the external compartment leading to values ranging from $5.12 \cdot 10^{-8}$ to $7.94 \cdot 10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$. Parameter values of $k_{1 \leftrightarrow 2,1}$ and $k_{1 \leftrightarrow 2,2}$ allowed calculation of $k_{1 \leftrightarrow 2}$ which varied from $3.38 \cdot 10^{-6}$ to $7.10 \cdot 10^{-5} \text{ s} \cdot \text{m}^{-1}$. Based on the geometry of a flat slab, which corresponds to our experimental situation, it is possible to estimate the effective diffusion coefficient of water from $k_{1 \leftrightarrow 2}$ (?). For these two experimental situations, the diffusion coefficient ranges between $8.77 \cdot 10^{-11}$ and $3.88 \cdot 10^{-10} \text{ m}^2 \cdot \text{s}^{-1}$. These values are of the same order of magnitude as those found in the book by (?) for different meat products (*e.g.* pork, beef, ...) which range from $5.10 \cdot 10^{-11}$ to $5.10 \cdot 10^{-10} \text{ m}^2 \cdot \text{s}^{-1}$. Furthermore, ? reported values for the water diffusion coefficient ranging from $0.7 \cdot 10^{-10}$ to $1 \cdot 10^{-10} \text{ m}^2 \cdot \text{s}^{-1}$ during drying of salted pork meat at 26°C . In the study by ? on sun drying of beef jerky, the water diffusion coefficient ranged from $1.14 \cdot 10^{-10}$ to $1.67 \cdot 10^{-10}$. These slightly lower values can be explained by the use of lower drying temperatures by these authors than the temperatures used in our study. In salted beef kaddid dried at 30°C , ? reported a water diffusion coefficient of $2.57 \cdot 10^{-10} \text{ m}^2 \cdot \text{s}^{-1}$.

4.2. Model validation

Figure ?? shows four biltong meat drying kinetics for which the air conditions and dimensions of the pieces of meat varied. At other temperatures and with medium 1-size pieces of meat (?? b, c and d) the difference in the mean absolute water content between the experimental points and values predicted by the model ranged from 0.003 to 0.069 *d.b.*. These values are small and within the experimental error. In the case of small pieces (fig. ?? c) the mean absolute difference in water content was higher (0.128 *d.b.*) but still acceptable considering the greater uncertainties in the exact dimensions of small pieces of meat. The biltong drying kinetics were hence well-simulated for differently shaped pieces of meat and for different air temperature and relative humidity. We also tested use of the model in experimental conditions farther from ours (table ??), using data from the literature (?) (figure ??). In the published data, the kind of meat and the shape of the pieces were different, the drying were carried out in an industrial environment and therefore less well controlled than at the laboratory scale. It should be noted that the simulation also yielded acceptable results with a mean absolute water content difference of 0.161 *d.b.*. This confirmed the robustness of the model, as already observed in other studies (??) when it comes to predicting drying rates in wide ranges of situations. The final test concerned the ability of the model to predict the drying kinetics of fresh meat (figure ??). Not surprisingly, a larger error was obtained in this situation, with a difference in mean absolute water content of 0.186 *d.b.*. An overall overestimation of moisture content was observed. This can be explained by the fact that fresh meat dried slightly faster than biltong pieces which were salted and acidified. The increase in drying time with salt is well documented (?) and can be explained by the increase in water holding capacity (WHC). The higher WHC is due to the swelling of meat fibers induced by looser interactions between proteins induced by the Cl^- ions in the salt. The effect of salt on WHC differs when salt and acid are combined. Below the isoelectric point of proteins (*i.e.*, 5.0–5.2) salt reduces the electrostatic repulsion between positively charged group of proteins and thus reduces the WHC (?). As the pH of the pieces of meat after tumbling with salt and vinegar was 4.8, faster drying would thus be expected than for fresh meat. The combined effects of salt and acid on

drying kinetics is less documented. ? observed no difference in drying time between biltong formulated with salt and vinegar and biltong formulated only with salt. ? reported faster drying of pieces of meat previously formulated with salt (1%) and vinegar (5%) than that of fresh meat and meat formulated with salt only although the absence of repetition makes it difficult to conclude whether the difference is significant or not. Moreover, the drying temperature used by these authors was much higher than in our study as they dried the meat at 70°C, a temperature used for jerky processing but not for South African biltong. At 70°C, denaturation of proteins occurs and may influence the WHC of proteins.

5. Conclusion

Drying kinetics of small meat products previously salted and acidified by tumbling were assessed using different sized pieces (from small strips to large pieces) and different air conditions (up to 55°C) as used conventionally for biltong processing. Sorption isotherms were modelled using Halsey's equation and literature data and were of the same order of magnitude as our measurements. A 2-compartment model was designed to simulate drying kinetics. Two of the experimental kinetics were used to build the model and four others to test its predictive capability. The results showed that the model satisfactorily predicted (mean error in moisture content < 0.1 *d.b.*, $r^2 > 0.99$ and $RMSE < 0.141$) the drying conditions used for the biltong despite the fact shrinkage was neglected. A fifth drying kinetic based on experiments in an industrial environment was tested with the model and resulted satisfactory prediction quality ($r^2 = 0.963$ and $RMSE = 0.216$) confirming the good robustness of our 2-compartment model for prediction of the final moisture content, and hence its shelf-life "quality". Further studies are needed to assess the other qualities of dried biltong, in particular its texture in relation to tumbling and drying conditions. Once the quality of the biltong has been integrated, coupled with a biltong tumbling model developed in a previous study (?), this model should be a very useful tool to optimise the processing conditions best suited to obtain the desired biltong quality.

6. Nomenclature

$A_{i \leftrightarrow j}$	contact surface between compartments #i & #j (m ²)
a_w	water activity (-)
C_p	specific heat (J·kg ⁻¹ ·K ⁻¹)
E_a	activation energy (J·mol ⁻¹)
k	mass transfer coefficient (s · m ⁻¹)
h	heat transfer coefficient (W·m ⁻² ·K ⁻¹)
L_v	latent heat of evaporation (J·kg ⁻¹)
M	molecular weight (kg·mol ⁻¹)
m	mass of biltong piece (kg)
P_a	atmospheric pressure (Pa)

P_v	partial pressure of vapour (Pa)
P_{vsat}	saturation pressure of water (Pa)
r^2	determination coefficient
R	universal gas constant ($\text{J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$)
RH	relative humidity (%)
RMSE	root mean square error
T	temperature ($^{\circ}\text{C}$)
t	time (s)
V	volume (m^3)
X	water content (dry basis)
Y	air water content ($\text{kg}\cdot\text{kg dry air}^{-1}$)

6.1. Greek symbols

ρ_{dm}	density when $X=0$ ($\text{kg}\cdot\text{m}^{-3}$)
ϕ_h	heat flux density ($\text{W}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)
ϕ_m	water flux density ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)
σ	standard deviation of measurements on triplicate experiments

6.2. Subscripts

0	initial (<i>i.e.</i> at time $t=0$)
1	compartment #1 (core)
2	compartment #2 (surface)
1 \leftrightarrow 2	between compartments #1 & #2
2 \leftrightarrow a	between compartment #2 & drying air
a	air
dm	dry matter
eq	equilibrium
exp	experimental
h	relative to heat phenomena
i	compartment #i
m	relative to mass phenomena
p	product
s	surface
v	water vapor
$vsat$	saturated water vapor

7. Appendix

Note: all temperatures are in Celsius degrees and moisture contents are on a dry basis. RH are in %.

Summary of all equations:

$$\left\{ \begin{array}{l} \rho_{dm} \cdot V_1 \cdot \frac{dX_1}{dt} = k_{1\leftrightarrow 2} \cdot A_{1\leftrightarrow 2} \cdot (X_2 - X_1) \\ \rho_{dm} \cdot V_2 \cdot \frac{dX_2}{dt} = -k_{1\leftrightarrow 2} \cdot A_{1\leftrightarrow 2} \cdot (X_2 - X_1) \\ \quad + \frac{h_{2\leftrightarrow a}}{65 \cdot Lv} \cdot A_{2\leftrightarrow a} \cdot [Pv_a - a_w(X_2, T_p) \cdot Pv_{sat}(T_p)] \\ \rho_{dm} \cdot V_p \cdot (Cp_{dm} + Cp_w \cdot X_p) \cdot \frac{dT_p}{dt} = A_{2\leftrightarrow a} \cdot h_{2\leftrightarrow a} \cdot \left(T_a - T_p + \frac{1}{65} \cdot (Pv_a - a_w(X_2, T_p) \cdot Pv_{sat}(T_p)) \right) \\ X_p = \frac{V_1 \cdot X_1 + V_2 \cdot X_2}{V_p} \end{array} \right.$$

with following product-related properties: $\rho_{dm} = 263.0 \text{ kg dry matter} \cdot \text{m}^{-3}$, $Cp_{dm} = 1650.0 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$, $h = 0.24613 + 0.21508 \cdot Ta \text{ W} \cdot \text{m}^{-2}$, $k_{1\leftrightarrow 2} = 1.6193 \cdot 10^{-6} \cdot \exp(0.029284 \cdot X_p \cdot T_p)$, $A_w(X, T) = \exp\left(\frac{-k_C \cdot \exp\left(\frac{Ea_C}{R \cdot (T + 273.1)}\right)}{X^{k_n \cdot \exp\left(\frac{Ea_n}{R \cdot (T + 273.1)}\right)}}\right)$, with $k_n = 3.1943$, $Ea_n = -2617.5$, $k_C = 5.0901 \cdot 10^{-7}$, $Ea_C = 28917.7$, and $R = 8.31 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$.

and following water/steam properties: $Cp_w = 4186.0 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$, $Pv_{sat}(T) = 10^{\left(\frac{7.5 \cdot T}{T + 237.3} + 2.7858\right)}$, $Pv_a(RH, T) = \frac{RH}{100.0} \cdot Pv_{sat}(T)$, $Lv(T) = 2501000.0 - 2450.0 \cdot T$.

Acknowledgments

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Conflict of interest disclosure

The authors have no conflict of interest to declare.

List of Tables

Table 1: Experimental conditions. T, RH, V: temperature, relative humidity and velocity of drying air; e, W, L: thickness, width and length of meat pieces. Note: in (?), meat pieces were tumbled with 2% (w/w) fine salt instead of 2.5%.

T(°C)	RH (%)	V ($m \cdot s^{-1}$)	Format	e (mm)	W (mm)	L (mm)	Tumbling with salt and vinegar
35	30	1.8	Large	20	65	200	x
45	30	1.8	Large	20	65	200	x
55	30	1.8	Large	20	65	200	x
55	30	1.8	Medium 1	20	32.5	100	x
55	30	1.8	Medium 1	20	32.5	100	
35	40	1.8	Medium 2	20	65	130	x
55	30	1.8	Small	10	32.5	10	x
25	30	?	?	20	20	260	x

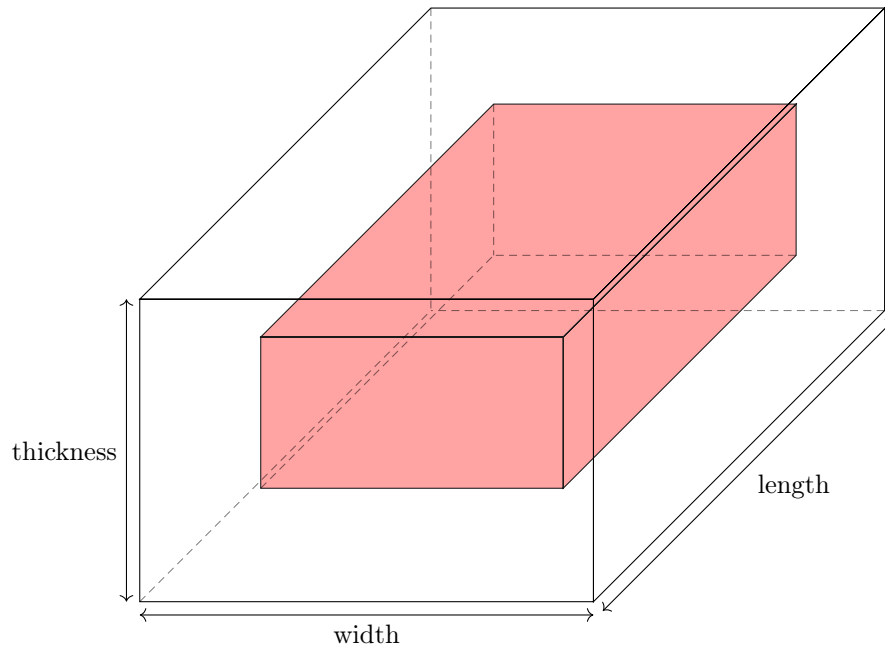
Table 2: Volumes and exchange areas of beef pieces.

format	V_p (m^3)	$A_{2 \leftrightarrow a}$ (m^2)	$A_{1 \leftrightarrow 2}$ (m^2)
Large	0.00024	0.0344	0.031592
Medium 1	0.00006	0.0112	0.009796
Medium 2	0.000156	0.0232	0.021148
Small	0.00003	0.0086	0.007898
?	0.000104	0.0216	0.018576

Table 3: Identified parameters for heat and mass transfer coefficients.

transfers	coeff. equation	parameter 1	parameter 2
Water diffusion	$k_{1\leftrightarrow 2} = k_{1\leftrightarrow 2,1} \cdot \exp(k_{1\leftrightarrow 2,2} \cdot X_p \cdot T_p)$	$2.170 \cdot 10^{-6}$	0.02536
Heat convection	$h = h_1 + h_2 \cdot T_a$	0.2527	0.2019

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Air

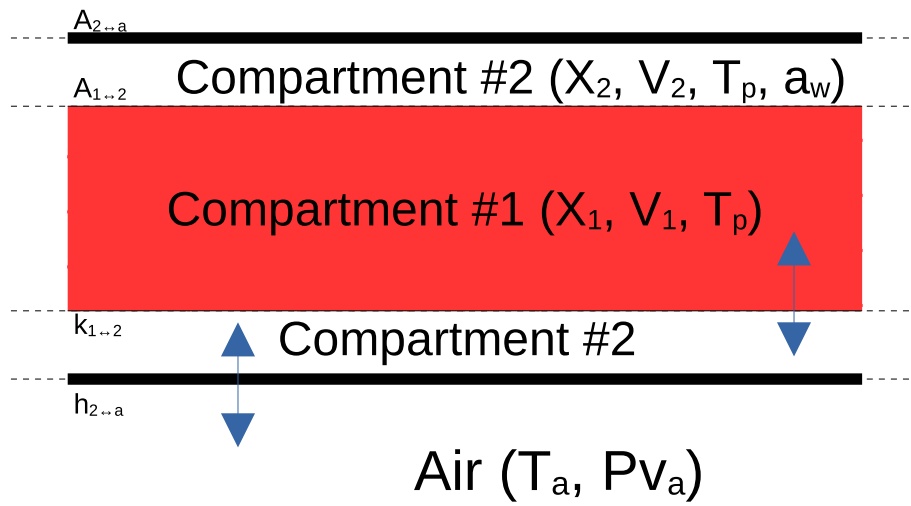


Figure 1: Geometry of beef pieces seen as two concentric compartments (numbered from the center to the surface).

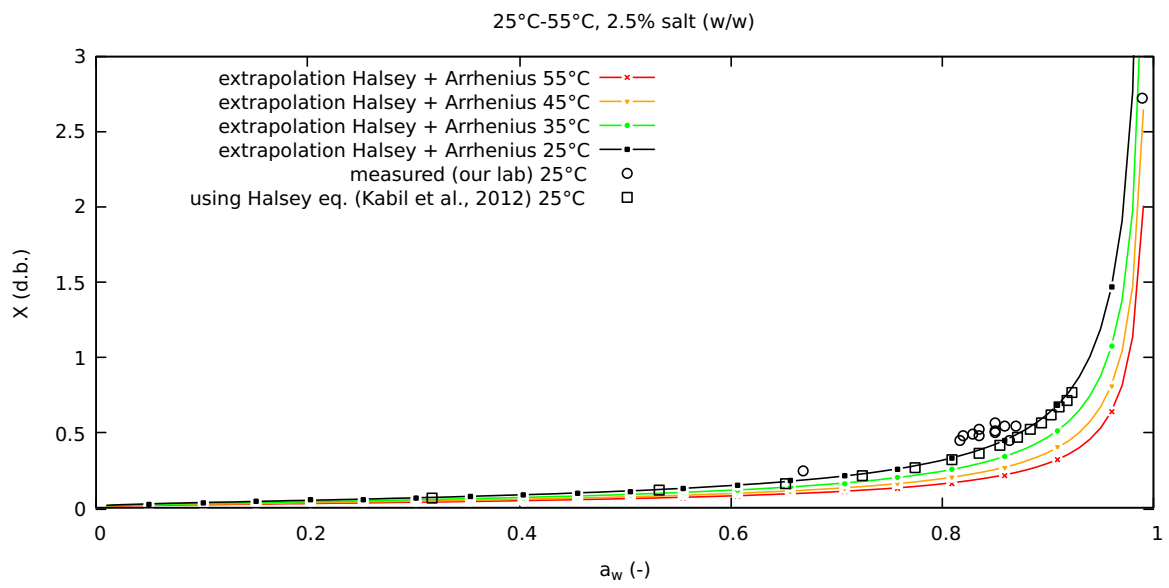


Figure 2: Comparison of measured values (at our lab) of water activity a_w and sorption isotherm using Halsey equation and parameters from ?. Lines are calculated using Arrhenius extrapolation of Halsey parameters from 15–25°C (as given by ?) to 25–55°C.

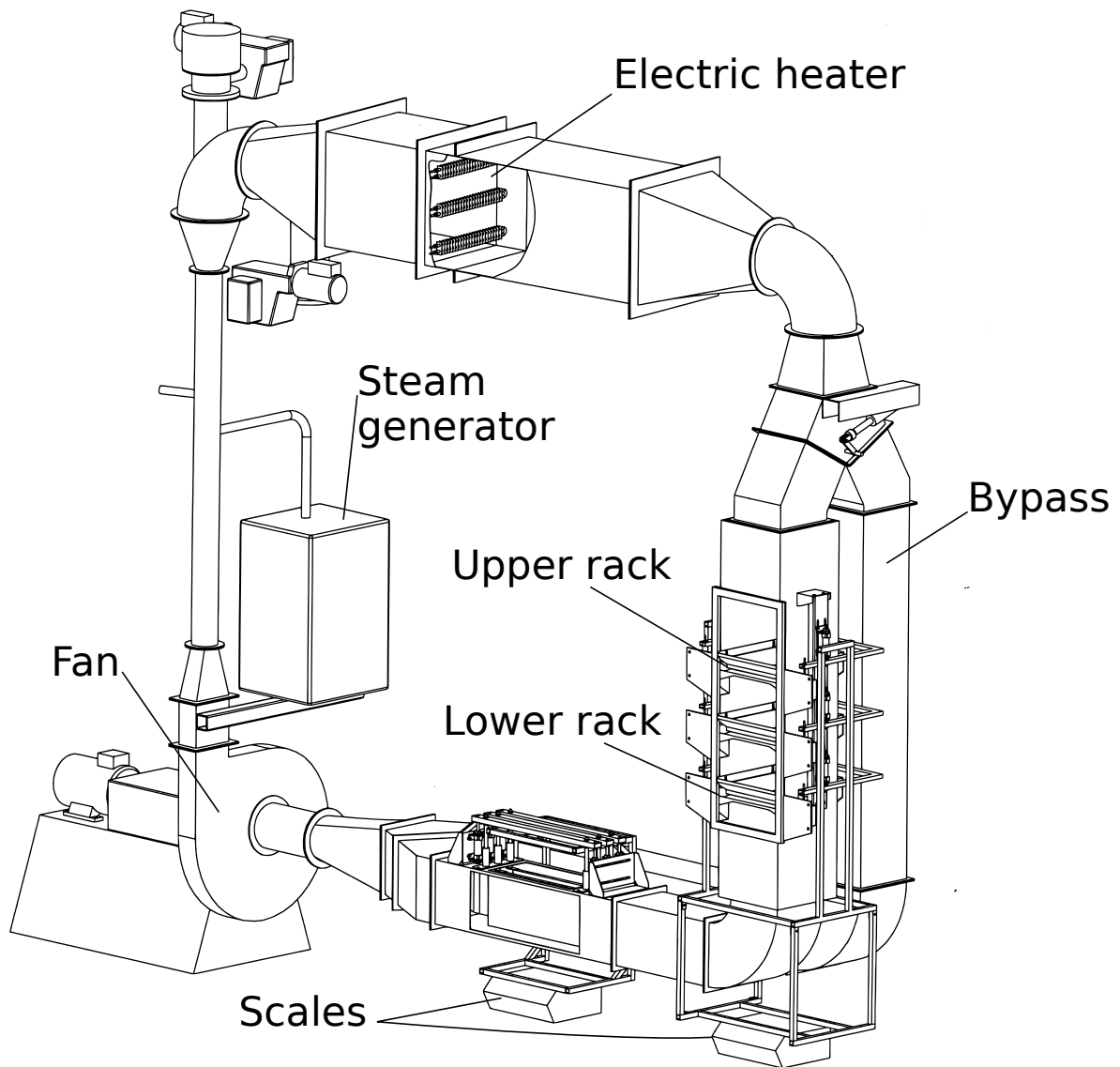


Figure 3: Dryer apparatus using for the determination of drying kinetics.

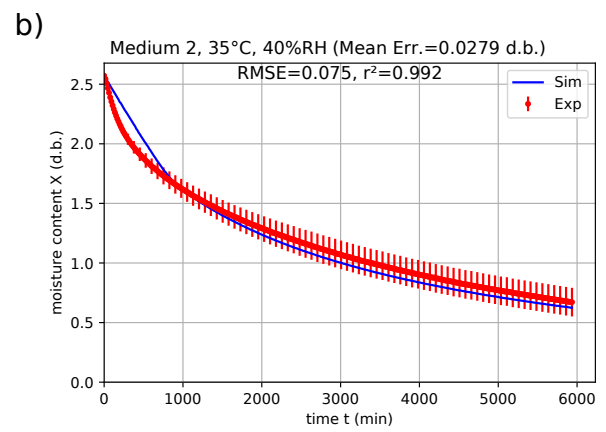
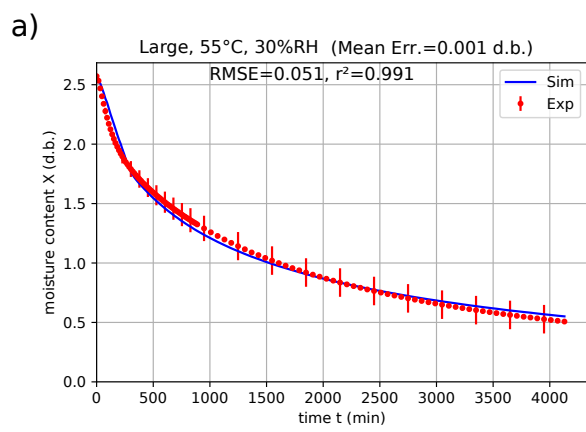
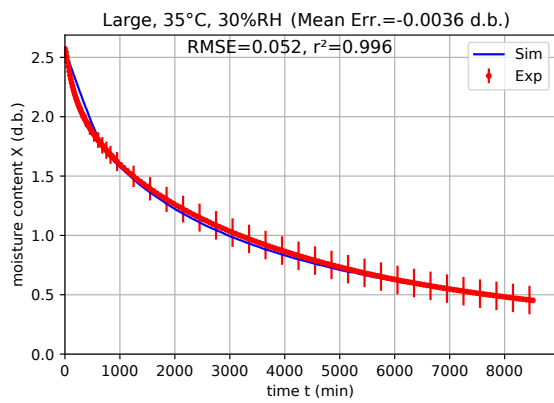
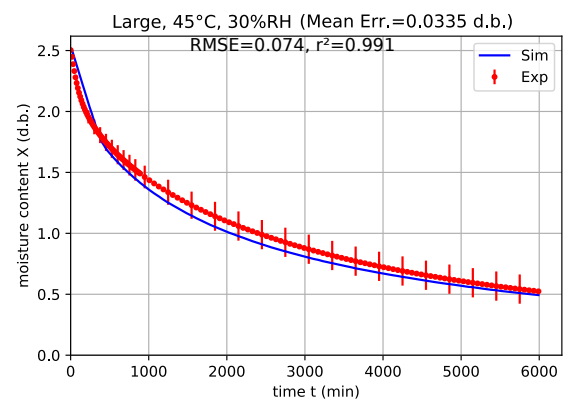


Figure 4: Learning set.

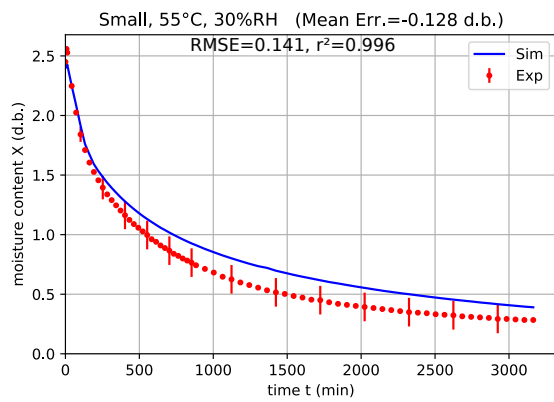
a)



b)



c)



d)

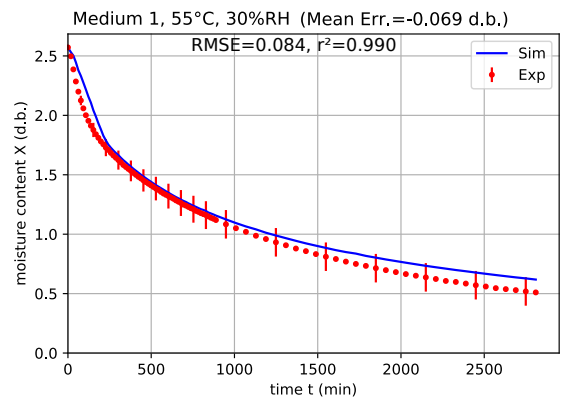


Figure 5: Main validation set.

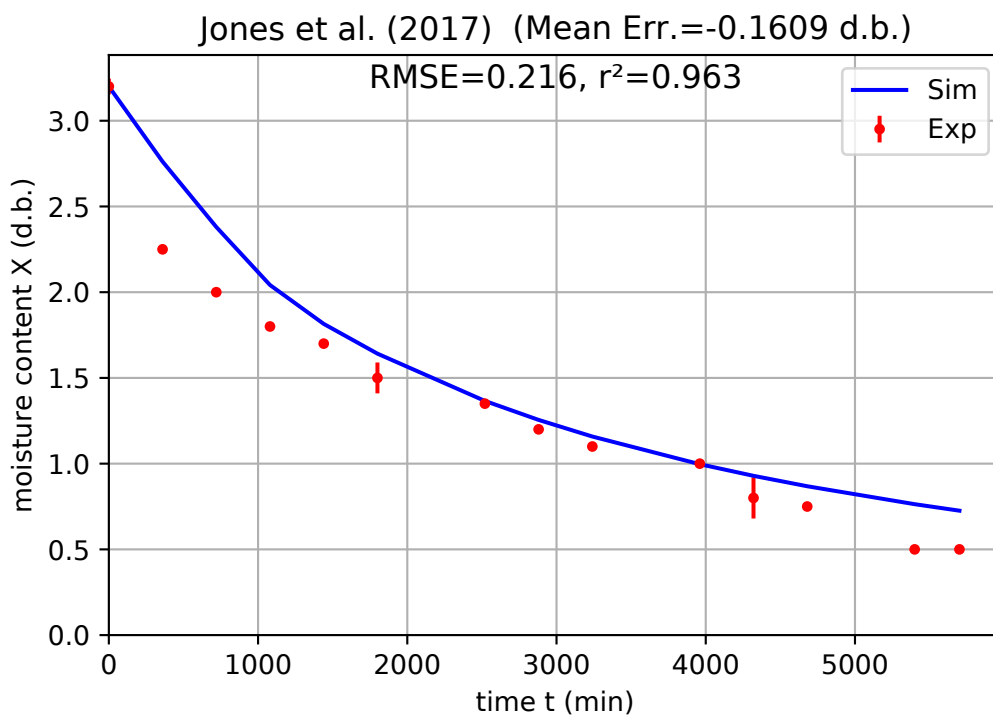


Figure 6: Validation of the drying model with work from ?, at 25°C and 30%RH.

Fresh, Medium 1, 55°C, 30% RH, R1 (Mean Err.=-0.1859 d.b.)

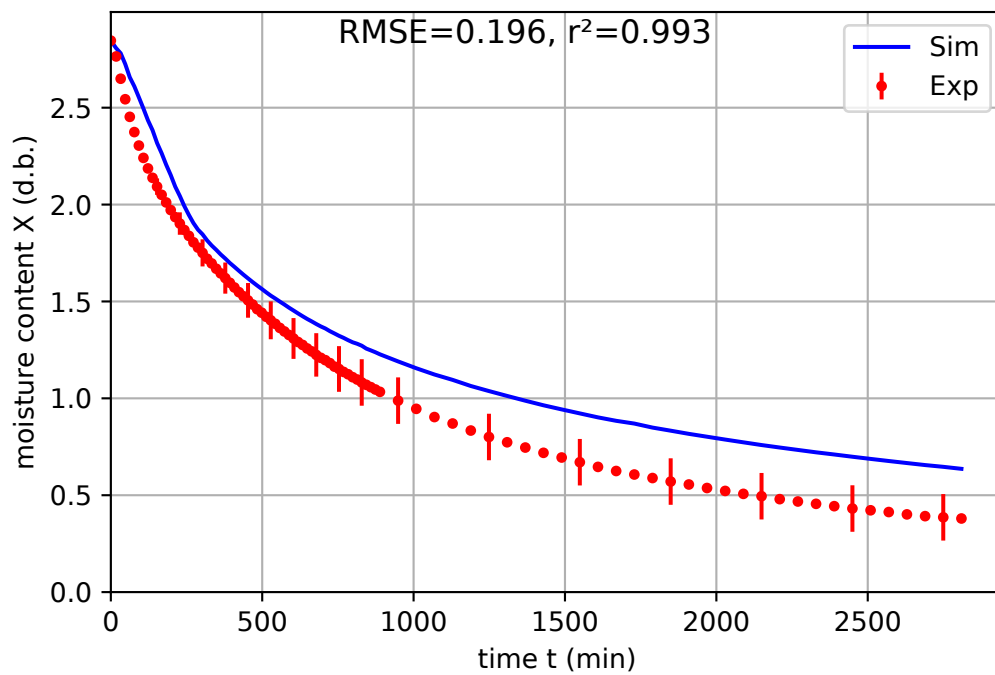


Figure 7: Comparison of the drying model with a drying kinetics with fresh beef meat.