Finite element model of salami ripening process and successive storage in package

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Abstract

Salami are typical European dry fermented sausages manufactured mainly with pork meats. Water loss is a crucial aspect of industrial ripening process because it is responsible for the lowering of water activity, which determines limitations to successive conservation.

This paper describes two parametric numerical models developed to study the moisture diffusion physics, during ripening and storage in package. Mass transfer equations inside the sausage volume were numerically solved using a finite element technique. A first model describes diffusion phenomena occurring inside the salami and the exchange phenomena involving the surface of the product and the industrial environment, while a second one describes also the evaporation and condensation phenomena occurring between the salami surface and the atmosphere inside the packaging. The models were experimentally validated showing a good agreement with observed data.

The numerical models allowed to study the water transfer inside of dry fermented sausages with a detail unreachable by any experimental technique. In addition the models could be used to find the best conditions for ripening, packaging and distribution.

Keywords: numerical simulation, models, mass transfer, sausage.

1. Introduction

Dry fermented sausages are the result of a fermentation process and a ripening period during which the products reach the desired characteristics. From several centuries, different kind of dry fermented sausages have been produced in the Mediterranean area (Toldrá et al., 2007; Zeuthen, 1995; Ordóñez et al 1999). The wide variety of dry fermented sausages is a consequence of variations in formulation, raw material, manufacturing and ripening processes which come from the traditional habits of different countries and regions (Zanardi et al., 2010). Often fermented sausages get different names according to geographic origin (Toldrá, 2006). In particular, salami are typical

European dry fermented sausages manufactured mainly with pork, but also with bovine, ovine and equine meats, with the addition of salt, curing agents (nitrate and nitrite), spices, and sometimes herbs and/or other ingredients (Feiner, 2006).

The primary European countries producing salami are Germany, Italy, Spain, France and Hungary, with a production of several hundred-millions kg per year, and ripening and storage periods play an important role on the final characteristics of these fermented sausages (Bertolini et al., 2006). In particular, in the dry fermented sausages industry, ripening is considered one of the most important stages of the integrated supply chain needed to ensure that end products have the final requirements in terms of quality and safety standards (Grassi and Montanari, 2005). In fact, the ripening stage influences over the main physical, chemical and microbiological transformations that take place in salami after manufacturing.

A large number of studies regarding the influence of ripening conditions on the microbiological, physical and chemical properties of dry fermented sausages are available (Baldini et al., 2000; Campbell-Platt and Cook, 1995; Zanardi et al., 2010; Tabanelli et al 2012; Tabanelli et al. 2013). All these researches show that the final quality and safety standards achieved by the sausage manufacturing process can be considered to be strictly dependent from the conditions under which ripening stage is designed and carried out (Rizzi, 2003).

The most important mass transport phenomenon occurring inside the matrix during ripening is the water transfer. Many theoretically and experimentally studies about transfer of water and solutes through meat and meat products matrices are reported in literature (Costa-Corredor et al., 2009; Graiver et al., 2006; Hansen et al., 2008; Sabadini et al., 1998; Unal et al., 2004). Water loss is a crucial aspect of ripening because it is responsible for the lowering of water activity (a_w), which determines limitations to the growth of many spoilage and pathogenic microorganisms. In addition, the water loss has to be as uniform as possible to avoid the formation of moisture gradients in the sausages causing the case hardening which is negative for the textural properties and also for the safety of the final products. Water loss can be modulated during ripening by controlling the temperature of the ripening chambers and their relative humidity (Feiner, 2006).

As reported in many specific reviews, the recent progress in computing efficiency coupled with reduced costs of codes has set out the numerical simulation as a powerful tool to study many food processes with the aim of providing effective and efficient plant design or operating solutions (Scott and Richardson, 1997; Xia and Sun, 2002; Wang and Sun, 2003; Norton and Sun, 2006; Smale et al., 2006; Verboven et al., 2006; Mirade, 2008). In this regard, the numerical simulation was used to study the mass transfer in various foods during drying, baking, freezing and ripening (Mirade, 2008; Sakin et al., 2007; Lemus-Mondaca et al., 2013; Floury et al., 2008).

As concerning the salami ripening, Rizzi (2003) developed a parametric model for the fluid dynamic simulation of ascending flow ripening chambers as a function of operational conditions. The model was experimentally validated comparing measured and simulated air velocity modules.

Grassi and Montanari (2005) developed a parametric model very similar to that of Rizzi (2003), but in addition, the authors built a sausage drying model that computes mass and heat exchange between sausage and the air flows. However, the model has not been experimentally validated.

The aim of this research was to develop two parametric numerical models, concerning the moisture diffusion physics, describing salami ripening and storage. Mass transfer equations inside the sausage volume were numerically solved using a finite element technique. A first model describes diffusion phenomena occurring inside the salami and the exchange phenomena involving the surface of the product and the environment, while a second one describes also the evaporation and condensation phenomena occurring between the salami surface and the atmosphere after the whole sausage packaging. The models was experimentally validated, comparing the numerical outputs of the simulations with experimental data. In addition, the models could be used to find the best conditions at which whole fermented sausages should be packaged for distribution.

2.Materials and methods

2.1 Ripening model

Commercial computational multiphysics codes are available nowadays, allowing an exceedingly flexible simultaneous numerical solution of the energy, mass and moment equation (Scott and Richardson, 1997) and are extensively adopted in the food engineering field (Xia and Sun, 2002; Wang and Sun, 2003; Norton and Sun, 2006; Fabbri et al., 2011).

The equations of mass transfer inside and on the salami surface were solved using Comsol Multiphysics 4.3 (COMSOL Inc., Burlington, MA, USA), a commercial partial differential equations solver, based on finite element technique. During ripening, the moisture diffuses from the inside, towards the salami surface and about half of the initial water content is lost through evaporation. To simulate moisture transfer inside of product, salami material was treated as homogeneous and isotropic, initial moisture was set uniform and salami volume was considered constant.

In order to limit the computation time, an one-dimensional model was built because the salami geometry is axisymmetric and it was considered an indefinite length salami. Subsequently, with a simple geometric operation, a 2D model can be visualized. The geometry dimensions reflect the real ones of the salami considered, in particular a simple radius (r: 25 mm) between the longitudinal axis and the external cylindrical surface was considered.

The moisture transfer is governed by Fick's law:

$$\frac{\partial C}{\partial t} = D_{H_2O}\left(\nabla^2 C\right) \tag{1}$$

where C is calculated moisture concentration (mol m^{-3}) at time t .

Mass diffusivity (D_{H_2O}) through the involved material was found in literature (Simal et al., 2003; Trujillo et al., 2007).

Initial moisture concentration (C_{Rin}) was considered constant in space and defined as following:

$$C_{Rin} = \left(\frac{X_{Rin} \cdot \rho_s}{PM_{H_2O}}\right) \tag{2}$$

where X_{Rin} is the initial moisture content on dry basis (experimentally determined: 1.2 kg kg^{-1}), ρ_s the dried salami density (experimentally determined: 600 kg m^{-3}), while PM_{H_2O} the water molecular weight (0.018 kg mol^{-1});

A flux condition was imposed on the interface between salami surface and air:

$$N_R = k_t\left(C_{bound} - C\right) \tag{3}$$

being N_R (mol m^{-2} s^{-1}) the water flux, k_t (m s^{-1}) the mass transfer coefficient and C_{bound} the moisture concentration of salami at equilibrium.

Mass transfer coefficient can vary within very broad limits, without problems of physical model fidelity: convergence could be compromised for high values, while for small values an artificial resistance to the moisture passage could be introduced. A value must therefore be determined empirically by choosing a level slightly lower than that which causes convergence problems (in our case k_t: 1E-6 m s^{-1}).

Moisture concentration of salami at equilibrium was defined by following equation:

$$C_{bound} = \left(\frac{X_{bound} \cdot \rho_s}{PM_{H2O}}\right) \tag{4}$$

where X_{bound} is the moisture content on dry basis at equilibrium. This value was determined by using the Oswin law:

$$X_{bound} = A\left[\frac{a_w}{\left(1 - a_w\right)}\right]^B \tag{5}$$

being a_w value equal to that of relative humidity of the ripening room by definition. A (0.4287) and B (0.2397) parameters were determined by fitting the experimental data of water activity vs moisture content, measured during the ripening, with the Oswin law.

Model was validated by comparing water activity and water concentration, numerically and experimentally determined. For the experimental determination a Milano type dry fermented salami made with pork shoulder (72% w/w) and streaky bacon (28% w/w), NaCl (2.6% w/w), dextrose (0.30% w/w), KNO_3 (0.015% w/w), $NaNO_2$ (0.010% w/w), wine (1% w/w) and spices (white pepper powder and black pepper whole grain, 0.12% w/w) was used (Tabanelli et al. 2013).
Salami had a length of about 200 mm, a diameter of about 50 mm and an initial mean weight of about 430 g. The drying conditions were the following: 48 h at 23 °C and relative humidity (RH) of 70%, 48 h at 21 °C and RH of 80%, 24 h at 19 °C and RH of 83%, and finally 24 h at 17 °C and RH of 86%. Then salami were transferred to the ripening chamber at 15 °C and RH of about 80%.
During the ripening, the weight loss was monitored and a_w was measured by using an Aqualab CX3-TE (Labo-Scientifica, Parma, Italy). All the measures were done in triplicate at different days of ripening.

2.2 Storage model

Sausages were taken off from ripening chamber at different mean a_w values, packaged in plastic film and stored at room temperature The physical and biochemical activities inside the sausages are not stopped at this phase and proceed with a rate depending on several factors, the main of which is temperature. The main goal of plastic package is to avoid further water loss that can cause economic damages. During storage exchange phenomena (evaporation and condensation) between product and air within packaging, as function of temperature, were possible.
For the storage model, the same software, geometry and physical parameters of the salami (D_{H2O}) of ripening model were used. Salami material was considered homogeneous and isotropic while its volume was considered constant. Also the total water mass of the salami/air packaging system was defined as constant, as the packaging material were a perfect barrier for air and water. Even in this case, the phenomenon of mass transfer inside solid phase is governed by Fick's law.
Initial moisture concentration (C_{Sin}) was defined as following:

$$C_{Sin} = \left(\frac{X_{Sin} \cdot \rho_s}{PM_{H_2O}} \right) \tag{6}$$

where X_{Sin} is the initial moisture content on dry basis determined by previous model as function of coordinate r.
A flux condition (N_S [mol m^{-2} s^{-1}]) on the interface between the surface of the salami and the air of the packaging, as function of the partial pressure, was imposed (Mujumdar and Menon, 1995):

$$N_S = k_t\left(\frac{\rho_{air}}{PM_{H_2O}}\right)\cdot\left(\frac{PM_{H_2O}}{PM_{air}}\right)\cdot\left(\frac{\varphi_{air}\cdot P_{airSat}}{P_{atm}-\varphi_{air}\cdot P_{airSat}}-\frac{a_{w\,air}\cdot P_{airSat}}{P_{atm}-a_{w\,air}\cdot P_{airSat}}\right) \qquad (7)$$

where:

$\rho_{air} = \left(\frac{P_{atm}\cdot PM_{air}}{RT}\right)$: air density [kg m^{-3}]; (8)

P_{atm}: atmospheric pressure [1E+5Pa];

PM_{air}: air molecular weight [28.84 g mol^{-1}];

R : gas constant [8.314 J K^{-1} mol^{-1}];

T : temperature, sinusoidally varying on a 24 h basis [K];

$\varphi_{air} = \frac{P_{air}}{P_{airSat}}$: relative humidity of air/water vapour mixture; (9)

$P_{air} = \frac{M_{H_2Oair}\cdot RT}{PM_{H_20}\cdot V_{air}}$: partial pressure of water vapour [Pa]; (10)

$M_{H_2Oair} = (M_{H_2OTot} - M_{H_2OS} - M_{H_2OLq})$: water mass in the headspace calculated considering mass conservation equation [kg]; (11)

$M_{H_2OTot} = M_S \cdot X_{Sin}$: total water mass in the system [kg]; (12)

M_s : mass of dry salami [0.280 kg];

$M_{H_2OS} = (\bar{\rho}_{H_2OS}\cdot V_s)$: water mass in salami [kg]; (13)

$\bar{\rho}_{H2OS} = \bar{C}\cdot PM_{H2O}$: mean water density [kg m^{-3}]; (14)

$\bar{C}$: space average concentration [mol m^{-3}]

$\frac{dM_{H_2OLq}}{dt} = F_c - F_e$: water mass conservation equation as function of evaporation and condensation phenomena [kg]; (15)

$F_c = K_c\cdot(\varphi_{air}-1)\cdot\left(\frac{M_{H_2Oair}}{M_{H_2O_{Tot}}}\right)\cdot\bar{A}$: mass flow of condensing water (always positive but nonzero only for saturated or oversaturated air) [kg s^{-1}]; (16)

$F_e = K_e \cdot (1-\varphi_{air}) \cdot \left(\frac{M_{H_2OLq}}{M_{H_2O_{Tot}}} \right) \cdot \bar{A}$: mass flow of evaporating water (always positive but nonzero only for unsaturated air) [kg s^{-1}]; (17)

$\bar{A} = L\,\pi \cdot (r + r_p)$: mean exchange area [$m^2$]; (18)

L: salami length [200 mm];

r_p: packaging salami radius [30 mm];

K_c: condensation parameter [kg s^{-1} m^{-2}];

K_e: evaporation parameter [kg s^{-1} m^{-2}];

V_{air}: headspace volume [m^3];

$P_{airSat} = \left(10^{\left(8.07131 - \frac{1730.63}{233.426+T}\right)} \cdot \frac{P_{atm}}{760} \right)$: saturation pressure of water vapour in air as function of temperature (August-Antoine, 1888) [Pa]; (19)

$$a_{wair} = \left(\frac{\left(\frac{X_S}{A}\right)^{\left(\frac{1}{B}\right)}}{1 - \left(\frac{X_S}{A}\right)^{\left(\frac{1}{B}\right)}} \right)$$
: relative humidity of air near to salami calculated by using Oswin law;

(20)

$X_S = \left(\frac{\bar{C}_c \cdot PM_{H2O}}{\rho_s} \right)$: dry basis moisture content on the salami surface [kg kg^{-1}]; (21

$\bar{C}_c$: mean water concentration determined on the exchange surface [mol m^{-3}].

Model was validated by comparing water activity and dry basis moisture content, numerically and experimentally determined in triplicate. For the experimental determination salami ripened for 28 days at 80% of RH and 15°C (the same type used to validate the ripening model), were packaged in a Flexible OPA/PE laminated plastic film (O_2 transmission: 28±1.4 $cm^3/m^2/24$ h/atm and CO_2 transmission: 150±7.5 $cm^3/m^2/24$ h/atm) and stored at room temperature (daytime: about 30°C and night: about 20°C) for 60 days (Tabanelli et al. 2013).

3. Results

3.1 Ripening model

To validate the ripening model, only fermented sausages after 28 days of ripening were considered. In particular, experimental and calculated values of mean water concentration (figure 1) and a_w (figure 2) were compared.

The experimental data of mean water concentration were defined by starting from the weight loss (%) at 0, 3, 5, 8, 11, 14, 18, 23, and 28 days of ripening. In this case the agreement between simulated and experimental values was represented by a determination coefficient R^2 of 0.923 ($p<0.05$). Mean difference between calculated and experimental data is of 4.69% with a minimum and maximum value of 0.403 and 7.04%, respectively. Calculated data were higher, except for 23 and 28 days of ripening.

The a_w was measured in triplicate at 0, 11, 18, 23, and 28 days of ripening. The agreement between simulated and experimental values is represented by a determination coefficient R^2 of 0.994 ($p<0.05$). In this case mean difference between calculated and experimental data is of 0.85% with a minimum and maximum value of 0.34 and 1.17%, respectively.

Both for water concentration to the a_w, simulated and experimental data were in good agreement. This result shows that the numerical model was able to reproduce the mass transfer phenomenon inside of salami.

Simulated moisture concentration and relative dry basis moisture content and a_w inside of salami after 28 days of ripening is reported in figure 3 (under the same ripening condition used for the model validation). It can be seen that the moisture was not uniformly placed (Figure 3a), and a considerable difference between internal (about 16500 mol m^{-3}) and external (about 26300 mol m^{-3}) zone is shown. For the producers, the presence of this gradient can be very critical. In fact, when its entity is not strictly controlled, the formation of case hardening can take place. This sausage defect is dependent on the formation of a dry superficial layer due to a too fast removal of water. This layer forms a barrier which is harder and less permeable than the inner part of the product and opposes to further water removal. Consequently, water concentration remains high and not uniform inside (Ruiz-Ramírez et al. 2005), increasing the risks of unwanted microbial growth of both spoilage and pathogenic species. For this reason, in the fermented sausages the water loss is regulated through the rigorous control of temperature and relative humidity in the ripening chambers and also through the growth of moulds in the outer side of casing. This risk is more evident taking into consideration the a_w value reported in Figure 3b. These data evidence a thin layer immediately below the casing in which the a_w is considerably lower, with the possibility of crust formation.

Also Baldini et al. (2000) found this lack of uniformity in water concentration inside sausages and reported that in different type of salami, at the end of ripening stages, the drying is much more marked in the external fractions and considerably lower in the internal ones. In particular for salami characterized by a diameter of about 50-60 mm, an initial moisture content of about 58% and a ripening time of 28 days (similar conditions to those used in this study), the authors showed that the final percentages of moistures (internal fraction about 43%, external fraction about 33%) are similar to those determined by the model (internal fraction about 44%, external fraction about 34%).

The variation in water quantity in the internal and external zone during the ripening depends on salami size. In this study, to evaluate the size effect on the mass transfer, the final water concentrations (after 28 days of ripening) as a function of radius dimension and position inside of salami, are reported in Figure 4. It can be seen that the salami size significantly affects the mass transfer. In fact, doubling the salami radius (from 20 to 40 mm), the final water concentration in the central zone (radius from 0 to 10 mm) increases of 65% (from 20918 to 34611 mol m^{-3}). This aspect highlights that the assessment of size is an important aspect for the ripening stage.

Considering that the variation in water quantity inside of salami should be also connected to the ripening condition (temperature, RH), mean moisture contents on dry basis as function of RH (75, 80 and 85%) and days of ripening are reported in figure 5. For the first six days the curves were overlapped because the drying conditions were maintained the same (48 h RH of 70%, 48 h RH of 80%, 24 h RH of 83%, and finally 24 h at RH of 86%). Real ripening time starts after 6 days. It can be seen that after 28 days, the moisture content on dry basis increased of 5.24% (from 0.642 to 0.675 kg kg^{-1}), passing from 75 to 80% of RH and of 6.19% (from 0.675 to 0.717 kg kg^{-1}), passing from 80 to 85% of RH. Also in this case, similar results are reported by Baldini et al. (2000). In particular for salami characterized by a diameter of about 50-60 mm, and ripened for 28 days, the authors showed an increase of about 6.42% of moisture on dry basis, passing from 0.82 to 0.87% of RH (step of 5%).

3.2 Storage model

To validate the storage model, experimental and calculated values of water activity and dry basis moisture content determined after 60 days at room temperature (daytime: about 30°C and night: about 20°C) were compared.

Experimentally, moisture content changes were not observed. However, some minor variations in the mean a_w values were recorded during storage and the values further decreased by about 0.01 units. According to the model a small decrease of mean a_w (passing from 0.8689 to 0.8691) and dry basis moisture content were observed (passing from 0.6735 to 0.6738 kg kg^{-1}).

Moisture content as function of days of storage and position inside of salami is reported in figure 6. Considering the minimal loss of water, it is possible to confirm that the packaging prevents further dehydration of the product. Globally, salami water do not diffuses outside but tends to internally redistribute and equilibrate water content. The moisture content inside of salami was uniformly placed only after about 35 days of storage.

Mass changes of water in air (headspace of the package), inside of salami and liquid (available for evaporation) during storage, are shown in figure 7. According to what written above, it can be seen that salami water mass slightly decreases during the storage. However, this reduction causes a liquid water increase during about the first ten days of storage. In fact, the water moves from salami to headspace until the air is saturated. The air saturation level depends on the temperature that varying produces condensation and evaporation phenomena on the salami surface causing a very small oscillation of moisture content during storage. As the temperature decrease, the headspace air became over-saturated releasing some water. Particularly, when temperature increase (≤30°C), water evaporate and moisture content of salami slightly decrease, while when temperature decrease (≥20°C), water condense and moisture content of salami increase.

In the figure 8, it can be seen that the moisture variation, as an example for a salami storage for 20 days , affects about the outer 4 mm of salami radius. The black lines concern the temperature decrease, while the grey line are relative to the temperature increase. These continuous variations of moisture content and consequent liquid film deposition, in the first few millimeters closer to the surface, could affect the texture of external zone of salami. In addition, variation of a_w in microareas of the surface of sausages, even if minimum, can create conditions more favorable to a intermittent activity of microbial species whose presence is negative for sausage overall quality. In agreement with this hypothesis, salami used for the storage model validation showed a softening of the first millimetres of product that could significantly compromise the product quality.

Conclusions

The numerical models allowed to study the mass transfer of the water inside of dry fermented sausages, during the ripening and storage phases, with a detail unreachable by any experimental technique. The results of the models, in integral form, were in good agreement with those experimentally observed.

The model clarifies the mass diffusion mechanism that moves moisture from the inner part of salami to its surface: whatever are the environmental conditions, the moisture in the headspace reaches an equilibrium with the moisture inside the meat. During the conservation the moisture concentration tends, by mass diffusion, to become uniform in space, flowing from the centre to the periphery. As the environmental temperature decreases, the head-space air becomes over-saturated releasing some water. This liquid state water drops on the salami surface and can compromise the conservation conditions in relation to the packaged sausage a_w. During the conservation time, every temperature oscillation activates this water movement mechanism.

Ultimately, the numerical model represents a powerful and versatile industrial instrument and, being parametric, wide spanning data input regarding time, ripening and storage temperatures, size and type of sausage, etc. can be tested.

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Highlights

Ripening and storage stages influence the physical, chemical and microbiological transformations that take place in salami. The most important mass transport phenomenon occurring inside the matrix is the water transfer. In this work two parametric numerical models developed to study the moisture diffusion physics, during ripening and storage in package. The models were experimentally validated showing a good agreement with observed data. The models could be used to find the best conditions for ripening, packaging and distribution.

Figure Captions

Figure 1: experimental and calculated values of mean water concentration determined during 28 days of ripening.
Figure 2: experimental and calculated values of mean water activity determined during 28 days of ripening.
Figure 3: simulated moisture concentration dry basis (a), moisture content (a) and water activity (b) inside of salami after 28 days of ripening.
Figure 4: final water concentrations (28 days of ripening) as function of radius dimensions and position inside of salami.
Figure 5: mean moisture contents on dry basis as function of relative humidity (75, 80 and 85%) and days of ripening.
Figure 6: moisture content as function of days of storage and position inside of salami.
Figure 7: Mass of water in air (headspace), inside of salami and liquid (available for evaporation and condensation) during storage.
Figure 8: Effect of evaporation and condensation on moisture content inside of salami.

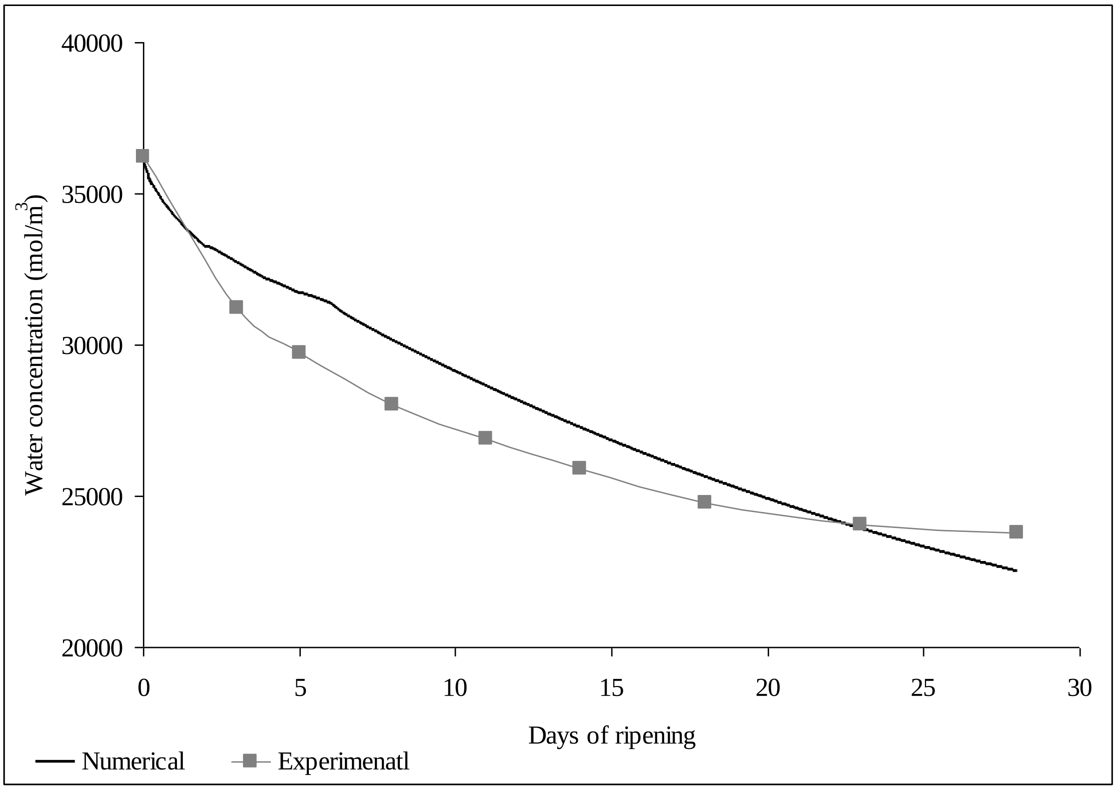

Fig1

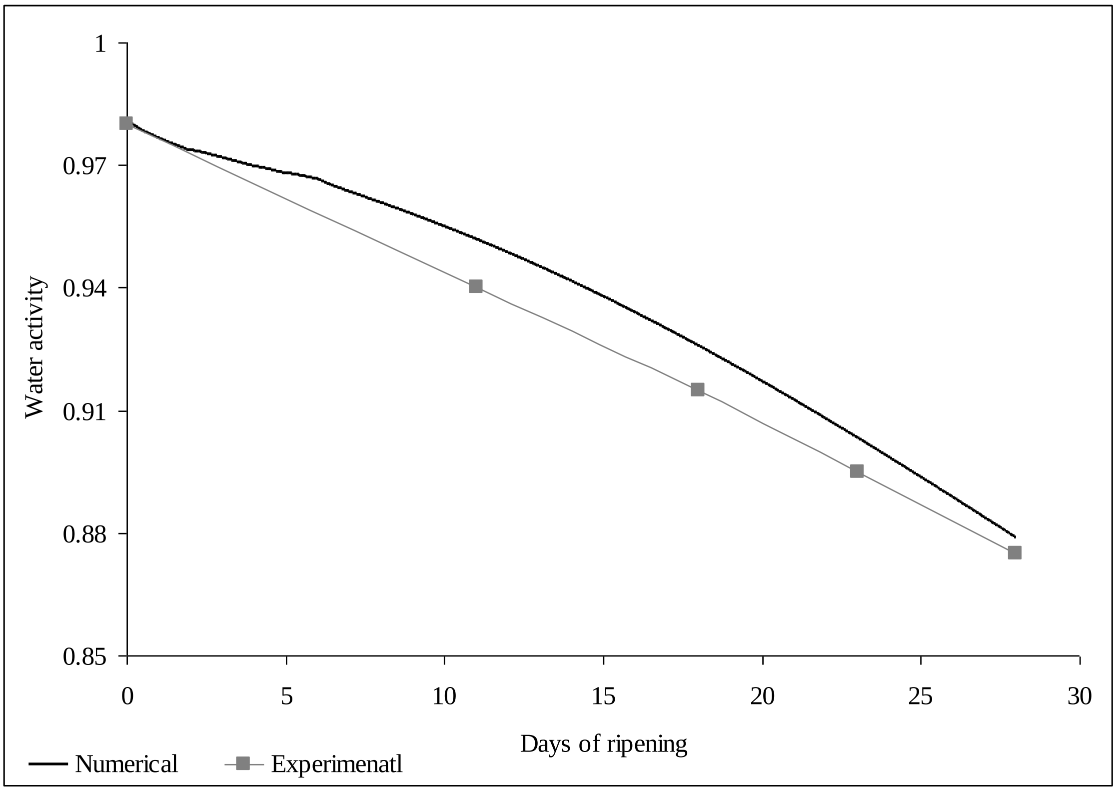
1
0.97
0.94
0.91
0.88
0.85
Water activity
0
5
10
15
20
25
30
Days of ripening
Numerical
Experimenatl

Fig 2

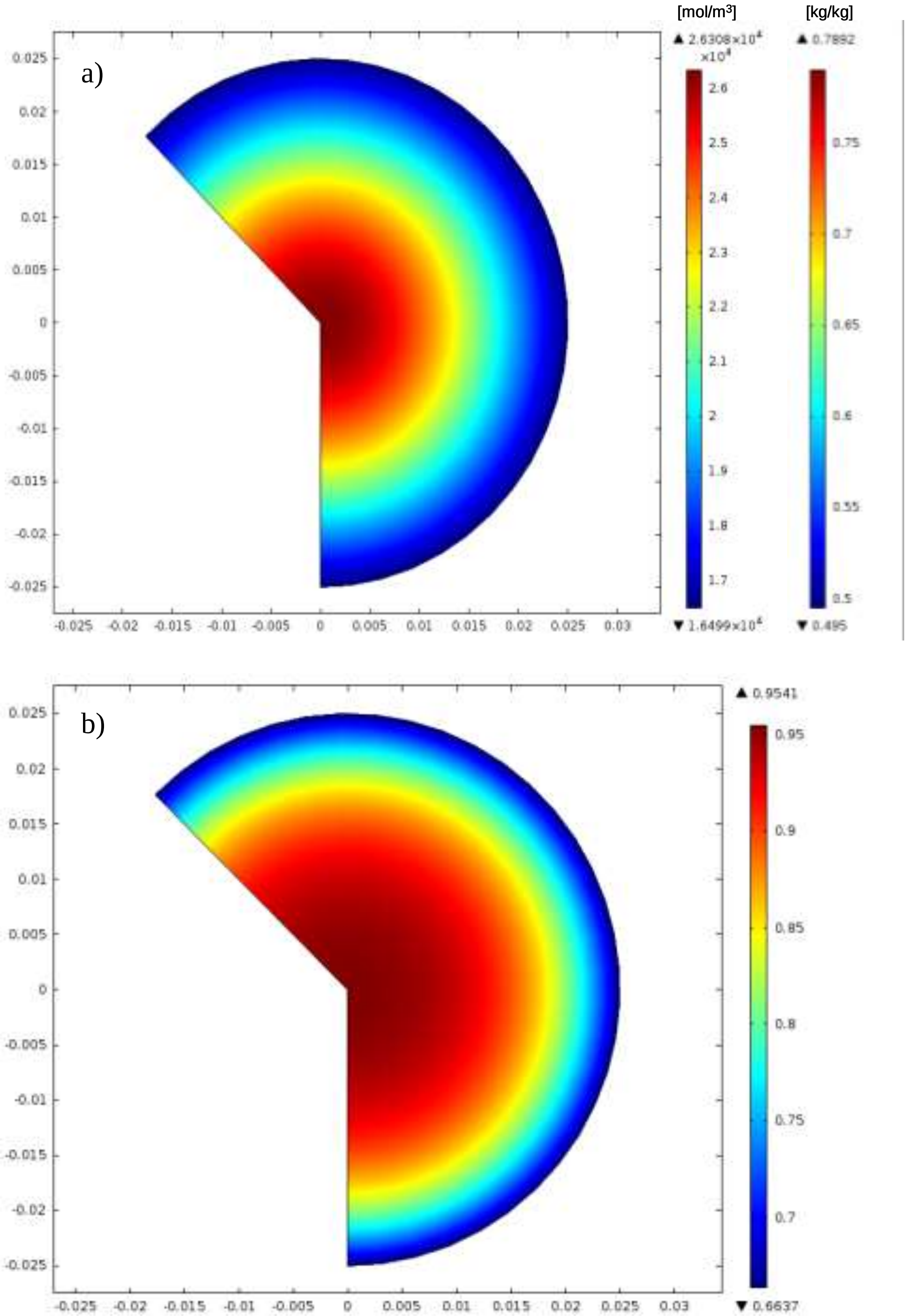

Fig 3

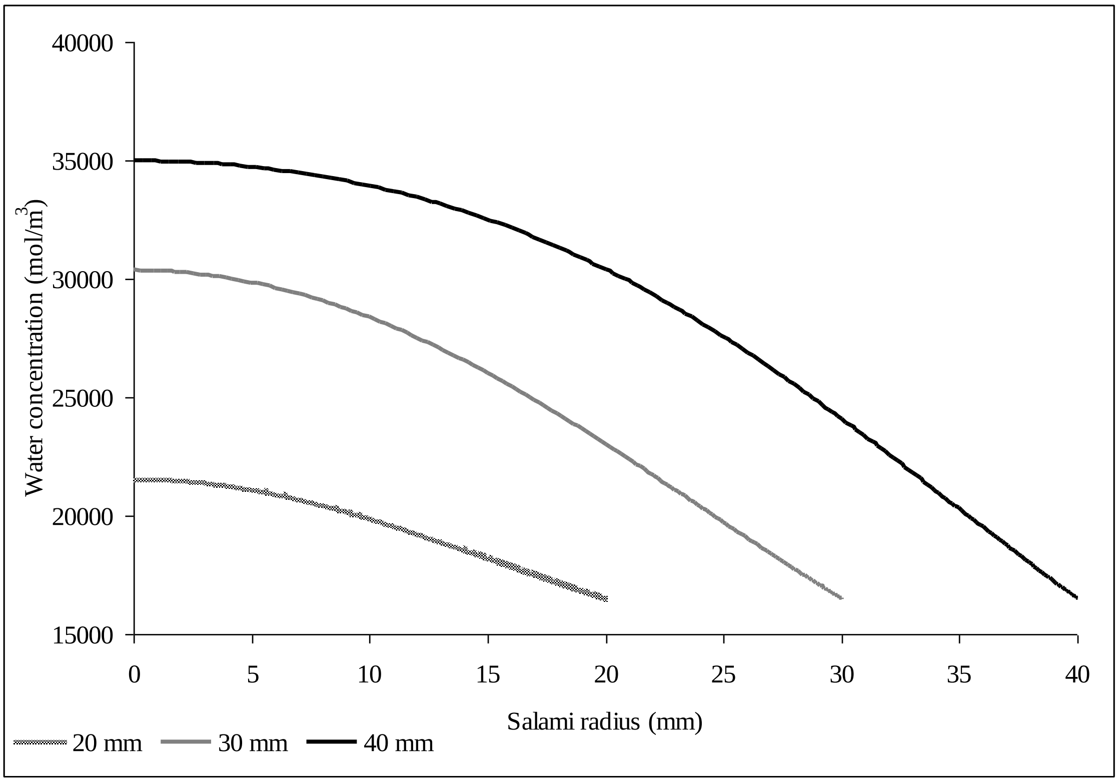
40000
35000
30000
25000
20000
15000
Water concentration (mol/m3)
0
5
10
15
20
25
30
35
40
Salami radius (mm)
20 mm
30 mm
40 mm

Fig 4

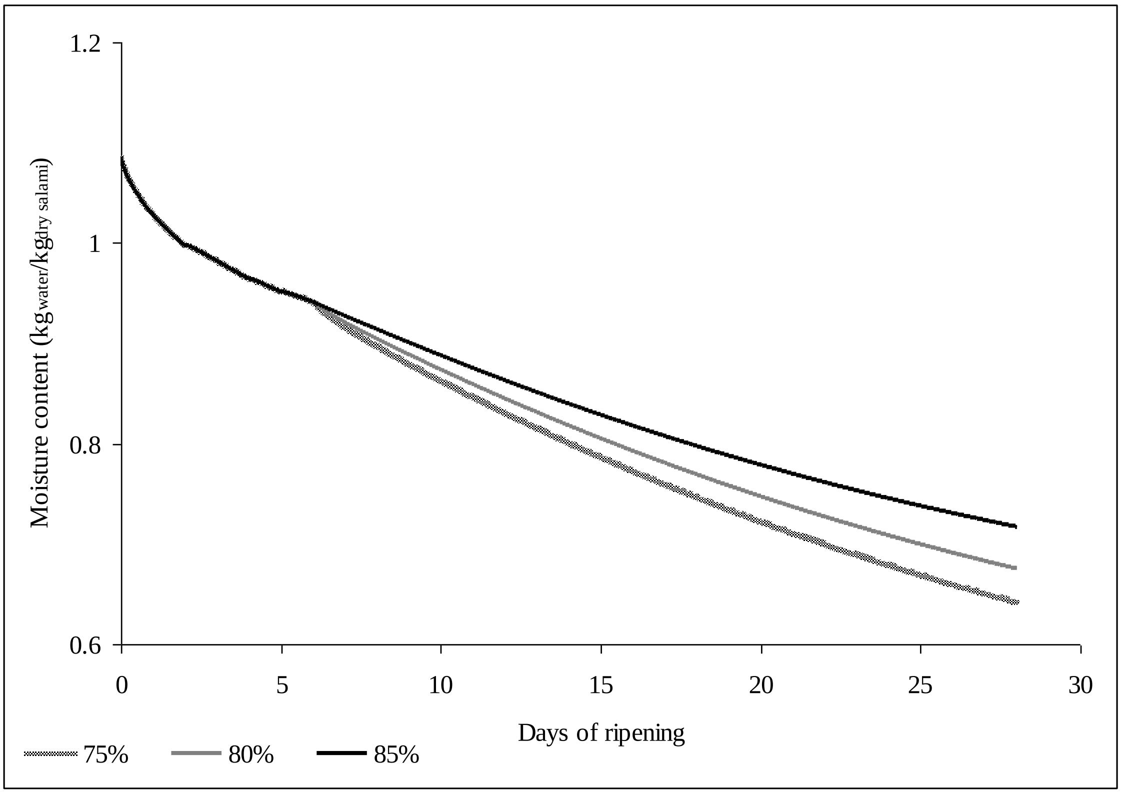
1.2
1
0.8
0.6
Moisture content (kgwater/kgdry salami)
0
5
10
15
20
25
30
Days of ripening
75%
80%
85%

Fig 5

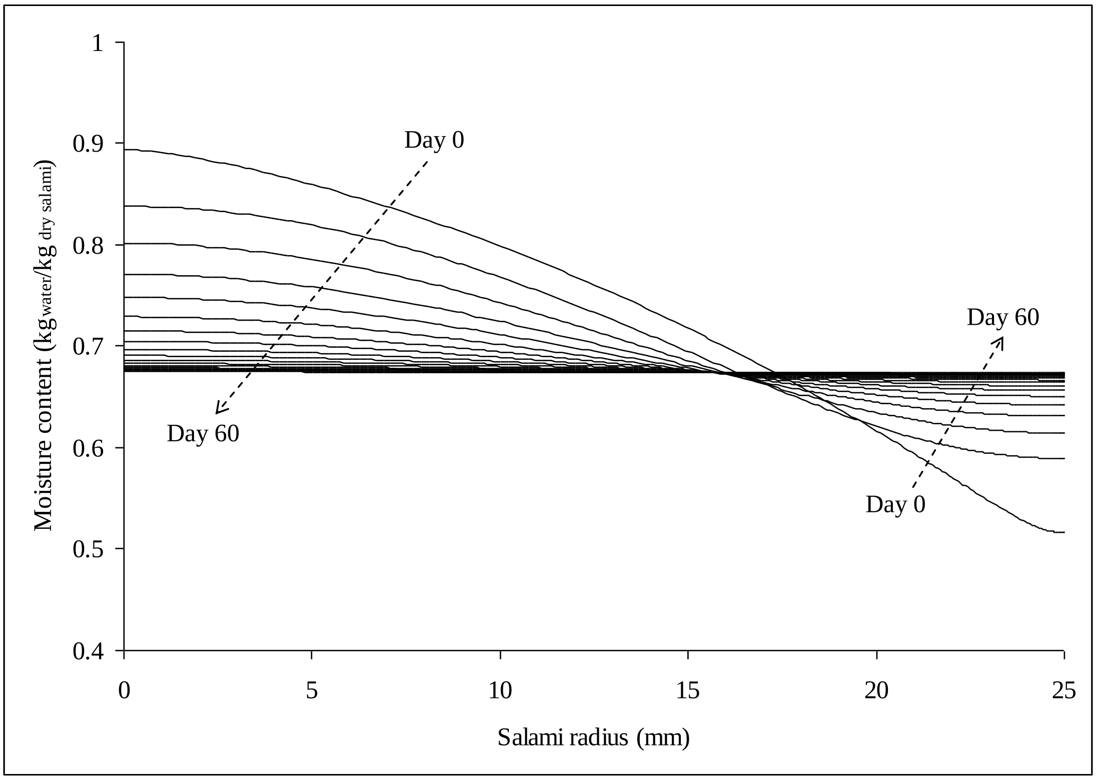
Day 0
Day 60
Day 60
Day 0
Moisture content (kg water/kg dry salami)
Salami radius (mm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0
5
10
15
20
25

Fig 6

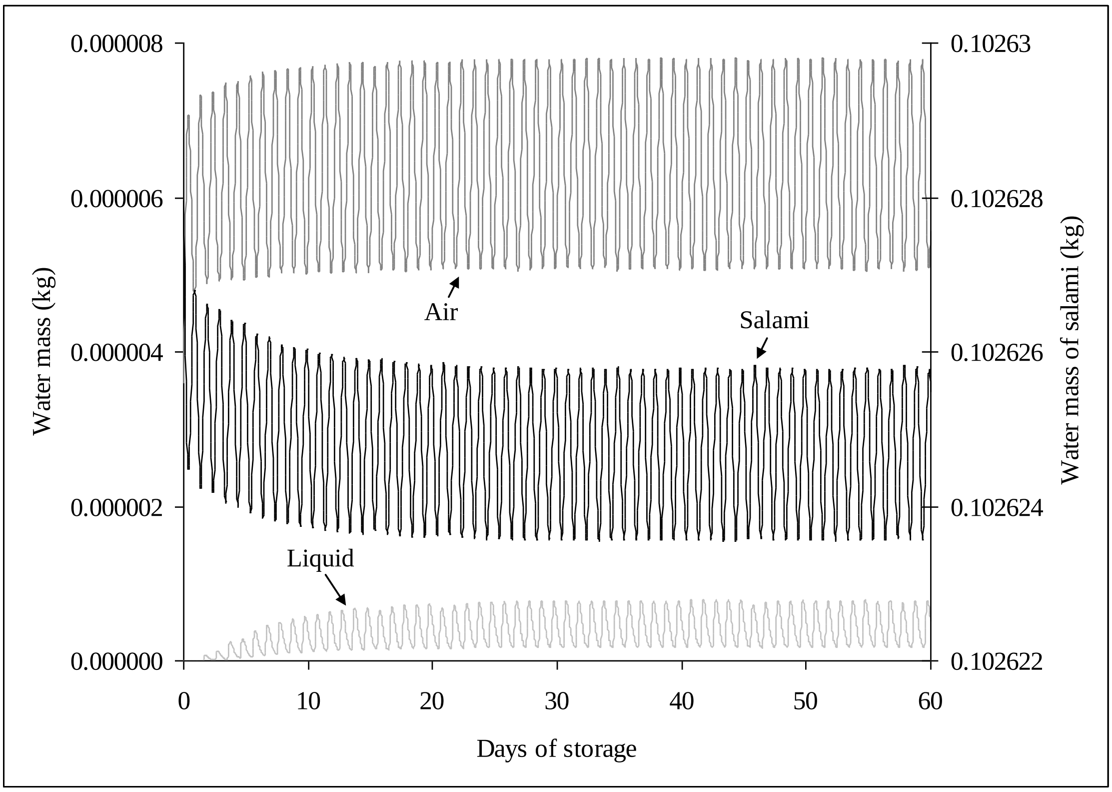
Air
Salami
Liquid
Water mass (kg)
Water mass of salami (kg)
Days of storage
0.000008
0.000006
0.000004
0.000002
0.000000
0.10263
0.102628
0.102626
0.102624
0.102622
0
10
20
30
40
50
60

Fig 7

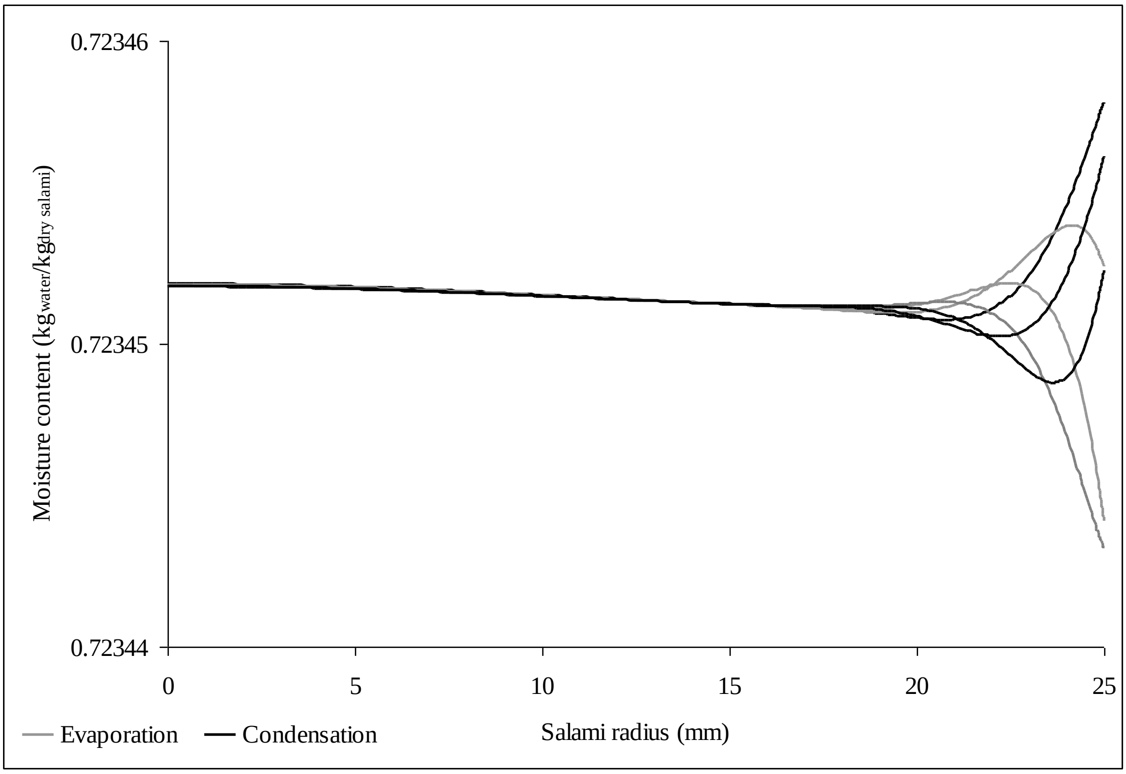

Fig 8

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