6 : 20

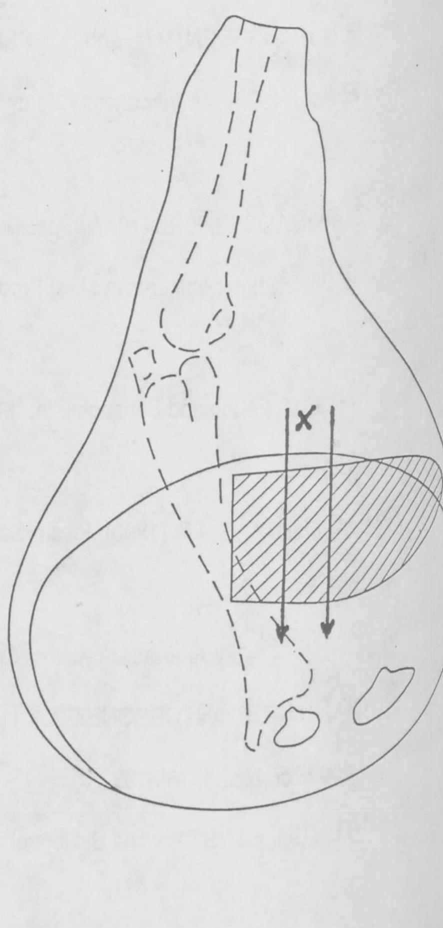
Salt Diffusion in Dry-Cured Ham

F. PALMIA and E. BOLLA
Experimental Station for the Food Preservation Industry - Via Tanara 31/A - Parma - Italy

SUMMARY: The classical solution of Fick's second equation for the problem of uni-directional diffusion from a semi-infinite medium containing an initially uniform concentration of a diffusing substance into a contiguous semi-infinite medium initially free of solute, expressed by the relation: $C = 1/2\ Co\ erfc\ (x/(2\sqrt{De\ t}))$ in which C = concentration (kg/m^3), Co = external concentration (kg/m^3), x = penetration distance (m) and De = effective diffusion coefficient (m^2/s), proved to represent adequately chloride distribution in industrially processed dry-cured hams. The mean De value of chloride in pork muscle Semimembranosus at a temperature between 1 and 4°C calculated from the concentration profiles of four hams, was $0.225 \times 10^{-9}\ m^2/s$ with a standard deviation of $0.0191 \times 10^{-9}\ m^2/s$. On the basis of these results the improvement of the process control by means of objective methods can be foreseen.

INTRODUCTION: Salt penetration into muscle and water removal, by lowering the water activity in the meat, are the factors responsible for the final keeping quality of the cured ham; they take place during the course of a long processing period which can be divided into three main stages: salting and resting at low temperatures, for a period of 80-100 days, and maturation at higher temperatures, for a period of 150-300 days, depending on the size of the ham. Salt diffusion in muscle has been the object of several studies which have analyzed the problem from various points of view and yielded De values for sodium and chloride ions corresponding to different, but generally strictly controlled, experimental conditions (KORMENDY and GANTNER, 1958; WISTREICH et. al., 1959 and 1960; WOOD, 1966; FOX, 1980; ANDUJAR et al., 1981; DJELVEH et al., 1988; PALMIA, 1989); the published data of sodium and chloride as well as of other solutes diffusivities in pork and beef muscles have been collected and re-examined by GROS et al., (1984). In a recent study by FROYSTEIN et al., (1989), the salt distribution in hams has been examined by computer X-ray tomography; this technique showed very clearly the changes in salt uptake and distribution at various stages of the curing process. The salting process of industrially prepared hams has nevertheless not yet been the object of diffusion-theory based studies; the aim of the present work was to check the reliability of a solution of Fick's second equation in the representation of the chloride distribution in industrially processed dry-cured hams.

Figure 1 - The shaded area shows the location of the slab for the determination of the concentration profiles; the arrows indicate the sampling lines and the salt diffusion direction (x).



MATERIALS AND METHODS: Four hams having a weight ranging between 10.85 and 12.50 kilograms were picked at the end of the salting stage, which for hams No's 1 and 2 lasted 12 days and 13 days for hams No's 3 and 4, in a processing plant where the preparation technique allows a dry salt excess to cover the ham for the duration of the salting period; during this first processing step, the duration of which depends on the size of the thighs, the hams were kept at a temperature of 1-4°C. In order to establish if a proper processing had been applied, the hams were analyzed for salt content as well as to obtain the concentration profiles of chloride; the salt content was determined on the lean part of each ham, after removal of the bones, skin and surface fat. To determine the concentration profiles of chloride a slab about 1 cm thick was isolated from each ham in the location marked by the shaded area of Figure 1; the slabs were quickly frozen and stored at -20°C. At the time of the analyses, from each slab ten samples were drawn, by means of a 4 mm internal diameter cork borer, along two parallel lines normal to the upper side which during processing was part of the surface acting as meat-salt interface (see Figure 1); chloride content of each sample was then determined by water extraction and tritation by means of a digital micro-tritator Hach mod. 16900; the results were expressed as kg of chloride per cubic meter of meat product (KORMENDY and GANTNER, 1958). The mathematical model for the data representation was chosen according to the following conditions:

i) the hams are initially salt-free. The little chloride content depends on the green meat composition and is not due to a diffusion process, therefore it can be disregarded when dealing with salt diffusion. The chloride contents of the samples were obtained by subtracting the mean value (i.e. 2 kg/m^3) of ten determinations carried out by following the aforementioned analytical procedure on samples of fresh pork muscle Semimembranosus;

ii) the dry salt excess covering the ham throughout salting allows the external solution to be regarded as a semi-infinite medium containing a uniform concentration of chloride, that, the dry salt on the surface of the ham being largely in excess with respect to the amount of water lost by the meat, was assumed to be equal to the saturation concentration at low temperature (i.e. 192 kg of chloride per cubic meter of solution);

iii) diffusion only occurs from the upper side of the slab, the rest of it being framed in a thick layer of surface fat; by adopting the published values of the effective diffusion coefficient of chloride in pork leg muscles it is easy to establish that the Fourier number $Fo=Det/l^2$ (where t = time (s) and l = distance (m)) is in each case less than 0.05, this allows us to formulate the hypothesis that the salt does not reach the opposite side of the ham (or the lower side of the slab) before salting has been completed.

The fundamental differential equation of uni-directional diffusion is Fick's second law which relates time, concentration and concentration gradient of the diffusing substance; the solution to this equation under the aforementioned conditions expressed as boundary conditions is (CRANK, 1975): $C = 1/2\ Co\ \mathrm{erfc}(x/(2\sqrt{Det}))$, (where C = concentration (kg/m^3), Co = external concentration (kg/m^3), x = penetration distance (m), t = time (s) and De = effective diffusion coefficient (m^2/s)); this is the classical solution for the problem of uni-directional diffusion from a semi-infinite medium containing an initially uniform concentration of the diffusing substance into a contiguous semi-infinite medium initially free of solute. Due to the form of the mathematical solution it is clear that at x = 0 (i.e. at the meat-brine interface) the diffusant concentration is constant and equal to a half of the external one during the diffusion time.

RESULTS AND DISCUSSION: The salt content of each ham is shown in Table 1; these values indicate that the hams have been treated correctly and the salt uptake can be considered as regular, the slight variations being within acceptable limits under good industrial processing. The chloride content of the samples drawn from the slabs were used in the De value calculation; in doing this for each ham the value was identified which minimized the sum of the squares of the deviations between the observed and the calculated chloride concentrations by means of the adopted solution of Fick's second equation; the De values are shown in Table 1, the mean was 0.225×10^{-9} m^2/s with a standard deviation of 0.0191×10^{-9} m^2/s. Owing to the location of the sampling points in the slabs, the aforementioned value has to be regarded as the effective diffusivity of chloride in pork muscle Semimembranosus at a temperature of 1-4°C (i.e. the working range of the salting chambers); it must be pointed out that these results fall within the range of the published data generally obtained under

Table 1 - Hams weight, treatment time and salt uptake data, the amount of salt adsorbed (g) is determined on the lean fraction of each ham.

Ham No.	Weight (kg)	days of salting	salt (g) adsorbed	% salt/ lean meat	chloride Dex10^9 m^2/s
1	10.850	12	188	3.03	0.24
2	10.850	12	175	2.97	0.22
3	12.470	13	184	2.67	0.20
4	12.440	13	188	2.62	0.24

strictly controlled laboratory conditions. Figures 2 and 3 show the plots of the concentration values (kg/m^3) vs. the penetration distance (mm) for the hams after 12 and 13 days of salting, respectively. Each point represents the mean of two determinations; the curves are the graphical results of the mathematical model with a De value of 0.225×10^{-9} m^2/s. The fairly good agreement between experimental data and calculated curves leads to the conclusion that the proposed model is suitable for the representation of diffusion in industrially processed hams; in addition it permits the consideration that the dry-salting procedure limits the interfacial solute concentration to just one-half of the external one thus reducing the overall solute penetration rate when compared, for example, with the diffusion from well stirred solutions, in which the build up of concentration gradients in proximity of the inferface is avoided. The concentration values expressed as kg/m^3 were to be adopted in the calculation of the De values and in plotting the data and the diffusion model; on the other hand it is more useful to express the concentrations as weight percentages; therefore Figure 4 shows a plot of the data points as %

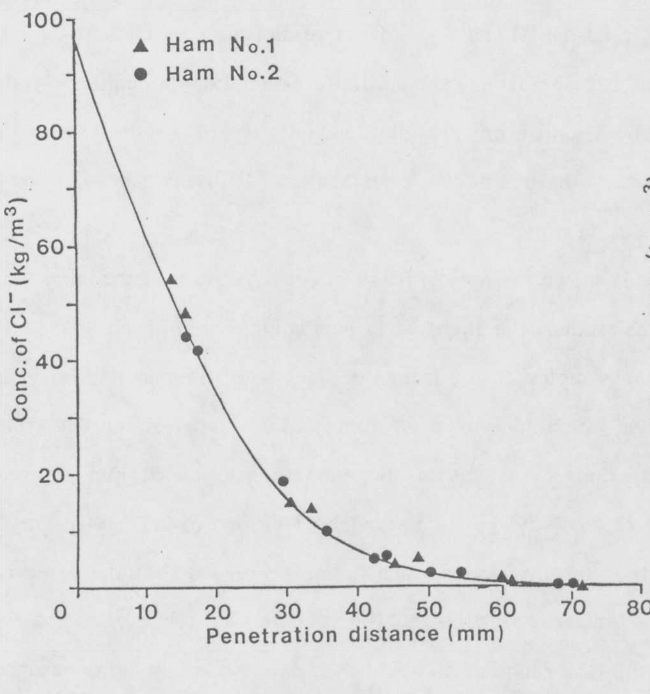


Figure 2 - Plot of the concentration of chloride (kg/m^3) vs. penetration distance (mm) for the hams No's 1 and 2; the curve is the graphical result of the adopted model with De = 0.225×10^{-9} m^2/s and t = 1.0368×10^6 s (or 12 days).

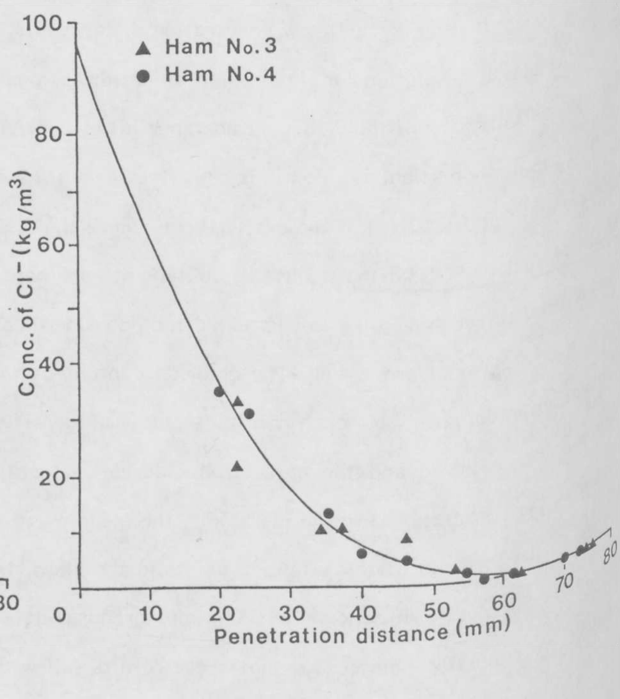


Figure 3 - Plot of the concentration of chloride (kg/m^3) vs. penetration distance (mm) for the hams No's 3 and 4; the curve is the graphical result of the adopted model with De = 0.225×10^{-9} m^2/s and t = 1.1232×10^6 s (or 13 days).

w/w salt content vs. penetration distance (mm); in drawing this plot an approximation was made in order to make the effective diffusivities of sodium and chloride ions the same. In published studies (MITTAL et al., 1982) this was found to be untrue for heat-treated meat products; in the present case however, this approximation could be valid if account is taken of the diffusion time, the width of the sampling holes and the fact that sodium and chloride ions are the chemical species mainly responsible for the electrical neutrality of the medium.

CONCLUSION: The verified reliability of the basic diffusion theory as applied to this particular industrial-processing technique allows a possible way of objectively evaluating the processing state to be fereseen and also the changes in the course of ageing of some parameters related to the final keeping quality of the product to be forecast.

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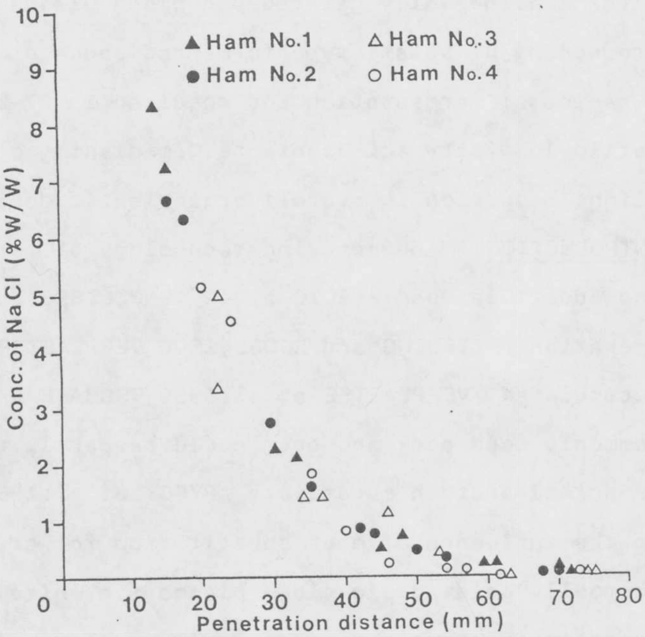
Figure 4 - Plot of the sodium chloride concentration (%w/w) vs. the penetration distance (mm).



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