Optimising Chilling Time of Cooked Pork Ham using Finite Element Modelling Tools

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Abstract — **The aim of this study was to propose to French industrials chilling abaci for cooked pork hams built from numerical simulation. To do this, deboned pork hams presenting no fat rind and weighing 7.5 kg were injected at 8% rate using a brine solution and cooked at 66°C at ham core. The study was divided in 4 steps: 1) acquiring chilling kinetics under different experimental conditions, 2) determining some physical properties of material, e.g. density and thermal conductivity, 3) building numerical models including the real shape of the product and 4) determining the convective heat transfer coefficient from experiments conducted on aluminium-made objects having the same shape than the cooked hams and being subjected to the same chilling conditions. Experimental data were used to validate the numerical models built using Comsol Multiphysics® v3.5a software. Differences between experimental and predicted chilling times were lower than 5%. Using the model shows that, in the best chilling conditions, i.e. air velocity higher than 3 m.s^{-1} and air temperature near -5°C, a minimal time of 6.5 h is required to reach 10°C at the cooked ham core. Increasing air velocity appears as being more efficient than lowering air temperature to reduce chilling time. Finite element modelling can be an efficient method to help industrials in controlling their process. With the model, 80 chilling conditions can be simulated in a 12 h period, i.e. the time needed to test experimentally only one chilling condition.**

Keywords— **Cooked pork ham, Chilling, Abacus.**

I. INTRODUCTION

French industrials do not have any technical information, guidelines or official rules to pilot the chilling of their large cooked pork meat products. The present study aims at building, from numerical simulation, chilling abaci for two types of cooked pork meat products: pâtés and cooked hams, to help industrials in controlling and optimising the cooling process. Through lack of this type of information, the chilling criterion used for ready-to-eat meals is currently applied, i.e. a decrease in temperature allowing to reach a temperature of 10°C at the product core under only two hours. Therefore, this criterion is unsuitable for such large products, unless negative air temperatures are used for cooling, which presents a risk of freezing of the product surface.

This paper presents the four-step methodology developed for modelling, simulating and validating chilling times of large cooked pork hams cooled under various cooling conditions, by combining finite element numerical models and experimental data. Once the numerical models were validated, we built several chilling abaci giving the cooling time necessary for reaching a temperature of either 10°C or 4°C at the core of cooked pork hams.

II. MATERIALS AND METHODS

In this study, a four-step methodology was developed: 1) acquisition of chilling kinetics under different experimental conditions, 2) determination of some physical properties of material, e.g. density and thermal conductivity of cooked pork ham, 3) development of numerical models including the real shape of the product and 4) identification of the convective heat transfer coefficient from experiments conducted on aluminium-made objects having the same shape than the cooked hams and being subjected to the same chilling conditions. Experimental data collected during the first step were used to validate afterwards the numerical models built using Comsol Multiphysics® v3.5a software.

A. Acquisition of the chilling kinetics

Several experiments of cooling of cooked pork hams were performed under the conditions of air temperatures and velocities reported on Table 1.

Table 1 Experimental conditions used for cooked pork ham cooling

Air temperature (°C)	Mean air velocity ($m.s^{-1}$)
T1 = 0.5	Vmin = 1.1
T2 = -4.5	Vmax = 3.4

Before cooling, deboned pork hams presenting no fat rind at the surface and weighing 7.5 kg were injected at 8% rate using a brine solution and cooked in a small-sized industrial oven at 66°C at core.

In addition to the air temperature and velocity, the effect of introducing a 30-min or 90-min washing step just after cooking on the chilling time was also experimentally tested. In industry, washing is sometimes realized prior to cooling in order to increase the cooling process, to clean the products just at the end of cooking, or to decrease the oven temperature.

Taking into account the replicates, a total of 14 trials were performed. During each trial, the product temperature was recorded at three points (at the core – Tc -, at 1 cm from the air/ham surface – Tsurf - and 1 cm from the mould/ham interface – Tm) by means of calibrated K-type thermocouples connected to a data logger. A fourth thermocouple was placed in the cooling cell to measure the air temperature.

B. Physical properties of cooked pork ham

Density, specific heat capacity and thermal conductivity are essential physical properties for heat transfer by conduction. Concerning cooked pork ham, some data were available in literature, i.e. constant values of 1040 $kg.m^{-3}$ and 3100 $J.kg^{-1}.K^{-1}$ in the range 10-80°C, for density and specific heat capacity, respectively. As regards thermal conductivity, we considered a temperature-dependent variation, with values ranging from 0.34 $W.m^{-1}.K^{-1}$, at 0°C, to 0.44 $W.m^{-1}.K^{-1}$, at 80°C [1].

C. Numerical model

We used Comsol Multiphysics® v3.5a software for building numerical models to simulate the cooling step of cooked pork hams under the conditions of Table 1. To obtain a model as realistic as possible (Fig. 1), the real 3D shape of a cooked pork ham was numerically re-built from a series of 2D digitalized photographs corresponding to 2 cm-thick slices of ham. The shape was then discretized in approximately 60,000 mesh elements (Fig. 1), in which all the heat transfer equations were solved using finite element method.

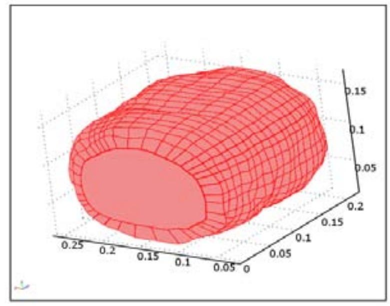

Fig. 1 Numerical model built for simulating cooked pork ham cooling

To determine the cooling kinetics, an air-product thermal balance was numerically solved under transient conditions. In few words, this thermal balance describes that, at each time step, the internal heat flux by conduction is counterbalanced by the external heat flux by convection. It can be noted that the heat transfer due to water evaporation from the product surface was neglected because pork hams were wrapped in an airtight plastic bag during cooking and cooling. When writing the equations, two types of parameters appear: the ones corresponding to the material properties - thermal conductivity, density, among others - and the ones corresponding to the cooling properties - air temperature and convective heat transfer coefficient, which is related to the air velocity.

Once built, the solving of the numerical models allows the product temperature to be calculated and visualized in any point of the 3D structure.

D. Identification of the convective heat transfer coefficient

The convective heat transfer coefficient (noted hm) was experimentally determined from specific experiments consisting in cooling an aluminium-made object previously heated in a hot water bath. This object had the same shape than the cooked pork hams (Fig. 2) and was subjected to the same chilling conditions. Aluminium was chosen because its physical properties are accurately known. A K-type thermocouple was inserted in the core of the aluminium block to follow the temperature kinetic at this location. In view of the high value of the thermal conductivity of aluminium, the convective heat transfer coefficient can be easily adjusted using inverse method, by minimizing the discrepancy between the temperature kinetic measured and the one calculated at the centre of an equivalent cylinder [2].

Fig. 2 Aluminium-made object having the same shape than a cooked pork ham

III. RESULTS AND DISCUSSION

A. Convective heat transfer coefficient

Before performing calculation, as indicated previously, values of mean convective heat transfer coefficient had to be determined experimentally for each cooling trial realized (all conditions of Table 1, plus during the washing step). Table 2 shows the values of hm identified further to experiments using the aluminium-made ham.

Table 2 Values of mean convective heat transfer coefficient (hm) identified further to experiments

Cooling conditions (Table 1)	hm ($W.m^{-2}.K^{-1}$)
T1 / Vmin	19.2 +/- 1.0
T1 / Vmax	38.6 +/- 2.4
T2 / Vmax	41.2 +/- 1.1
During washing	146.4 +/- 19.1

Analysis of Table 2 shows that increasing the air velocity around the object increases the mean convective heat transfer coefficient. Doubling air velocity allows a 40% increase of hm. Using water instead of air also increases strongly the hm coefficient, which exceeds 140 $W.m^{-2}.K^{-1}$.

B. Chilling kinetics

Once the convective heat transfer coefficients were identified, numerical models were solved to calculate chilling kinetics as well as chilling times for reaching either 10°C or 4°C at ham core. As an example, Figure 3 shows the chilling kinetics calculated on three points of a cooked pork ham cooled under the ‘T2 / Vmax’ condition of Table 1.

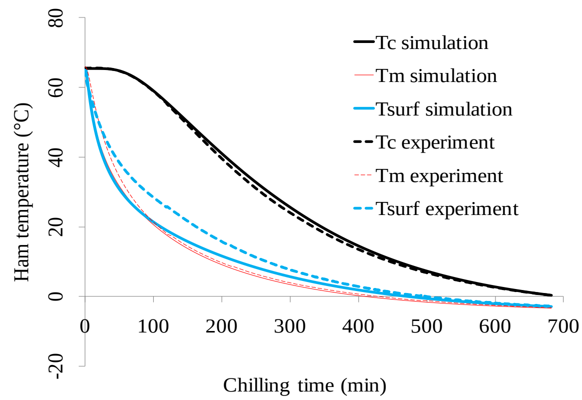

Fig. 3 Chilling kinetics calculated using finite element modelling on three points of a cooked pork ham cooled under -4.5°C and 3.4 $m.s^{-1}$ airflow

Table 3 shows the chilling times determined experimentally and necessary for reaching either 10°C or 4°C at the core of cooked pork hams subjected to the cooling conditions of Table 1 and also to washing.

Table 3 Measured chilling times necessary for reaching either 10°C or 4°C at the core of cooked pork hams

Cooling conditions (Table 1)	Time necessary for reaching 10°C at core (h)	Time necessary for reaching 4°C at core (h)
T1 / Vmin	9.9 +/- 0.2	14.0 +/- 0.3
T1 / Vmax	8.3 +/- 0.2	11.6 +/- 0.5
T2 / Vmax	7.3 +/- 0.2	9.2 +/- 0.2
30-min washing[1]	9.6 +/- 0.2	13.7 +/- 0.2
90-min washing[1]	9.4 +/- 0.3	13.4 +/- 0.5

[1] Washing of cooked pork ham was performed just after cooking and before cooling under the ‘T1 / Vmin’ condition of Table 1

Analysis of Table 3 highlights that, whatever the cooling conditions applied to the cooked ham, it is absolutely impossible to reach 10°C at core under

2 hours. According to this table, more than 7 hours are necessary when cooling the cooked pork ham under a -4.5°C and 3.4 m.s^{-1} airflow. This clearly demonstrates that the criterion applied to ready-to-eat meals is absolutely unsuitable for large pork meat products.

Table 3 also shows that introducing a washing step prior to cooling tends to reduce chilling times, but the reduction appears as being very low, even though washing lasted 90 min. Finally, washing can be considered of poor interest when comparing chilling time reduction obtained and water amount used.

Analysing Table 4 demonstrates that finite element modelling allows chilling times to be calculated accurately; the discrepancy between calculation and measurement does not exceed 5%, i.e. about 30 min. For all the cooling conditions investigated, numerical models were able to predict accurately chilling times.

Table 4 Discrepancy between calculation and measurement of chilling kinetics of cooked pork hams

Cooling conditions (Table 1)	Discrepancy on time necessary for reaching 10°C at core	Discrepancy on time necessary for reaching 4°C at core
T1 / Vmin	3.6% (23 min)	3.6% (33 min)
T1 / Vmax	-3.2% (16 min)	-2.8% (19 min)
T2 / Vmax	-4.3% (19 min)	-3.0% (16 min)
30-min washing[1]	4.2% (19 min)	3.0% (16 min)
90-min washing[1]	-3.0% (13 min)	-3.4% (13 min)

[1] Washing of cooked pork ham was performed just after cooking and before cooling under the ‘T1 / Vmin’ condition of Table 1

C. Chilling abacus

From the numerical models built, chilling abaci were constructed as a function of the desired core temperature (either 10°C or 4°C) and as a function of the values of the convective heat transfer coefficients and cooling air temperatures.

As an example, Figure 4 shows the abacus giving the chilling time necessary for reaching 10°C at the core of a cooked pork ham weighing 7.5 kg. In the most favourable case, a chilling time of 6.5 h is nevertheless required to cool at 10°C a cooked pork ham, provided that very low air temperature (-5°C) and very high air velocity (3.9 m.s^{-1}, i.e. a hm coefficient of 45 W.m^{-2}.K^{-1}) are used for cooling, which is impossible in most industrial plants.

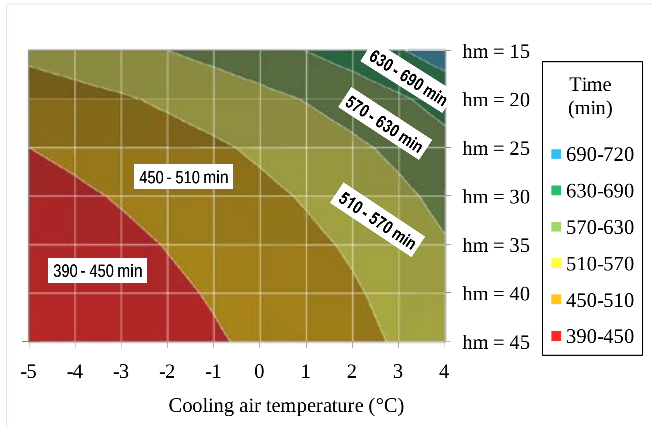

Fig. 4 Abacus giving the chilling time necessary for reaching 10°C at the core of a cooked pork ham

IV. CONCLUSIONS

In this paper, we demonstrated that using finite elements modelling tools allowed chilling times to be predicted rapidly and accurately at the core of large pork meat products. Modelling appears as being an efficient way to provide useful information to industrials in controlling the cooling process. With the model, 80 chilling conditions can be simulated in a 12 h period, i.e. the time needed to test experimentally only one chilling condition. Moreover, modelling can be subsequently used to simulate the cooling of food products under unsteady conditions to optimize at best this last step. Numerical results also highlighted that the convective heat transfer coefficient, which is related to air velocity, was a crucial parameter during cooling.

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