REFERENCE TRAJECTORY TRACKING OF SUPERFICIAL TEMPERATURE IN FOOD DECONTAMINATION

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Abstract

This paper proposes a preliminary study, for the tracking control of the superficial temperature in rapid decontamination of foods surface. The data are issued from a heat and mass transfer simulator, taking into account all the specificities of the process and of the product. This study, supported by a on-going European project, aims at imposing an increasing and decreasing ramp-type temperature profile to the surface of foods, to achieve a complete or partial destruction of microorganisms. A complete model including water activity, food desiccation and heat transfer is proposed to describe the phenomena induced by the process. A simplified model, based only on heat transfer, is finally proposed to design a tracking control of a superficial temperature reference profile. The robustness of the solution is discussed through different conditions of use.

Keywords

Heat transfer, mass transfer, decontamination, tracking control, trajectory planning.

Nomenclature

a_w	Water activity	%
C_v	Concentration of water vapor	kg. m^{-3}
Cp	Specific heat	J. kg^{-1}. K^{-1}
D	Diffusion coefficient	m^2. s^{-1}
h	Heat transfer coefficient	W. m^{-2}. K^{-1}
k_m	Mass transfer coefficient	m. s^{-1}
M	Moisture content	kg w. kg dm^{-1}
M_w	Molecular weight of water	kg. kmole^{-1}
t	Time	s
T	Temperature	°C
z	Vertical coordinate	m
α	Thermal diffusivity	m^2. s^{-1}
Δz	thickness of each finite volume	m
λ	Thermal conductivity	W. m^{-1}. K^{-1}
ρ	Density	kg. m^{-3}
R_u	Universal gas constant	J.kmole^{-1}. K^{-1}
P	Water vapor pressure	Pa

a-dimensional numbers

Le	Lewis number
Pr	Prandtl number
Sc	Schmidt number

Subscripts

a	Air
dm	Dry matter
m	melting
inf	Bottom surface
n	Top surface
p	Product
v	Vapor
w	Water

Introduction

The surface of food products may be contaminated by microorganisms which could threaten the health and even the life of consumers. Decontamination of the surface of meat products is necessary and very important. It is proved that heat treatments are efficient to decrease significantly this microbial contamination. However, the determination of the level of microbial destruction that a thermal treatment induces in a product requires the understanding of the amount of heat delivered to every portion of the food product. A too intensive treatment should be avoided as it may cook a thin layer of product and affect the surface color. For these reasons, the treatment consists, in a first stage, in heating the product at the desired temperature and, in a second stage, in cooling it towards a low temperature which will prevent recontamination. A on-going European project (EU QLK1-CT-2001-01415, BUGDEATH) coordinated by the Food Refrigeration and Process Engineering Research Centre (University of Bristol, UK) aims, in part, to develop models and control strategies that predict and optimize the effect of thermal treatments of decontamination of food products surfaces. The key parameter of decontamination processes is the surface temperature which depends on the heating/cooling medium and on the thermal properties of the food. In this work, we consider the decontamination treatment of lean beef by hot/cold air at high velocity (20m/s). The physical phenomena close to the surface are rather complex because the heat is transferred by convection and evaporation during the heating stage and by convection and condensation in the cooling phase. The evaporation is crucial because it is governed by the water activity of the food which evolves with time. The evaporation modifies the water content of the product and leads to coupled heat and mass transfer. An accurate modeling of this process requires the knowledge of all parameters and a robust numerical algorithm.

To follow a ramp-type (heating then cooling) set point profile for the superficial temperature, we propose to design a simple but robust reference tracking control, computed from a simplified model of the phenomena. The control law obtained is applied on a simulator derived from a complete modeling of the phenomena, that is, taking into account water activity, mass diffusion inside the food and evaporation at the surface The follow-up of the internal temperature could thus be used to reconsider the procession parameters, as instance to avoid non expected cooking of the internal layers and to dimension heating and cooling systems.

This paper is organized as follows:

- The first part is dedicated to the process description,
- In a second part, a complete model of heat transfer inside the food is developed, taking into account the evaporation phenomena at the exchange surface. This model constitutes the simulator on which the control algorithm will be tested in simulation.
- The third part deals with the tracking control of the superficial temperature, presenting a particularly efficient and simple way to implement closed-loop approach.

Process description.

The decontamination rig used for the decontamination process can heat the surface of a food sample from 5 to 100°C in a time span of up to 900 seconds, and a cooling system allows quickly decreasing the temperature to prevent recontamination. The apparatus is fully computer controlled and the duration of heat treatment, holding and cooling phase is entered into a graphical user interface (GUI) written in Microsoft® Visual Basic, constituting the reference to track.

For the process, the food sample is first placed in the sample holder of the machine, a small dish 18 mm deep with a diameter of 50 mm. By pressing an initial button from the GUI, a pneumatic actuator moves the sample into the chamber. The sample is then subjected to a very high velocity air stream heated by a 3.3 kW heater, allowing a rapid increasing of the superficial temperature of the products. Then, the temperature is hold at a constant set superficial temperature during a variable time, and at last a rapid cooling is provoked with air at –20°C. Hot and cold air jets are blown through 2 separate nozzles placed inside the chamber 35 mm away from the leading edge of the sample in such a way that each airflow is parallel to the surface (no impingement). The rotation of the sample using a motor ensures a uniform temperature of the food surface during treatment. So heat and mass transfer can be assumed to be 1D. The surface temperature is measured using an infra red (IR) sensor attached to the top of the chamber 80 mm above the surface of the sample. During treatment, a control status box on the computer display informs the user of what is currently happening and the time remaining of the different tasks. Especially, a control accuracy bar displays the surface temperature measured by the IR sensor and the desired temperature. Today, the surface temperature control is limited to a basic split-range threshold controller, acting either on the heater or on the pneumatic valves of the cooling system. It is obvious that such a control strategy is particularly insufficient to warrant the microbiological specifications.

Process modeling.

heat – mass transfer model.

In the considered process, heat and mass transfer must be taken into account together, so the evaporation phenomena are important with elevated temperature and convection coefficient. To develop an efficient control of the superficial temperature during decontamination, a preliminary study must be undertaken. We propose beforehand to develop an accurate model of the heat and mass transfers, which will be used as a simulator for the control law development.

Let us now consider the following assumptions:

- sample is an infinite slab;
- the product is isotropic and homogeneous;
- no internal heat generation and uniform initial conditions are considered;
- the physical and thermal properties are constant;
- water vapor flux in the product during drying is negligible.

The flow of moisture within the product occurs by diffusion and is governed by the diffusion coefficient according to Fick’s second law (Braud et al., 2001):

$$\frac{\partial M}{\partial t} = D_w \cdot \frac{\partial^2 M}{\partial z^2} \tag{1}$$

Heat transfer within the product is driven by conduction as a temperature gradient develops along its thickness according to Fourier’s second law:

$$(\rho \cdot Cp)_p \cdot \frac{\partial T}{\partial t} = \lambda_p \cdot \frac{\partial^2 T}{\partial z^2} \tag{2}$$

The bottom surface is insulated, and the top one receives heat by convection:

$$(\rho \cdot Cp)_p \left.\frac{\partial T}{\partial t}\right|_{z=0} = h(T_a - T(0,t)) \tag{3}$$

For the boundary condition at z=0 (top surface), the liquid flux to the surface plus vapor flux away from the surface into the external drying media must be equal to the instantaneous variation of water mass content in the solid:

$$\rho_{dm} \cdot D_w \cdot \frac{\partial M}{\partial z} + k_m \cdot (C_{va} - C_{vn}) = \rho_{dm} \cdot \left(\frac{\Delta z}{2}\right) \cdot \frac{\partial M}{\partial t} \tag{4}$$

The corresponding boundary condition for heat transfer is:

$$\lambda_p \cdot \frac{\partial T}{\partial z} + h \cdot (T_a - T_n) + \rho_{dm} \cdot D_w \cdot \frac{\partial M}{\partial z} \cdot Cp_w \cdot T_n + k_m \cdot (C_{va} - C_{vn}) \cdot Cp_v \cdot T_n = (\rho \cdot Cp)_p \cdot \left(\frac{\Delta z}{2}\right) \cdot \frac{\partial T}{\partial t} \tag{5}$$

Concerning the boundary condition at z=L (bottom surface), it is assumed that there are no mass and heat transfers across that surface of the drying material:

$$D_w \cdot \frac{\partial M}{\partial z} = \left(\frac{\Delta z}{2}\right) \cdot \frac{\partial M}{\partial t} \tag{6}$$

$$\lambda_p \cdot \frac{\partial T}{\partial z} + \rho_{dm} \cdot D_w \cdot \frac{\partial M}{\partial z} \cdot Cp_w \cdot T_{\inf} = (\rho \cdot Cp)_p \cdot \left(\frac{\Delta z}{2}\right) \cdot \frac{\partial T}{\partial t} \tag{7}$$

Parameters used in the model.

The thermal properties of the product (Rahman, 1995), air and water (Wark, 1996 and Holman, 1997) were taken from the dedicated literature.

Assuming water vapor as ideal gas (Wang and Brennan, 1995), the concentrations of water vapour is equal to

$$C_v = \frac{P_v \cdot M_w}{R_u \cdot T} \tag{8}$$

The mass transfer coefficient can be related to convective heat transfer coefficient (Kuitche et al., 1996) using the Lewis relation:

$$k_m = \frac{h}{\rho_a \cdot Cp_a \cdot Le^{2/3}} \tag{9}$$

The water activity is approximated by the ratio of the partial pressure of water vapor at the surface of the product to the vapor pressure of pure water at the product temperature (Lind and Rask, 1991)

$$a_w = \frac{P_{vn}}{P_{vsat}} \tag{10}$$

The equilibrium moisture content and the water activity of a food at given temperature and pressure are related by the sorption isotherms graphs. The sorption isotherm can also be described mathematically, and several mathematical models have been suggested (Delgado and Sun, 2002).

Tracking control of reference superficial temperature.

Model simplification

The solutions to track a reference trajectory are numerous, especially in the literature dedicated to robots (Ider et al., 2002), but they can be found process engineering as well (Sakamoto et al., 1998, Boillereaux et al., 1999). The tracking problem can be seen two ways, either by following a reference trajectory function, or by specifying position, velocity and acceleration (if necessary) at each time.

Simple PID controllers can be employed to achieve such control strategies, but it is well-known that their robustness in regards with the modeling errors is limited. Some authors (Alonso et al., 1998) propose to use adaptive control strategies that are more robust since they are, e.g., coupled with an IMC strategy. In this work, we propose a simple and robust strategy based on an approximated model of the process, assuming that the requested state variables are available (measured or estimated).

A complete model of the phenomena has been proposed and discussed in the previous section, and comprises a certain number of uncertainties, as for instance the water activity evolution, the mass diffusion coefficient and the convective exchange parameter. Moreover, the measurement of the mass transfer is very difficult even impossible to get on-line. Due to these drawbacks, the control law will be established considering a simplified model of the phenomena, but will be applied on the complete simulator.

In the simplified model, we propose to neglect the mass transfer. By neglecting the evaporation term, the evolution of the superficial temperature, issuing from an energy assessment at the superficial volume, is:

$$\frac{dT_n}{dt} = \frac{2h}{(\rho Cp)_p \Delta z}\left(T_a - T_n\right) + \frac{2\lambda_p}{(\rho Cp)_p \Delta z^2}\left(T_{n-1} - T_n\right) \qquad (11)$$

For all the internal volumes, it can be written that, following the same reasoning of simplification, the temperatures evolve as expressed in the following equation:

$$\frac{dT_i}{dt} = \frac{\lambda_p}{(\rho Cp)_p \Delta z^2}\left(T_{i+1} - 2T_i + T_{i-1}\right) \quad \forall i \in [2, n-1] \qquad (12)$$

$$\frac{dT_1}{dt} = \frac{2\lambda_p}{(\rho Cp)_p \Delta z^2}\left(T_{i+1} - T_i\right) \qquad (13)$$

Control law design

Consider the ambient temperature as the manipulated variable, denoted *u*(*t*), and the surface temperature measurement, which is the control one, denoted *y*(*t*). The previous system can be written in the following matrix form, leading to a linear state space representation:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \qquad (14)$$

$x = \begin{bmatrix} T_n & T_{n-1} & \cdots & T_1 \end{bmatrix}^T$ represents the vector of the temperatures of each finite volume,

$$A = \frac{\alpha}{\Delta z^2}\begin{bmatrix} -2 - {}^{2h\Delta z}\!/\!_{\lambda} & 2 & 0 & \cdots & \cdots & \cdots & 0 \\ 1 & -2 & 1 & 0 & \cdots & \cdots & 0 \\ 0 & 1 & -2 & 1 & 0 & & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & & \vdots \\ \vdots & & \ddots & \ddots & \ddots & \ddots & 0 \\ \vdots & & & \ddots & 1 & -2 & 1 \\ 0 & \cdots & \cdots & \cdots & 0 & 2 & -2 \end{bmatrix}$$ is a 3-diagonal matrix,

$C = \begin{bmatrix} 1 & 0 & \cdots & 0 \end{bmatrix}$ and $B = \frac{h}{\rho C_p \Delta z}\begin{bmatrix} 1 & 0 & \cdots & 0 \end{bmatrix}^T$ are respectively the output and input vectors.

By replacing y in Eq. (11), the following expression is straightforwardly obtained:

$$u = \frac{(\rho Cp)_p \Delta z}{h}\left(\dot{y} - \frac{\alpha}{\Delta z^2}\left(T_{n-1} - y\right)\right) + y \qquad (15)$$

Let us denote y_{sp} the set point profile of the superficial temperature. The expression of the input to apply to the process, in an open-loop scheme, is obtained by replacing $\dot{y}$ and y respectively by $\dot{y}_{sp}$ and y_{sp} in Eq. (15).

However, it appears that the computation of the control variable requires the knowledge of the temperature in the second volume of the meshing, denoted T_{n-1}. As mentioned previously, all the state variables requested are assumed available, either by direct measurement or estimation.

Let us now design the closed-loop solution. Denote $\varepsilon = y_{sp} - y$ the output error. This error must respect the following differential equation:

$$\varepsilon^{(p)}(t) = k_0\varepsilon(t) + k_1\dot{\varepsilon}(t) + k_2\ddot{\varepsilon}(t) + \cdots + k_{p-1}\varepsilon^{(p-1)}(t) \qquad (16)$$

where the scalars $k_0, \cdots, k_{p-1}$ are chosen to warrant the stability of Eq. (16). p is the relative degree of the considered output. In our case, it can be easily verified that:

$$p = \min_{k \in N}\left\{\frac{\partial x_n^{(k)}(x, u)}{\partial u}\right\} = 1 \qquad (17)$$

The closed-loop control is directly obtained from Eq. (15) by replacing $\dot{y}$ by $\dot{y}_{sp} + k_0\left(y_{sp} - y\right)$, according to Eq. (16):

$$u = \frac{(\rho Cp)_p \Delta z}{h}\left(\dot{y}_{sp} + k_0\varepsilon - \frac{\alpha}{\Delta z^2}\left(T_{n-1} - y\right)\right) + y \qquad (18)$$

Application in simulation

The control approach has been carried out on a simulator built from the model expressions given in the section dedicated to the process modeling, using an implicit finite volumes schemes to solve the problem.

The food under consideration is lean beef, and the thermal parameters used in the simulator and in the control law are assumed to be well known.

The control objective is to track a superficial set point temperature composed first of a 1 K.s^{-1} ramp-type profile, and second of a -0.5 K.s^{-1} ramp-type profile.

In this first example, the evaporation term is omitted, as if the product were packed. Figure 1a represents the reference to track (solid line), the superficial temperatures with $k_0 = -0.5$ (dashed lines) and $k_0 = -3$ (dotted lines), while Figure 1b represents the corresponding control temperature evolution.

In a second example, we consider that the food is exposed directly to the air jet, and an important evaporation appears. We propose here to test the model robustness of our control approach. The control approach is used with the same parameters, that is, $k_0 = -0.5$ and $k_0 = -3$ (see Figure 2a and Figure 2b).

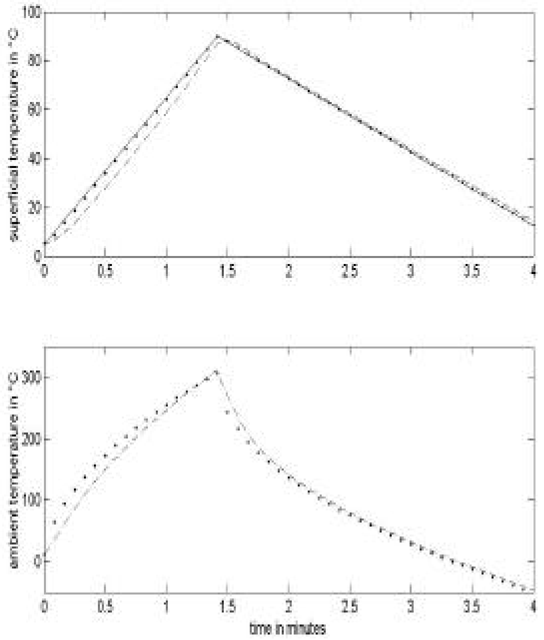

Figure 1.a- Reference tracking without evaporation.
b- Control variable evolution

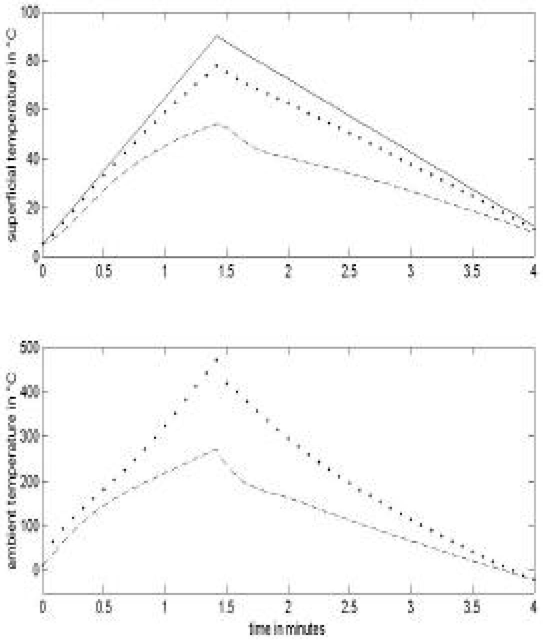

Figure 2.a- Reference tracking with evaporation.
b- Control variable evolution

It can be noticed that the robustness is limited, especially when the corrective gain k_0 is small. Of course, the temperature decrease due to the evaporation leads to an important increasing of the control temperature, as expected.

Addition of an integral correction

To reduce the effects of model uncertainties, an efficient improvement consists in adding an integral action to the correction. With this modification, the expression of the input becomes:

$$u^* = \frac{(\rho Cp)_p \Delta z}{h}\left(\dot{y}^* + k_0\varepsilon + k_I\int_0^t \varepsilon(\tau)d\tau - \frac{\alpha}{\Delta z^2}(T_{n-1} - y)\right) + y \tag{19}$$

On Figure 3a, the tracking error is represented with (k_0, k_I) equal to $(-3, -1)$, while the corresponding control variable evolution is given on Figure 3b.

The addition of an integral term leads to a increasing of energy consumption of about 13% in a first approximation (proportionally to $\int u^*(t)dt$ on the whole experiment), with $k_0 = -3$, but the robustness is considerably improved.

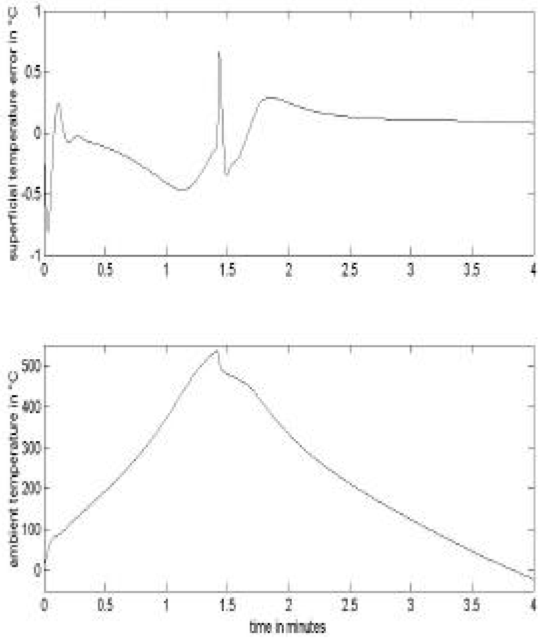

Figure 3.a- Superficial temperature tracking errors.
b- Control variable evolution

Conclusion.

The aim of our investigations about food preservation consists in imposing a specific temperature profile to the surface of a food during decontamination. The superficial temperature profiles presented in the previous section are recommended by the microbiologists taking part in the project, but must be adapted to each type of food. However, to achieve this objective, the profile is composed of ramp-type set point temperature profiles, in heating then cooling modes, with or without an intermediary plateau. We have thus proposed a tracking control of the reference of the superficial temperature, based on a simplified model of the transfer phenomena, totally neglecting the evaporation phenomena. The control law has been carried out in different cases, on a simulator resulting from a complete modeling of the phenomena, including water activity, weight loss due to evaporation and thermal properties evolution with mass transfer.

In this paper, it has been shown that the robustness of the control is limited, when the evaporation phenomena is considerable. To improve the results, a corrective term based on the integral of the tracking error has been added, leading to an efficient superficial temperature planning.

However, it is important to notice that the control law requires the knowledge of the temperature located in volume 2, that is, immediately under the superficial layer. In further investigations, this measurement (here the simulator) will be removed and replaced by an observer, based on the surface temperature measurement.

The next stage of this work, of course after experimental validation on the rig, presented in a next work, is to develop a tracking control strategy considering some constraints on state variables, as instance limited time-temperature couples to avoid partial cooking of the product during decontamination.

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