# DYNAMIC MODELLING AND SIMULATION OF THE BISCUIT BAKING OVEN PROCESS

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## ABSTRACT

A heat and mass transfer model is built to describe a natural gas indirect fired baking tunnel-oven. The model includes heat transfer from gas combustion to the biscuits. In the baking chamber, conduction (for the band conveyor), convection and radiation fluxes are considered. Mass transfer coupled with heat transfer is described. The velocity of the air inside the oven, as well as the drying of the biscuit are modelled. Physical parameters are taken into account by correlations or identificated laws. Dynamic simulations are performed.

## INTRODUCTION

Biscuit baking in tunnel-ovens is not yet very well known and controlled. In practice, manufactures decide by experience which one of the countless possible combinations of air temperature, air hygrometry and air velocity will provide the required biscuits. Previous studies on heat and mass transfer during baking of pastries and biscuits (Audidier, 1967) and on the coupled influence of the temperature and humidity of the baking atmosphere on product characteristics (Brunet et al., 1987) suggest a lack of knowledge of cooking mechanisms in band-ovens.

Few publications can be found on modelling of industrial baking. Therefore the modelling of related processes such as keramics tunnel-furnaces, tunnel dryers etc ... have been studied. Kinetic models, as described by Paulus (1984), require a good knowledge of the kinetics of each phenomenon involved in the baking reaction (gelatinisation, drying, thickness evolution, coloration etc ...). But, as each interacts with the others, it is not realistic to look at such models. In the case of mass transport, none of the publications deal with the complexity of air circulation in baking ovens, due to the mechanisms of air input and removed at the ends of the oven, and of steam extraction by chimneys. This leads to a mixed scheme of air circulation : co-current at the beginning of the oven and counter-current at the end.

## DESCRIPTION OF THE OVEN

The 15 meter long pilot-scale oven is an indirectly fired multi-burner oven, heated with natural gas. It consists of 4 combustion chambers in the roof and base, equipped by 34 independently controlled ribbon burners. The baking chamber can be separated into 6 zones by paddles, and is equipped with a wire mesh band of 0.65 meters width. Each zone is independently controlled respectively for the roof and base temperatures. The baking atmosphere (steam, volatile products) can be drawn out the baking chamber through 5 exhausts, fitted with variable rate fans. Each fan can be independently varied.

The model is built up so as to fit easily any type of oven (direct or indirect heating). As a result, the chosen structure is modular, and in the case of an indirectly fired oven consists of 3 types of model units.

- the heating unit, describes the heat production in the combustion chamber and the exchanges with the outside. It is divided into modules of equal volume symmetrically positioned around the burners. The model is composed of two heating units, one for the upper combustion chamber and the other for the lower one.

- the internal wall unit, expresses the heat transfer between the heating unit and the baking chamber. Two units, one for the upper internal wall, and one for the lower one are developed.

- the unit of the baking chamber : because of the complexity of the internal geometry of a tunnel-oven, this block includes the band conveyor, the lateral walls and the atmosphere divided into two sections (one above the band, the other below), as well as the biscuits. This unit takes account for all mass and heat transfer between these elements.

## MODELLING HEAT AND MASS TRANSFER

**- Modelling the heating unit**

Heat transfer by convection, conduction and radiation between gases and walls are expressed by means of overall coefficients. Heat and mass balances are described globally in a module, using average temperature and gas composition.

**- Modelling the units of internal walls and baking chamber**

The model of this unit is composed of heat and mass balances at a given location in the oven, using the average temperature and composition, if necessary, of each element at that cross section of the oven. The thermophysical properties of all the elements of the baking chamber but the atmosphere and the water activity ($a_w$) of the biscuit, are assumed to remain constant during baking.

Among all the mass and heat fluxes considered in a balance, the model differentiates between fluxes parallel to the biscuits movement ($q_{par}$, $qm_{par}$) and perpendicular ones ($q_{per}$, $qm_{per}$). The figure 1 describes this fluxes (the nomenclature is on this figure). Therefore, the balance equations have the following structure :

(1) mass balance : $$\frac{dm}{dt} = - \mathrm{div}(qm_{par}) + qm_{per}$$

(2) heat balance : $$\frac{dH}{dt} = - \mathrm{div}(q_{par}) + q_{per}$$

**- Mass balances for the baking atmosphere**

The model takes into account mass transfer fluxes occuring by diffusion between the roof atmosphere and the base atmosphere (qmair), fluxes at the extraction points (qmstea), fluxes inside the oven by air circulation, and also moisture transfers from the biscuit to the atmosphere (qmvap). A specific equation is defined for the points at the air outlets, in order to take into account loss in energy and mass due to the air exhaust.

**-Heat balances for the baking atmosphere**

Heat transfer between the internal walls and the biscuits takes place either directly by radiation, or indirectly through the atmosphere, the conveyor and the lateral walls. In this case, mechanisms of radiation between the elements of the baking chamber are involved, as well as convection with the atmosphere and conduction between the band conveyor and the biscuit. The model is built up so as to describe individually each of these modes of transfer. The same principles have been used by Nebelung, as it has been described by Hällström et al. (1988); emission fluxes qei from each element i (walls, air, conveyor and biscuit) and absorption fluxes $q_{ai}$ in each element i are calculated separately. Convection fluxes between the baking chamber atmosphere and these elements qcvi are taken into account, and also heat fluxes linked to mass transfers ($q_{vap}$, $q_{air}$, $q_{stea}$).

## MODELLING OF THE BISCUIT DRYING

Biscuit baking includes drying of the biscuit and biochemical transformations of the dough as well as an expansion. Because of the complexity of these phenomena, drying is the only process described in the model. In this first approach to the modelling of biscuits, it is assumed that the biscuits have a uniform temperature and moisture content. Heat and mass balances are expressed as follows :

- Heat balance :

$$e_b.r_{dm}.Cp_{dm}.(\frac{\partial T_b(x,t)}{\partial t})+ v_t.e_b.r_{dm}.Cp_{dm}.(\frac{\partial T_b(x,t)}{\partial x}) = q_{cv3}(x,t) + q_{cv7}(x,t) + q_{a3}(x,t) + q_{a7}(x,t) - q_{e3}(x,t) - q_{e7}(x,t) + q_{tb}(x,t) - q_{vapv}(x,t) - q_{vaps}(x,t))$$

- Moisture balance :

$$e_b.r_{dm}.(\frac{\partial X_b(x,t)}{\partial t}) + v_t.e_b.r_{dm}.(\frac{\partial X_b(x,t)}{\partial x}) = - qm_{vapv}(x,t) - qm_{vaps}(x,t)$$

The mass transfer fluxes in the biscuit are described so as to take account for three different modes of transfer : condensation of steam on the surface of the biscuit at the inlet, convection drying and then boiling drying .

As long as the partial pressure of saturated vapour in the biscuit remains lower than partial pressure of the vapour in the baking air, condensation occurs on the surface of the biscuits. As soon as it exceeds the vapour partial pressure in air, the biscuit undergoes convection drying, until the vapour partial pressure in the biscuit equals the ambient pressure in the biscuit. Then boiling drying takes place. In the model, since we assume that the biscuit is homogeneous in temperature and moisture content, the ambient pressure in the biscuit is equal to the ambient pressure in the baking chamber.

Since the biscuit is assumed homogeneous in temperature and moisture content, the water activity applied in the model is an average within the biscuit. But during baking $a_w$ varies with the degree of baking (starch gelatinisation, coagulation of proteins, moisture content ...) and with the temperature in the biscuit. A model of Aw is developped and validated from laboratory experiments, (Savoye, 1989).

## PRINCIPLE OF THE MODEL

Three model units describe the modelling of the temperature and/or moisture content profiles of each element of the oven, calculated through heat and mass balances. However, to obtain a model closer to real phenomena, models for some variables and phenomena had to be added.

Thermophysical properties of each element in the oven (walls, band conveyor, biscuit, air) are required to build up the model. In a simplified approach of the biscuit, constant thermal properties during baking are assumed. Data are given from published review (Knudsen (1973), Rask (1989)). For gaseous mixtures (smokes and air), models of specific heat, density, heat conductivity and viscosity based on composition and temperature proposed by Mureau et al. (1981) are used.

The method of radiosities is used for the modelling of radiating fluxes. It requires a knowledge of view factors in the oven, obtained geometrically on charts given by Knudsen (1973), and of correlations between emissivity and absorptivity of the air and its temperature and humidity, given by Mureau et al. (1981). Metals and biscuits are supposed to behave as gray bodies, and their emissivity is taken equal to 0.9.

The air velocity in the oven is calculated from mass balances on dry air at each air inlet or outlet in the oven. A "mixing coefficient" gives an estimate of the proportion of air coming from the chamber under the band conveyor in the air drawn out by the chimneys.

The values of heat transfer coefficients through the walls are calculated from the thermal properties of metallic materials. Heat transfer coefficients by convection are modelled by means of correlations. Concerning mass transfer coefficients, no correlation that can be applied to the case of tunnel-ovens could be found in publications, except for mass transfer between biscuits and air. We apply a correlation resulting from the Colburn analogy . The figure 2 presents the organization of the model units.

## SIMULATIONS

Simulations results permit to explain fluxes influence on baking and drying. For example, with or without the air circulation inside the baking chamber, we establish that the radiative flux is different (60% of the total heat fluxes to 75%). Others results are concerning the influences of operating parameters on the products specificities (moisture content, dimensions and color). The results shows that the temperature is an important parameters, but we establish that the air circulation is a good variable to control the oven. This is a new result, because actually only the tempearture is used. The air velocity appear to be a good parameter, because the actuators are sensible. The figure 2 is an illustration of the simulations results. More advanced works were carried out in the future of this study. Optimization is able to be performed on this basis. The start-up procedure is studied, especially to build a start up procedure which is able to reduce the off-specifications biscuits.

## CONCLUSION

The transport model presented above has been developed for an indirect heated tunnel-oven. It takes into account every possible heat and mass transport mode occuring during the baking of biscuits, and can be fitted to every type of oven, for example by eliminating the internal wall unit in the case of an direct fired oven, or just changing the equation of heat production of the combustion chamber unit in the case of an electric indirect oven. All parameters were determined as precisely as possible from published data.

The model of the biscuit baking seems simplified with respect to reality ; a model of expansion and coloration will be established from the results of the impending experiments.

Results of dynamic simulations are easy to obtain. They give the capability to interprete with more understanding the phenomenas occuring during baking inside the ovens.

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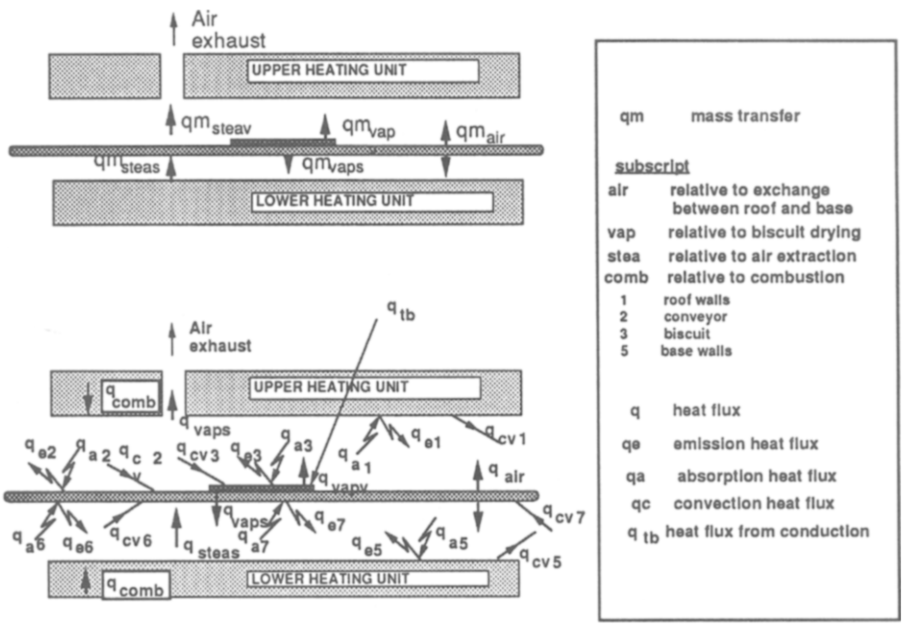


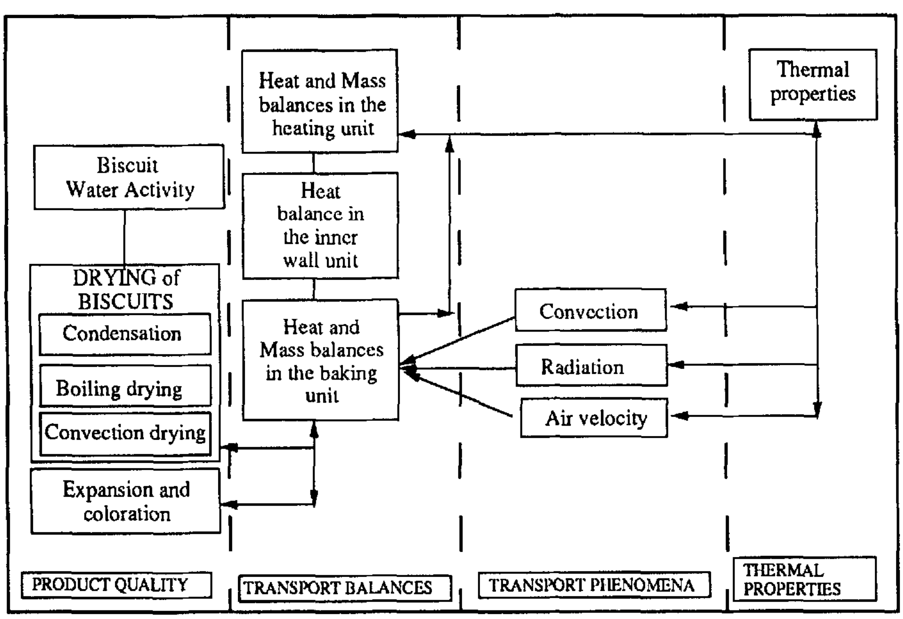
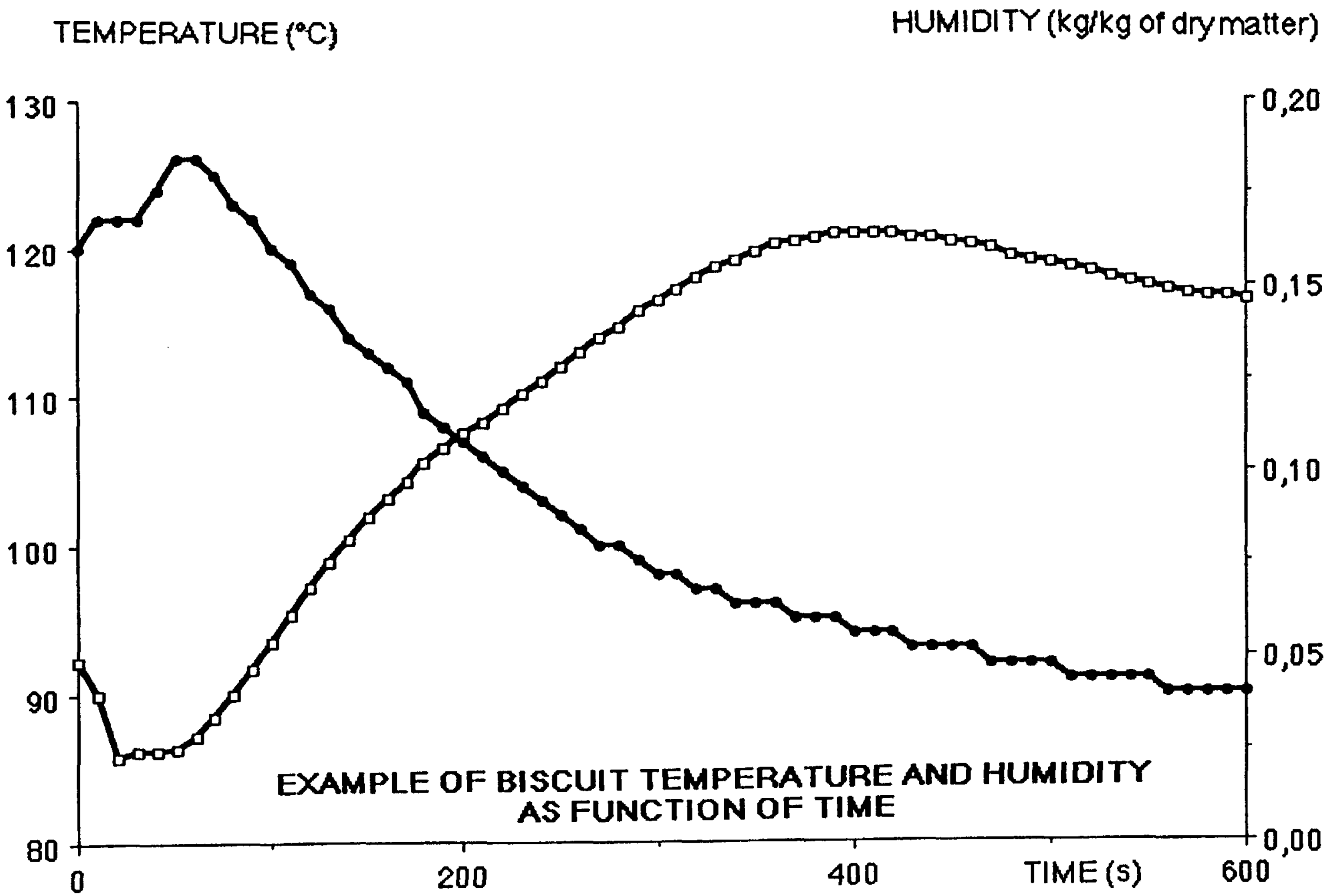




Figure 4: Modules du modèle et interactions




EXAMPLE OF BISCUIT TEMPERATURE AND HUMIDITY AS FUNCTION OF TIME