Journal of Food Engineering 147 (2015) 79–88

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Bread baking modeling: Coupling heat transfer and weight loss by the introduction of an explicit vaporization term

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ARTICLE INFO

Article history:
Received 16 July 2014
Received in revised form 15 September 2014
Accepted 21 September 2014
Available online 30 September 2014

Keywords:
Food processing
Food model
Bread baking
Water vaporization
Food mixture

ABSTRACT

A model for the description of bread baking that includes heat transfer, water transport and vaporization has been developed and applied to a test case. The bread physical properties are defined considering it as made of macro-components (water, carbohydrates, proteins, fats, fibers), based both on the initial formulation and on the dynamic evolution of the system (in terms of temperature and composition). Baking experiments have been conducted in a commercial oven for the model validation with temperature dynamics and weight loss data. Water vaporization is introduced in the conservation equations by an explicit term that directly couples heat and mass balances.

1. Introduction and scopes

Food modeling is deserving increasing attention both from the scientific community and from the industrial world. Bread making consists of several phases (Della Valle et al., 2014), but when dealing with bread models, the most investigated one is certainly the baking phase. In this context, various assumptions can be made and several phenomena can be taken into account at different detail degree. Among these, water vaporization has rarely been described explicitly. The few authors that considered explicit formulation rates, used water vapor concentration dependent rates (Ousegui et al., 2010) based on the hypothesis of non-equilibrium evaporation in porous hygroscopic solids (Halder et al., 2011). This formulation (Eq. (1)) has two main problems: first, it needs the definition of a material and process-dependent parameter, not easy to estimate. Second, in the original dissertation (Scarpa and Milano, 2002), it is specified that a linear relationship between the evaporative flux and the vapor density difference is valid only in the case of small departure from the hygrometric equilibrium:

$$I_v = K(\rho_{v,eq} - \rho_v)S\varepsilon \qquad (1)$$

In addition, even though considering the impact of the evaporation term into the energy balance (multiplying it by the latent heat of vaporization), the temperature "plateau" at 100 °C is rather described by using effective thermal properties (Ousegui et al., 2010). A different approach that seems to be more physical does not consider explicit formulation of evaporation rate (Zhang and Datta, 2006; Nicolas et al., 2014), choosing to describe water vapor and liquid water as a unique moisture variable. In that case, the evaporation term is avoided in the water mass balance, but not in the energy one: it is then substituted inserting the equation for liquid water or vapor, generating a dependence of the thermal balance from different partial derivatives.

Thus, it is a main aim of this paper to propose a different explicit vaporization term, fully coupling energy and mass balances. This formulation does not require to define a process-dependent parameter, better describing the physical problem of water vaporization inside bread during baking. Another aim of the current paper is that of using thermal properties depending on the macro-component mixture. This is another uncommon trend in bread baking modeling, especially considering properties varying with both temperature and composition. This can be useful for further studies on chemical kinetics applied on bread and, more generally, food cooking, as well as to take into account possible properties variation with food kind and chemical composition (e.g. viscoelastic properties).

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http://dx.doi.org/10.1016/j.jfoodeng.2014.09.031
0260-8774/

Nomenclature

A	pre-exponential factor for gas binary diffusivity
C_j	compound mass concentration per mixture unit volume, kg/m^3
C_p	heat capacity, kJ/kg/K
$C_{p,j}$	compound heat capacity, kJ/kg/K
D_w^i	water diffusivity, *i*th phase, m^2/s
D_{cv}	standard binary diffusivity between vapor and CO$_2$, m^2/s
h	convective heat transfer coefficient, W/m^2/K
H_{ev}	water latent heat of vaporization, J/kg
I_v	vaporization rate, kg/m^3/s
k_c	concentration numerical step function parameter, kg/m^3
K_m	mass transfer coefficient, m/s
K	non-equilibrium evaporation constant
k_t	temperature numerical step function parameter, K
m	mass, kg
m_j	mass of the *j*th component, kg
M_j	atomic mass of the *j*th component, kg
$\mathbf{n}$	normal direction
n_j^i	mass flux of *j*th component, *i*th phase, kg/m^2/s
Nu	Nusselt number
p	pressure, Pa
Q	heat flux, W
R	universal gas constant, 8.314 J/mol/K
S	pore saturation
t	time, s
T	temperature, K
v	oven average air velocity
V	volume, m^3
V_j	volume of the *j*th component, m^3
$\tilde{V}_j$	molecular volume of *j*th gas component, m^3
W	moisture content, kg/kg
x, y, z	coordinates

Greek symbols

δ	differential operator
ε	porosity
κ	step function
λ	thermal conductivity, W/m/K
ρ	intrinsic density, kg/m^3
τ	oven temperature trend parameter, s
φ	volumetric fraction
ω	mass fraction

Subscript

ash	ash
C	with concentration
carb	carbohydrate
CO$_2$	carbon dioxide
env	oven environment
fat	fat
fiber	fiber
j	*j*th compound
prot	protein
start	oven initial
sp	set point
T	with temperature
w	water

Superscript

0	initial
CHOI	from the paper of Choi and Okos (1986)
eff	effective
eq	equilibrium
f	final
l	liquid
i	*i*th phase
v	vapor

To satisfy these aims, some idealities have been assumed, going to the detriment of model accuracy for specific cases. Anyway, further details can be added by refining the models for the related phenomena (e.g. considering convection in the energy balance, using specific thermal properties, taking volume expansion into consideration, etc.).

2. Materials and methods

The validation of the bread baking model needed to perform baking experiments for getting temperature vs. time data and weight loss measurements. The baking test was repeated three times, with a couple of analog cases and a third case with different initial weight for a sensitivity analysis. Since the experimental data are consistent between the series of experiments, only one configuration is presented and discussed in details.

2.1. Bread samples

Samples were prepared using a standard recipe for bread: wheat flour (100%), water (58%), salt (2% g), dry yeast (2%). The flour composition is (g per 100 g): carbohydrates (70.8), proteins (12.0), fats (1.5), fibers (3), water (12.7). Dough was made by mixing the ingredients manually, then underwent double leavening process for a total time of about 1 h at ambient temperature. The individual sample of about 810 g (shaped as an Italian “Pagnotta bread” – approximate oblate ellipsoid, ca. 0.217 m diameter 0,05 m height, see also Papasidero et al., 2014) was formed and placed on a grid covered by a piece of oven paper to hold the dough avoiding any drip on the oven base and minimizing the fluid dynamics and heat distribution effects of the support.

2.2. Baking tests

The domestic oven (KitchenAid, USA) was pre-heated to the set point temperature of 200 °C. Then, the grid with the sample was positioned in the central zone of the oven to achieve homogeneous air distribution. The sample was baked under forced convection ($v = 2$ m/s) for about 40 min, terminating when a golden-brown crust format on the bread. The temperature was measured all along the test in the oven and inside the bread, while weight was measured before and after the baking process.

3. Experimental results

3.1. Temperature

The temperature trend for the bread center and for the oven is reported in Fig. 1. From this it can be seen the oven temperature increase till the set point temperature is reached. The oven controls this parameter with ±5.7 °C accuracy, oscillating.