Energy requirements during sponge cake baking: experimental and simulated approach.

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Abstract

Baking is a high energy demanding process, which requires special attention in order to know and improve its efficiency. In this work, energy consumption associated to sponge cake baking is investigated. A wide range of operative conditions (two ovens, three convection modes, three oven temperatures) were compared. Experimental oven energy consumption was estimated taking into account the heating resistances power and a usage factor. Product energy demand was estimated from both experimental and modeling approaches considering sensible and latent heat. Oven energy consumption results showed that high oven temperature and forced convection mode favours energy savings. Regarding product energy demand, forced convection produced faster and higher weight loss inducing a higher energy demand. Besides, this parameter was satisfactorily estimated by the baking model applied, with an average error between experimental and simulated values in a range of 8.0 to 10.1 %. Finally, the energy efficiency results indicated that it increased linearly with the effective oven temperature and that the greatest efficiency corresponded to the forced convection mode.

Keywords: Baking, Energy demand, Efficiency, Sponge cake.

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Nomenclature

Cp	Specific heat, J kg^{-1} ºC^{-1}
f	Usage factor, dimensionless
h_c	Effective heat transfer coefficient, W m^{-2} ºC^{-1}
k	Thermal conductivity, W m^{-1} ºC^{-1}
m	Product mass, kg
N_p	Power, W
OEC	Specific oven energy consumption, kJ kg^{-1}
PED	Specific product energy demand, kJ kg^{-1}
r	Radius, m
SEC	Specific energy cost, \$ kg^{-1}
t	Process time, s or min
T	Temperature, ºC
WL	Weight loss, %
x	Mass fraction

Subscripts

0	Initial
app	Apparent
ave	Average
b	Baking
eff	Effective
exp	Experimental
fan	Fan
heat	Heating
i	Component
lat	Latent
oven	Oven
sen	Sensible
sim	Simulated
water	Evaporated

Greeks symbols

ε	Average absolute relative error, %

ρ	Global density, kg m^{-3}
λ	Latent heat of vaporization of water at oven pressure, J kg^{-1}
η	Efficiency of the baking process, %

1. Introduction

During the last years energy costs have been rising significantly simultaneously with international legislation that forces manufacturers to reduce their carbon footprint in order to mitigate climate change fears. These factors are encouraging greater understanding of high-energy processes [1]. Particularly in the bakery industry, [2] discussed energy management systems, energy efficiency measures and the strategies to reduce energy consumption. Even though the study was based on USA bakery products its findings can be generalized to bakeries internationally. Authors identified four major processes (fermentation, baking, cooling and freezing, and cleaning) that consume the vast majority of purchased energy. In this sense, the implementation of energy efficiency measures for these systems can reduce energy costs and lessen the impacts of volatile energy prices. Also, as bakery involves massive consumption products, there was developed specific technology in order to improve the efficiency of the process. To achieve this goal there has been of significant importance the research and innovation focused on process efficiency with special concern on product quality [3].

Among all the stages involved in the bakery industry (ingredients selection, mixing, storage/dosing, baking, cooling, packing, storage, distribution and commercialization) the baking process itself is crucial. It is estimated that the energy demand during this stage is in the range of 3 - 5 MJ kg^{-1}.

The energy requirement of the baking process depends on two different aspects: the energy needed to achieve the complete product transformation and the actual oven energy consumption. The ratio between both values provides a direct and simple measure of the process energy efficiency [4]. Besides, the difference between the oven energy consumption and the product energy demand is the amount of energy absorbed by the oven trays and walls and the energy lost to the ambiance. Therefore, improving oven design and optimizing the process conditions (temperature, convective heat transfer and baking time) leads to energy savings; and for this purpose mathematical modeling of the baking process is a powerful tool.

Le Bail et al. [5] compared the energy consumption of two bread baking processes. Authors used a macroscopic approach that includes product and oven energy requirements to estimate an energy efficiency index which showed that part frozen baking had higher energy consumption than conventional baking. Alamir et al. [6] studied energy savings using jet impingement during French bread baking. Authors proposed a mechanistic heat and mass transfer model, which was able to estimate product energy demand and the potential energy savings. Paton et al. [7] analysed the energy requirements in a continuous industrial oven using a macroscopic balance and proposed a CFD scheme to study the influence of the operative conditions. In addition, Khatir et al. [1] combined the CFD model of the oven with a multi-objective optimization methodology to develop an oven design tool. Ploteau et al. [8] compared in terms of energy consumption, conventional bread baking with baking performed under short infrared emitters (IR). Authors ensure the same kinetics of crust development and quality criterion maintaining baking time and lowering oven temperature for IR baking. IR technology allowed reducing 20% of the total energy consumption.

It is noticeable that all the mentioned works focused on energy management during bread baking being difficult to find precedents on other kind of bakery product. In consequence the aim of this article is to estimate energy requirements during sponge cake baking. For this goal, oven energy consumption was calculated and both experimental and modeling approaches were performed to calculate the product energy demand. Additionally, the process efficiency was evaluated relating the oven energy consumption and the product energy demand.

2. Materials and Methods

2.1 Experimental baking tests

For this study two batch-type electric ovens were used (Figure 1): a domestic oven (Ariston FM87-FC, Italy), and a semi-industrial convective oven (Multiequip HCE-3/300, Argentine). The first one was used for natural convection (NC) baking tests (with the upper and lower resistances on) while the second one has the heating resistance and a fan installed on the back wall, which propelled the air at 2.8 m/s (fixed air velocity) allowing to operate under forced convection mode (FC). Also, this equipment enables to perform steam-assisted forced convection mode (SFC). A connection pipe allows water input into the chamber, which evaporates instantaneously; each test consumed approximately 600 ml of water to generate steam. For all the tests, the samples were placed over a tray, in the middle of the oven chambers.

The nominal oven temperature was set at 140, 160 and 180 °C for the three different baking modes (9 total baking conditions). The oven was preheated until it reached the pre-set temperature before every test. Table 1 shows the experimental characteristics and the labels used to reference each condition. The measurement of effective temperature (T_{eff}) is detailed in [9]. Additional experiments were performed to characterize both ovens in permanent mode at high temperature (nominal temperature equal to 185 ºC), without samples inside the oven. In these cases T_{eff} were higher than the one obtained with the baking sample, being 206 and 196 ºC for NC and FC modes.

Sponge cake batter was made mixing 270 g whole fresh eggs for 2 min at a 240 rpm in a multifunction food processor (Rowenta Universo 700, France), then adding 360 g dry premix, Satin Cake Premix (Puratos, Argentine) and mixing 2 min more. The batter composition resulted: 45.6 % carbohydrates, 9.4 % proteins, 9.0 % fat, and 36.0 % water. Finally 500 g of batter were dosed in an aluminium cake pan (18 cm diameter, 7 cm height), which gives an initial batter height of 2.5 cm.

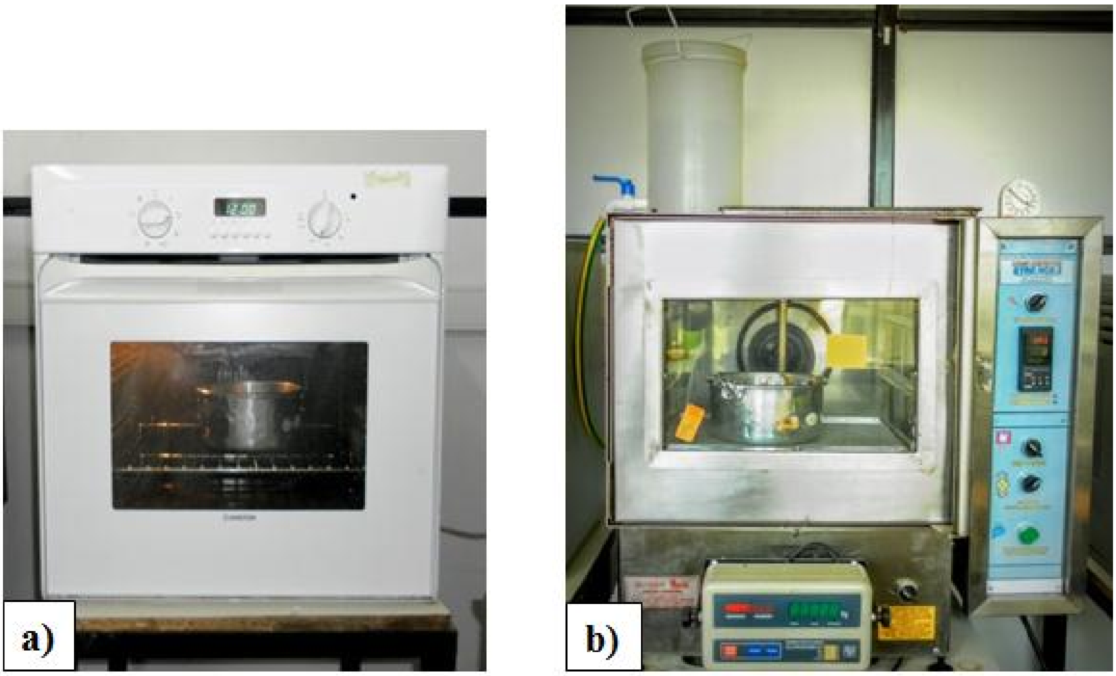

Figure 1. Ovens used for the baking experiences a) domestic oven and b) semi-industrial convective oven.

For sample and oven temperatures recording, T-type thermocouples (Omega, USA) connected to a data logger (Keithley DASTC, USA), were used. Cake temperature profile was obtained from three thermocouples fixed to the pan before filling it with the batter (without interfering with cake development). Their positions were carefully selected according to previous published results to ensure that the coldest region inside the product was monitored. Thus, two of them were positioned in the axial axis of the sample ($r = 0$) at 7.5 cm (*T1*) and at 5.5 cm (*T2*) from the pan bottom (being outside the sample at the beginning of the process and covered while expansion occurred). The third one (*T3*) was positioned near the pan wall ($r = 7.5$ cm), 2 cm from its bottom (inside the sample during the whole experiment). On the other hand, oven temperature (T_{oven}, ºC) was recorded by placing two thermocouples in the middle of the oven chamber, near the sample. Two replicates were performed for each baking condition.

Table 1. Experimental conditions of the baking tests.

	Set temperature (ºC)		
	140	160	180
		Natural convection	
	NC1	**NC2**	**NC3**
T_{eff} (ºC)	145.4 ± 4.5	161.4 ± 4.7	185.8 ± 4.1
t_b (min)	51.4 ± 0.3	42.6 ± 1.2	32.3 ± 1.6
		Forced convection	
	FC1	**FC2**	**FC3**
T_{eff} (ºC)	150.2 ± 6.9	175.6 ± 4.9	194.0 ± 5.5
t_b (min)	40.3 ± 0.6	32.1 ± 0.8	29.7 ± 1.0
		Steam assisted forced convection	
	SFC1	**SFC2**	**SFC3**
T_{eff} (ºC)	151.2 ± 6.3	166.2 ± 6.1	183.5 ± 6.7
t_b (min)	40.0 ± 0.5	31.8 ± 1.2	28.0 ± 0.4

The baking time, defined as the instant when the minimal internal temperature reaches 95 ºC [9], is also informed in Table 1. In spite of the wide range of baking times detailed in Table 1, the thorough analysis of the quality characteristics of the baked sponge cakes indicates that the colour kinetic parameters strongly depends on the baking condition. However, the final crust colour, measured by a browning index, was always in the range [100 - 110]. Additionally, no significant differences among baking conditions in crust thickness or crumb structure were found [10]. To account for the process yield, the sample weight was monitored during the whole process. Then, the weight loss ($WL(t)$) was calculated as a function of the initial cake weight (m_0) and the weight at time t ($m(t)$):

$$WL(t) = \frac{m_0 - m(t)}{m_0} 100 \qquad (1)$$

2.2 Oven energy consumption

The oven energy consumption depends on the electrical resistances heating power ($N_{p,heat}$), the fan power ($N_{p,fan}$, only in FC and SFC modes) and the effective heating time [11,12]. Both ovens used in this work have an ON/OFF control system, that is the heating resistances were turned on if the oven temperature was lower than the set value, when the set temperature was reached the heating resistances turned off and energy consumption stopped, and so on. Thus, the oven energy consumption was intermittent. Therefore, the specific oven energy consumption (OEC) was expressed according to Eq. (2):

$$OEC = \frac{1}{m_0}\left(N_{p,heat} f + N_{p,fan}\right) t_b \qquad (2)$$

$N_{p,heat}$ was measured with the oven empty working at the maximum temperature, using a clamp tester (SEW ST-300, Taiwan), values of 1.98 and 1.8 kW were obtained for Ariston and Multiequip ovens, respectively. The fan power was much lower than the heating one (0.05 kW), notwithstanding this contribution was considered in the estimation of OEC.

On the other hand, the usage factor f, which represents the effective heating time, depends on cooking temperature and on the product load. In the present work the product load was the same in all the experimental tests, thus the *f* value only depends on oven temperature and was calculated as the ratio between the total heating time and the baking time t_b. The total heating time was estimated from the oven temperature profile, adding all the periods with increasing oven temperature. The usage factor of the empty oven in permanent mode and high temperature was 0.46 and 0.47 for NC and FC ovens, respectively.

Once the oven energy consumption was calculated, the baking specific energy cost (*SEC*) was estimated on the basis of 160 working hours per month. Both variable and fixed costs were taken into account (reference price from the local energy distribution company [13]). The monthly fixed cost (medium commercial use) was 27.7 \$/month, and the variable one was 0.042 \$/kWh.

2.3 Experimental product energy demand

In the present study the experimental specific product energy demand (PED_{exp}) was defined considering sensible and latent heat contributions, assuming that water is the only component that evaporates during sponge cake baking, the latent heat can be expressed in function of the enthalpy of water vaporization (λ, 2257×10^3 J kg^{-1}) and the amount of evaporated water:

$$PED_{exp}(t) = \frac{m_0 Cp_{sen}(T_{ave}(t) - T_0) + \lambda(m_0 - m(t))}{m_0} \qquad (3)$$

In order to evaluate the sensible specific heat (Eq. (8) detailed later), Choi & Okos [14] approach was employed with an average temperature $T_{ave}(t)$, estimated from the experimental ones (*T1*, *T2* and *T3*).

As it can be seen the difference between Eq. (2) (*OEC*) and Eq. 3 (PED_{exp}) comprises the energy needed to heat the oven components (walls, tray, etc.) and mainly the heat loss through the oven walls to the ambient.

The efficiency of the process (η) is defined as the ratio of the energy demand of the product to the energy consumption of the equipment [5], with PED_{exp} calculated at the baking time t_b.

$$\eta = 100\frac{PED_{exp}}{OEC} \tag{4}$$

2.4 Simulated product energy demand

Usually, there can be found in the literature many mathematical models that describe the baking process in terms of energy conservation laws [15,16]; only a few of them have the intrinsic capacity to predict the product energy demand [1,7].

In the present study, a mathematical model previously developed for sponge cake baking [9] was used to estimate the product energy demand. This model comprises product expansion considering the simulation domain (Ω) as a continuous and homogeneous geometry that expands [9]. The energy balance in this domain is expressed as follows:

$$\rho Cp_{app}\frac{\partial T}{\partial t} = \nabla(k\nabla T), \forall\Omega \tag{5}$$

Water evaporation is considered through the thermal properties. Global density (Eq. (6)) was expressed according to Baik et al.[17]; the apparent specific heat (Eq. (7))

considered both sensible and latent heat contributions [18]; and the thermal conductivity (Eq. (10)) was evaluated with Rask [19] expression.

$$\rho = \begin{cases} 1013 - 6.13T & T < 100 \\ 400 & T \geq 100 \end{cases} \tag{6}$$

$$Cp_{app} = Cp_{sen} + Cp_{lat} \tag{7}$$

$$Cp_{sen} = \sum_i x_i Cp_i \tag{8}$$

$$Cp_{lat} = \frac{\lambda \, m_{water}}{\Delta T} \tag{9}$$

$$k = \begin{cases} 0.27 + 0.1810^{-2} T & T < 100 \\ 0.2 & T \geq 100 \end{cases} \tag{10}$$

In Eq. (8) the components are water, carbohydrates, proteins, fat and ashes, being $Cp_{water} = 4180$; $Cp_{CH} = 1547$; $Cp_{prot}=1711$; $Cp_{fat}=1928$; $Cp_{ash}= 908$. In Eq. (9) m_{water} represents the total mass of water evaporated during baking and ΔT is the temperature interval of this phase change (5 °C).

Particularly in the numerical simulation, the domain was defined as the half cross-sectional area of the cake using axisymmetric 2D geometry. Regarding the boundary conditions of the energy balance (Eq. (5)), axial symmetry was considered in ($r = 0$). Besides, convective heat transfer at the cake top, and mould bottom and wall was assumed, using an effective heat transfer coefficient (h_c) (Eq. (11)):

$$k\nabla T = h_c(T_{eff} - T) \tag{11}$$

The effective heat transfer coefficient was measured with a heat flux sensor (Omega HFS4, USA) considering an average value of h_c for the entire sample surface, being 15, 25 and 20 for NC, FC and SFC baking modes, respectively [9].

To take into account the product expansion, mesh deformation was applied assigning a prescribed displacement velocity to the top surface of the cake, being this parameter derived from experimental height evolution data analysis [9].

The prediction of the specific product energy demand (PED_{sim}) was coupled to the baking model. Thus, the simulated product energy demand at a given time can be expressed in terms of the local energy in the whole domain:

$$PED_{sim}(t) = \frac{1}{m_0}\int_0^t \left(\int_\Omega \rho Cp \frac{\partial T}{\partial t}\, d\Omega \right) dt \tag{12}$$

The baking model was solved with the finite element method using COMSOL Multiphysics 3.5 coupled with MATLAB 7.8.0 [9].

Finally, the model prediction accuracy was assessed by the average absolute relative error (ε) between the experimental and predicted specific product energy demand:

$$\varepsilon = \frac{100}{n}\sum_{i=1}^{n}\left(\frac{\left| PED_{exp} - PED_{sim} \right|}{PED_{exp}} \right)_i \tag{13}$$

3. Results and Discussion

3.1 Oven performance

In order to determine the energy consumption during the process it is essential to study and describe the oven performance. In this sense, oven temperature recordings during

27 minutes are shown in Figure 2a. Only three of the nine tested conditions are shown, one of each convection mode. In general their evolution was quite repetitive (different oven temperature, same convection mode). All conditions showed an oscillatory behaviour, typical of an ON/OFF control system as described in Section 2.2.

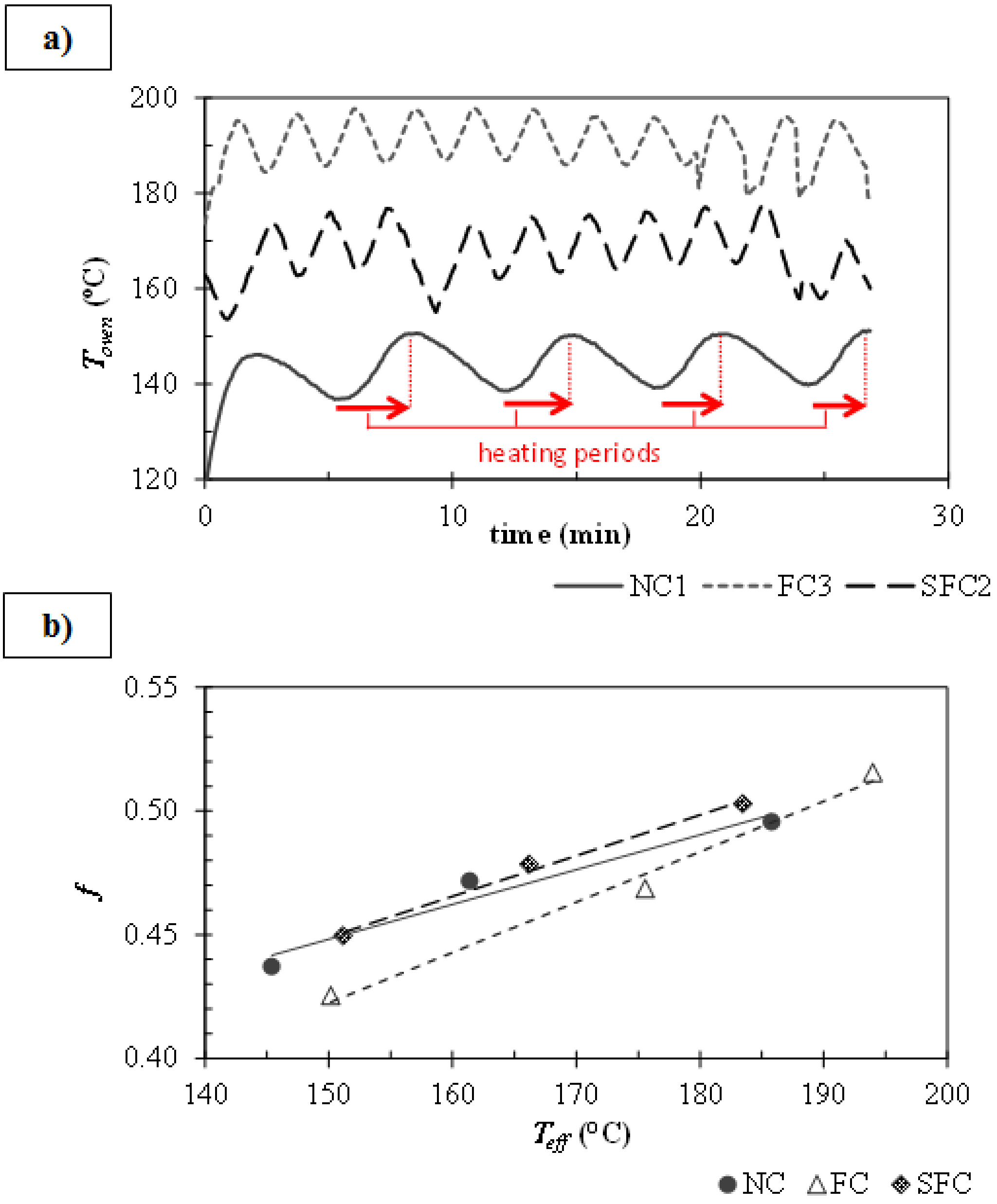

Figure 2. a) Experimental oven temperature (T_{oven}, °C) recordings of some baking conditions and b) usage factor (f) values vs. effective temperature (T_{eff}, °C) for each convection mode.

In the case of natural convection mode, there was observed a regular wave with smaller amplitude than the other two modes. Forced convection mode also presented a regular variation with a shorter period wave. On the contrary, vapour injection produced a non-regular oscillation making more difficult the temperature control. Therefore, each condition was characterized with an effective temperature as it was informed in Table 1. Also, in Figure 2a the intervals of time where the oven temperature increases are highlighted in order to obtain the total heating time to calculate the f factor. This way, with oven temperature profile and baking times informed in Table 1, f was calculated. Figure 2b shows these values as a function of T_{eff} for each baking mode. It is evident that f increases with oven temperature, while there is not a clear dependence with the convection mode. Thus, a higher operative temperature requires longer effective heating times during the baking test, no matter the convection mode.

Calculated *OEC* values are presented in Table 2, these results are in the same range reported by [5], in particular the authors informed an average value of 5.34 MJ/kg of bread considering fourteen electrical ovens. Also these values are comparable to the ones presented by [20] who measured the specific energy consumption in an industrial bakery, considering only the percentage of energy used in the baking process, the authors reported 1.27 kWh/kg processed flour for products baked in electrical oven, the average value of our results is 1.86 in the same basis. It was found that higher operative temperature favours energy savings and in addition, when comparing between convection modes, NC requires higher energy than the other modes. Even though f increases with oven temperature, smaller baking times are associated with higher oven temperatures which lead to lower energy consumption.

Table 2. Experimental variables calculated from Eqs. (1), (3), (4) and (5).

	NC1	**NC2**	**NC3**	**FC1**	**FC2**	**FC3**	**SFC1**	**SFC2**	**SFC3**
OEC (kJ kg^{-1})	5340.4	4772.2	3801.2	3947.1	3439.7	3481.5	4123.4	3481.0	3209.3
SEC ($ kg^{-1})	0.250	0.242	0.228	0.230	0.222	0.223	0.232	0.223	0.219
WL (%)	5.7 ±0.3	5.2 ± 1.0	4.9 ± 0.5	6.9 ± 1.0	7.2 ± 1.0	7.4 ± 1.0	6.6 ± 0.9	6.5 ± 0.6	6.4 ± 0.1
PED (kJ kg^{-1})	347.0 ± 1.7	364.2 ± 3.0	331.0 ± 9.4	399.0 ± 4.1	428.8 ± 4.0	453.9 ± 0.6	362.2 ± 0.6	356.8 ± 3.5	370.4 ± 1.0
η (%)	6.5	7.7	8.7	10.1	12.5	13.0	8.8	10.2	11.5

To complete the analysis, Figure 3 presents *OEC* vs. T_{eff} for each baking condition. This confirms the behaviour mentioned above and also shows that FC and SFC modes follow the same trend with the exception of the lowest oven temperature. In fact, steam addition is reflected in a decrease of the effective temperature.

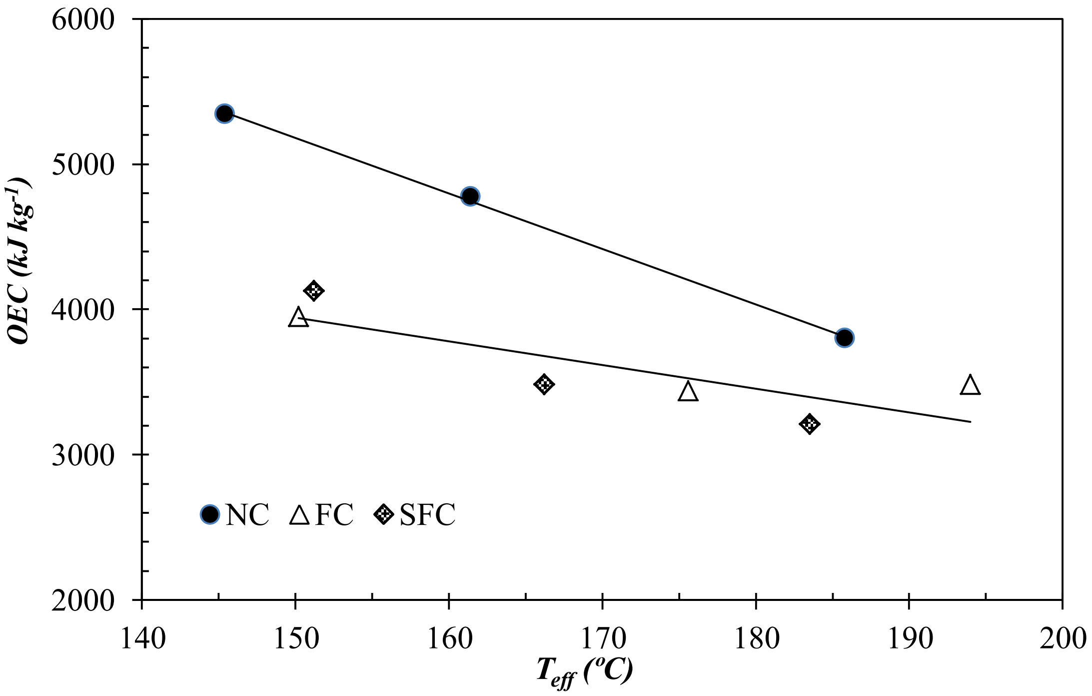

Figure 3. Specific oven energy consumption (*OEC*, kJ kg^{-1}) measured at the end of baking for each baking condition.

Also the specific energy cost is reported in Table 2. As it was expected, *SEC* presents the same trend that *OEC,* with a difference of 14 % between the maximum and minimum energy consumption conditions (NC1 and SFC3 respectively).

3.2 Product energy demand

As stated before, the amount of water that evaporates during the process strongly affects the energy demand. In this sense, sponge cake weight loss was monitored during the baking tests and the results are shown in Figure 4. First of all, the rate of *WL* evolution significantly increases when baking at the highest oven temperature for the three convection modes. Nevertheless, there were not significant differences between *WL* values at the end of baking in the same convection mode (Table 2), because of the combined effect of the *WL* rate and the baking time. Secondly, when comparing between convection modes it is noticeable that forced convection (Figures 4b and 4c) induces a faster and higher weight loss compared with natural convection mode (Fig. 4a) and that steam injection reduces this effect. Moreover, to reinforce this idea, *WL* values at the end of the process were 5.3 ± 0.4, 7.2 ± 0.3 and 6.5 ± 0.8, for NC, FC and SFC modes, respectively. This is consistent with the results informed by other authors [8,15].

PED_{exp} was calculated at each step time that *WL* was registered during the process. This evolution is presented in Figure 5. There was observed that for all the baking conditions this parameter increased with time and also that as baking evolves, the rate of change slows down. What is more, higher oven temperature induces higher energy demand.

Table 2 details the PED_{exp} calculated at the end of the process for each baking condition. There was observed that PED_{exp} is closely related to *WL* behaviour.

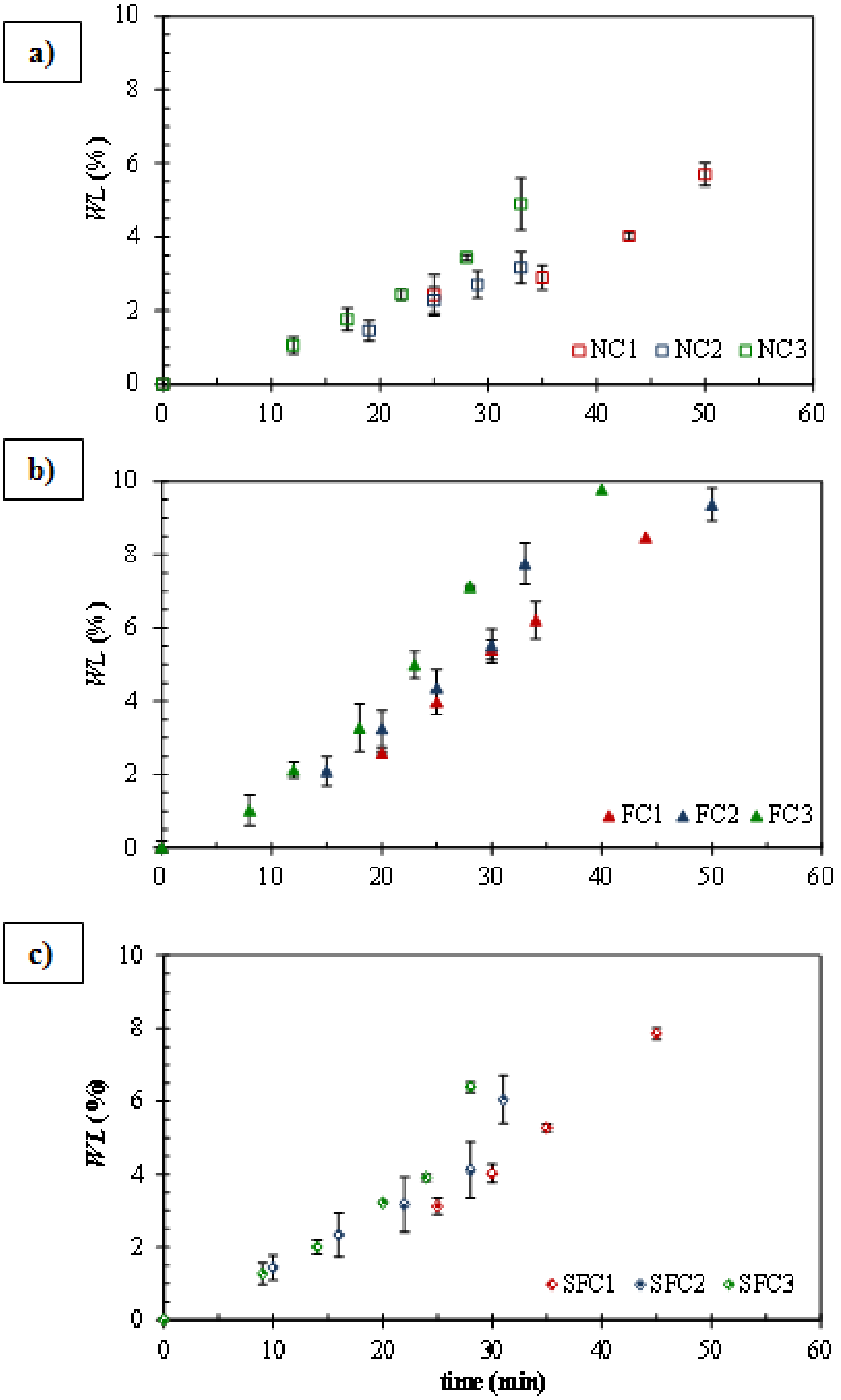

Figure 4. Weight loss (*WL*, %) evolution during baking of sponge cake: a) natural convection, b) forced convection and c) steam assisted forced convection mode.

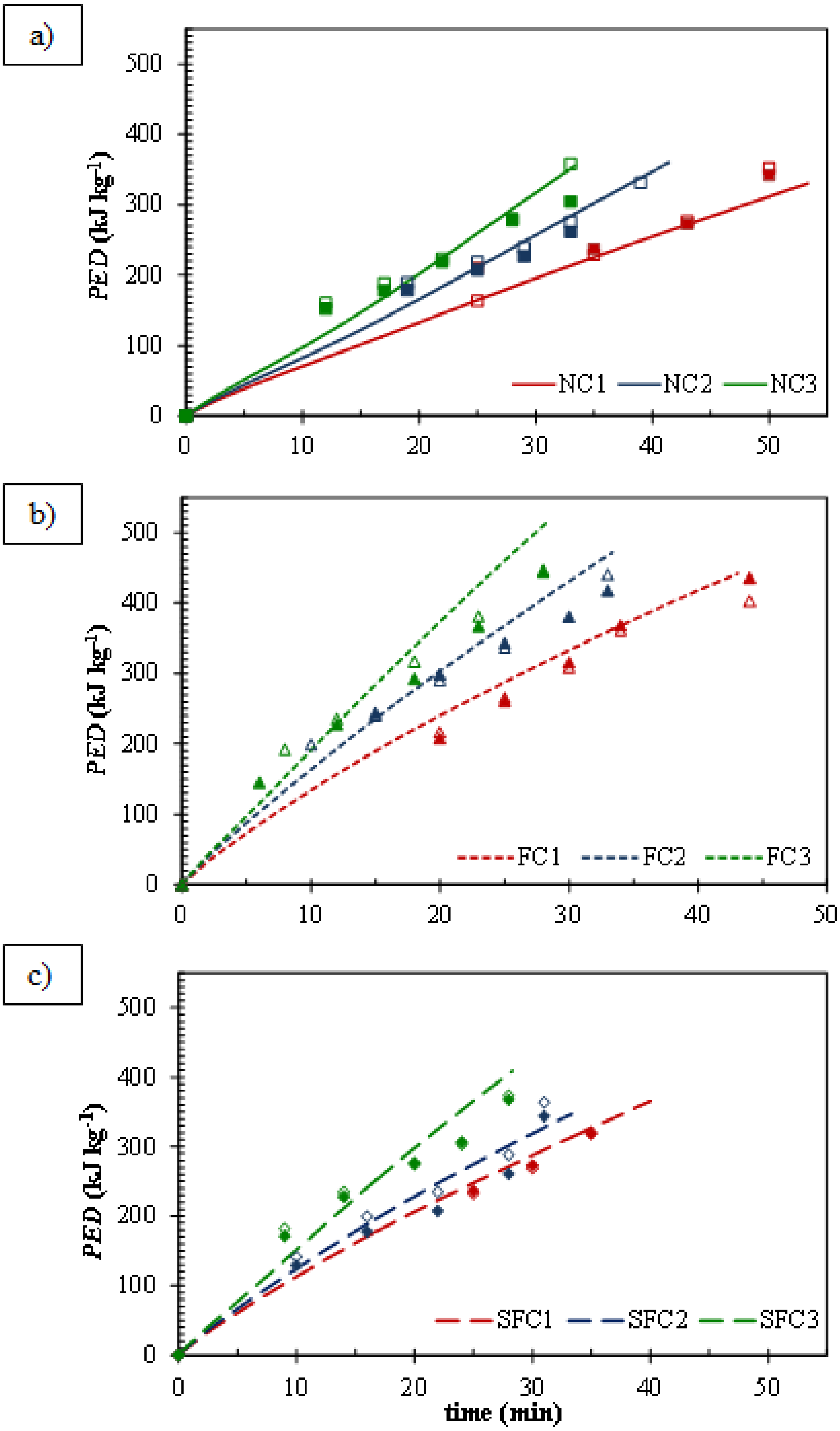

Figure 5. Specific product energy demand (*PED*, kJ kg^{-1}) during baking: experimental measured values (empty and full symbols) and simulated values (full lines).

Other researchers focused in this issue using a similar method to calculate energy demand particularly for bread baking. In this sense, Paton et al. [7] informed similar values considering the energy demand for heating the dough, the energy to evaporate around 10% of the initial moisture content and the energy required for starch gelatinization. Also, Ploteau et al. [8] estimated a similar energy demand taking into account the main transformation that occurs during baking (dough into crumb and crust) and water evaporation. Notice that, as was expected, the energy demand for bread baking is higher than the one required for sponge cake, due to the higher level of dehydration that this product suffers.

Besides, as stated in Section 2.4, PED_{sim} was coupled to the mathematical baking model. In addition to PED_{exp}, Figure 5 shows PED_{sim} values. In fact, the average error (Eq. (13)) was 8.0, 10.1 and 8.0 % for NC, FC and SFC, respectively. The highest relative error values were associated to the baking conditions with the highest effective temperature (NC3, FC2, FC3 and SFC3). From these results it is noticeable that the model successfully reproduces the experimental behaviour discussed above, demonstrating the ability of this mathematical model to incorporate product energy demand.

3.3 Efficiency of the process

Once the OEC and PED_{exp} were obtained, the energy efficiency of the process was calculated as the ratio between these two variables (Eq. (4)). The results are presented in Figure 6 as a function of T_{eff} for each baking condition. In all cases η increases linearly with T_{eff}, being more evident the effect of oven temperature in FC and SFC modes, even though this last one presented lower efficiency due to the energy to produce steam inside the oven chamber. Also from the values detailed in Table 2, the greatest efficiency corresponded to FC mode and the lowest to NC mode. This effect is mainly explained by the higher heat and mass transfer rates associated to the forced convection mode which reduces the baking time, in concordance with previous published results [5,6]. In addition, Paton et al. and Khatir et al. [7,21] who studied the optimization of bread baking process, suggested that one way to achieve energy savings is to reduce the baking time by improving the oven design.

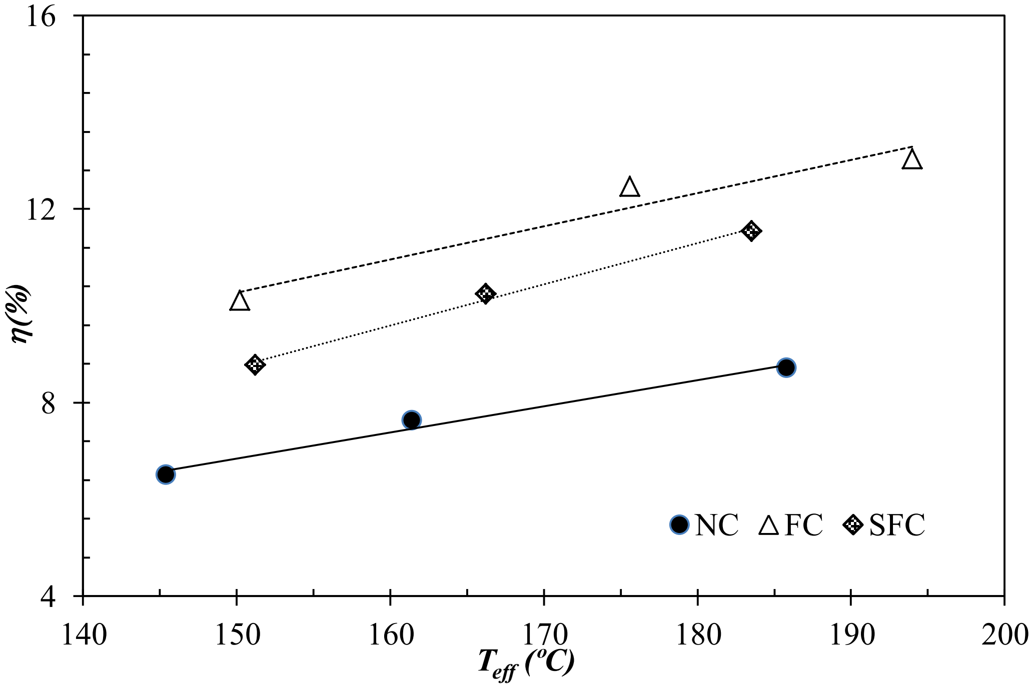

Figure 6. Process efficiency (η, %) vs. effective temperature (T_{eff}, ºC) for each convection mode.

4. Conclusions

In this work energy requirements during sponge cake baking were studied. The analysis of the oven energy consumption indicated that higher oven temperatures and forced convection favours energy savings, due to the decrease of the baking times. On the contrary, high oven temperature induces an increase of the product energy demand. This parameter is closely related to the weight loss, in consequence both present similar trends. Additionally, the baking model successfully represented the product energy demand evolution; in fact, the average error calculated between experimental and simulated values was less than 10 %.

To take into account the economic aspects, the specific energy cost was estimated, founding a difference of 14 % between the minimal and maximum values.

Finally, a measure of the process efficiency was obtained, it increased linearly with the effective temperature, and the greatest values corresponded to FC mode and the lowest to NC mode, indicating again the influence of the reduction of the baking time.

In conclusion, on the basis of the results presented in this work, the better baking condition was the fast one, FC3. Notwithstanding, complementary studies of the quality characteristics of the baked sponge cakes (results not shown in this work), shown that forced convection baking with high oven temperature was the condition with the lowest appreciation by the potential consumers, indicating that the selection of an optimal baking condition implies the joint analysis of diverse aspects.

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