Modeling of Microwave Drying of Fruits

Javier R. Arballo[ab]; Laura A. Campañone[ab]; Rodolfo H. Mascheroni[ab]

[a] CIDCA (Centro de Investigación y Desarrollo en Criotecnología de Alimentos), CCT La Plata—CONICET and UNLP, La Plata, Argentina [b] MODIAL-Facultad Ingeniería, Universidad Nacional de La Plata, La Plata, Argentina

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[1]CIDCA (Centro de Investigación y Desarrollo en Criotecnología de Alimentos),
CCT La Plata—CONICET and UNLP, La Plata, Argentina
[2]MODIAL-Facultad Ingeniería, Universidad Nacional de La Plata, La Plata, Argentina

Heat and mass transfer in foods during microwave drying was studied experimentally and theoretically through mathematical modeling. The food was considered as a system with physical properties that can vary with composition, structure, and temperature. Inner heat generation due to transformation of the electromagnetic energy was accounted for by using the approximation of Lambert's law. Two successive stages were considered: material heating that was followed by liquid evaporation. The coupled system of partial differential equations was coded in Matlab 6.5 (Mathworks, Natick, MA) and used to simulate the experimental runs of pear slices drying in a household microwave oven. Predicted temperature histories at the surface and center of the slab as well as mass loss during drying were in good agreement with experimental results.

Keywords Fruits; Lambert's law; Microwave drying; Modeling; Simulation

INTRODUCTION

Dehydration offers a means of preserving foods in stable and safe conditions because it reduces water activity and extends shelf life much more than that of fresh fruits and vegetables.[1] Microwaves (MW) have the ability to penetrate the material and heat it volumetrically, due to the interaction of the electric field with water molecules. Advantages of MW application include less environmental impact due to the use of clean energy, lower power consumption with respect to traditional drying methods, as well as the savings in space and process times. In the food industry MW applications include thawing, baking, cooking, dehydration, blanching, pasteurization, etc.[2]

Microwave drying (MWD) is applied as a unique dehydrating procedure or as a second stage of drying when combined with other conventional drying methods such as convective (hot air) drying or osmotic dehydration. When convective drying is the first stage, the product surface evolves to form a dried layer (crust), which is a limiting factor for further evaporation of water from the interior of the food, so an increase in surface temperature (using hot

Correspondence: Rodolfo H. Mascheroni, CIDCA, CCT La Plata—CONICET and UNLP, Calle 47 y 116, La Plata 1900, Argentina; E-mail: rhmasche@ing.unlp.edu.ar

air) only means greater damage to the food structure. Besides, water elimination generates shrinkage, the internal water diffusivity decreases, drying rates slow down, and consequently thermal degradation is amplified.[3] In these cases food quality may benefit from the use of MWD. Electromagnetic energy is mainly absorbed by liquid water due to its high loss factor compared with that of a dry product. Hence, the heating occurs instantaneously in the wet regions of the product once the microwaves are applied.

When using MWD as a final drying stage, the removal of inner water is enhanced because foods heat more uniformly, increasing water vapor pressure in the entire volume of the piece, which forces vapor toward the surface.

In order to characterize temperature and moisture distribution during microwave drying of foods, the coupled mass and energy balances must be solved taking into account the absorption of electromagnetic energy. At the microscopic level, models with a profound theoretical basis are considered, whereas at the other extreme, empirical approaches are commonly used at the macroscopic level. Various empirical methods have been developed to model moisture loss during drying. For example, a multiple linear regression technique was employed to relate the drying rate constant to design characteristics of the dryer and operational parameters as temperature, air velocity, MW power, and sample dimensions.[4]

Theoretical models for temperature and moisture distribution during microwave drying of materials, including foods, have been extensively studied. Water migration during MWD is a complex phenomenon that involves different means such as diffusion of liquid water and vapor, capillary flow, and hydrodynamic flow. There are numerous works devoted to mass transfer mechanisms.[5,6] The lower the scale of description, the greater the complexity, because a more detailed description of the phenomena is involved. At this level, the models usually associate energy, mass, and momentum transport equations with all thermodynamic interactive fluxes. This approach was used by several researchers.[6–9] These equations give rise to extremely complex systems, with parameter values subjected to uncertainties that can be transferred to the calculated values of

temperature and humidity. On the other hand, simple models are easy to handle with a limited number of parameters but with sufficient accuracy in temperature and moisture predictions. Several authors follow this method to model mass transport during drying. Some of them solved second Fick's law analytically[10] or numerically.[11–13] This simple approach is able to predict weight loss with high accuracy.

The pattern of electric and magnetic fields within an MW oven is complex, especially with the presence of the load which properties vary during processing such as drying. Maxwell equations describe the field distribution in the interior of MW ovens, either empty or with the charge.[14,15] Until now, two methods have been used to predict electromagnetic energy distribution within the food: solving Maxwell's equations[13,16] or using an approximate description such as Lambert's law, which considers an exponential decay of energy within the food.[5,7,11,12,17–20] When correctly considered, Lambert's law allows describing—with adequate precision—the radiation–product interaction.[21] With the aim of simplicity, this second approach was chosen in this work to model MWD to be able to predict water loss and temperature profiles for different heating conditions and to relate them to the final product characteristics (quality).

According to the aforementioned considerations the objectives of this work were

- To solve the coupled microscopic mass and energy balances during MWD, considering temperature- and moisture content–dependent properties.
- To validate model predictions against experimental temperature and water content data of microwave-dried MWD pears taken as the representative material.

MATERIALS AND METHODS
Mathematical Model

From a physical point of view, food can be considered as a combination of a solid matrix, an aqueous phase, and a gaseous phase (air and water vapor). A scheme of the model (1-D slab) is shown in Fig. 1.

A complete mathematical model has to permit solving the heat and mass transfer (weight loss) simultaneously. The following assumptions were made when developing the mathematical model:

1. Initial uniform temperature and water content within the product
2. Temperature- and moisture content–dependent dielectric properties; the second was considered taking into account the degree of dehydration
3. Constant size (volume changes are not considered)
4. Convective boundary conditions
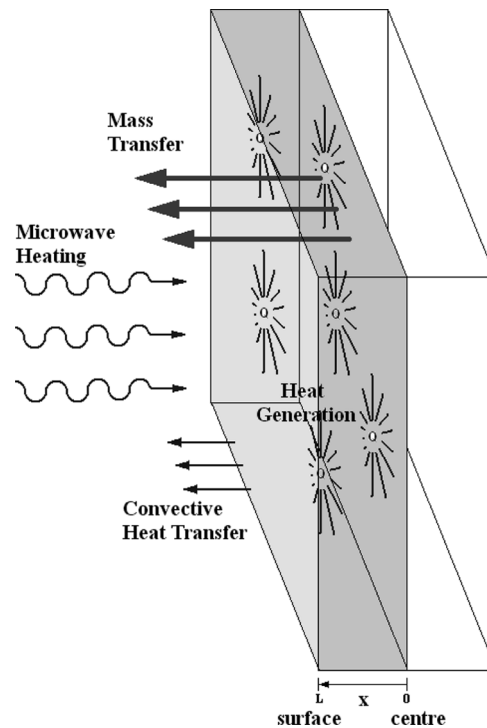5. Regular one-dimensional geometry (infinite plate)

FIG. 1. Scheme of the product slab and the energy and mass fluxes taken into account by the mathematical model.

6. Uniform electric field distribution around the sample and a dominant polarization of the electric field normal to the surface.

The dehydration process begins with the food at temperatures lower than that of water vaporization; the model must also consider the weight loss during the initial heating step. Then, the analysis is divided into two steps: Step 1 (heating with weak vaporization) and Step 2 (intensive vaporization). The same procedure was applied by other authors.[12]

Step 1 involves the heating of the food up to the moment when whole product reaches the equilibrium temperature T_{eq}. To describe heat transfer, an energy balance must be developed that considers a term of internal heat generation due to the energy supplied by MW.[22] The resulting microscopic energy balance is

$$\rho C_p \frac{\partial T}{\partial t} = \nabla(k\nabla T) + Q \qquad (1)$$

where Q accounts for the volumetric heat generation (W/m^3).

In terms of power, Eq. (1) can be rewritten as:[23]

$$V\rho C_p \frac{\partial T}{\partial t} = V(\nabla k\nabla T) + P \qquad (2)$$

where V is product volume (m^3) and P is the power generated by the absorption of MW (W).

In this balance, physical properties are taken as for the fresh food. To complete the model, the following initial and boundary conditions are considered:

$$t = 0 \quad T = T_{ini} \quad 0 \leq x \leq L \qquad (3)$$

$$x = 0 \quad -k\frac{\partial T}{\partial x} = 0 \quad t > 0 \qquad (4)$$

$$x = L \quad -k\frac{\partial T}{\partial x} = h(T - T_a) + L_{vap}k_m(C_w - C_{eq}) \qquad (5)$$

Equation (5) includes vaporization at the food surface. This assumption is valid only for the heating step because the exposure time is short and the product temperature over this period is below T_{eq}. In this step, it could be assumed that weak evaporation occurs and Eq. (5) can be applied. Other authors also used this boundary condition in microwave heating processes when modeling the initial heating step.[17,24,25] A value of 5 (W/[m^2 °C]) was employed for natural convection around the product slab.[26] The model considers the analogy between heat and mass transfer to evaluate k_m. The Chilton and Colburn's J factors for heat and mass transfer $J_H = J_D$ allowed estimating k_m from h values.[26]

The power absorbed during MW irradiation and converted into heat (P) is a function of the temperature in each point of the material. Because in this work Lambert's law is deemed valid,[23] the absorbed power is calculated as:

$$P = P_o e^{-2\alpha(L-x)} \qquad (6)$$

$$\alpha = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon'[(1 + \tan^2 \delta)^{1/2} - 1]}{2}} \qquad (7)$$

$$\delta = \tan^{-1}(\varepsilon''/\varepsilon') \qquad (8)$$

where P_o is the incident power at the surface (W), λ is the wavelength of radiation (m), and α is the attenuation factor, which is a function of the dielectric constant ε' and the loss factor ε''.

To predict the moisture content profile during heating, a microscopic balance of mass is needed that considers a diffusive transfer of water in the inner part of the food. The relevant equation is

$$\frac{\partial C_w}{\partial t} = \nabla(D_w \nabla C_w) \qquad (9)$$

The following initial and boundary conditions are considered:

$$t = 0 \quad C_w = C_{w,ini} \quad 0 \leq x \leq L \qquad (10)$$

$$x = 0 \quad \frac{\partial C_w}{\partial x} = 0 \quad t > 0 \qquad (11)$$

$$x = L \quad -D_w\frac{\partial C_w}{\partial x} = k_m(C_w - C_{eq}) \quad t > 0 \qquad (12)$$

Step 2 is the point when the whole product reaches T_{eq} and intensive evaporation begins. This step finishes at the end of the constant temperature period, unless there is a requirement to heat the material after it is dried.

Energy transfer: In the energy transfer step, the temperature is supposed to be at the equilibrium value inside the food T_{eq} (T_{eq} is the temperature achieved when the power absorbed is equilibrated with the energy spent in vaporization):

$$0 \leq x \leq L \quad T = T_{eq} \qquad (13)$$

Lambert's law was applied to evaluate the distribution of electromagnetic energy inside the food. The following equation was applied:

$$P = P_o e^{-2\alpha_d(L-x)} \qquad (14)$$

where α_d is the attenuation factor calculated from dielectric properties of the dehydrated material.

The model takes into account the continuous or intermittent application of MW power considering null the incident microwave power when the magnetron is turned off in the cycling operation mode.

Mass transfer: Water vaporization takes place volumetrically within the product. The generation of water vapor is calculated considering that all the power generated by MW is used for removal of water:

$$m_v L_{vap} = \int_0^V Q \, dV \qquad (15)$$

where m_v is the rate of water vaporization (kg/s).

The mass and energy balances in Step 1 are coupled. These balances, together with their boundary conditions, form a system of nonlinear partial differential equations. Due to these characteristics, an implicit method of finite differences (Crank-Nicolson method) was used. In Step 2, moisture content was calculated at each time step using Eq. (15). A complete description of the numerical method of solution is given in Campañone et al.[27] A scheme of the algorithm is shown in Fig. 2. The numerical method was coded in Matlab 6.5 (Mathworks, Natick, MA).
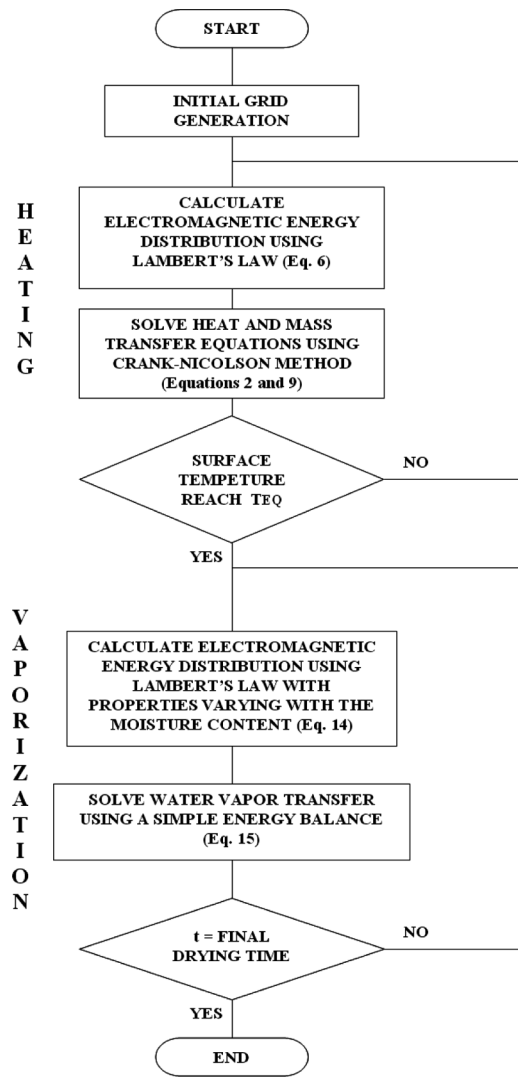
FIG. 2.   Block diagram of the solution algorithm.

MW power density was in the order of 9.11 W/g, considering that one sample was run in each individual experiment.

The material temperature was measured during MW dehydration with accuracy $\pm 1°C$ using fiber optic sensors (Model FOT-L-SD, Fiso Technologies Inc., Quebec, Canada) embedded in the geometrical center of the sample and 0.75 mm below its upper surface. The sensors were connected to a data acquisition device (Model FTI-10 single-channel signal conditioner, Fiso Technologies Inc.) linked to a PC. Software (FISO Commander, Standard Edition v 2.2.2.1, FISO Technologies, Quebec, Canada) was used to read and record values with any sampling interval (1 s was chosen for these tests).

The incident MW power (P_o) was determined with a calorimetric method.[28] Distilled water was placed into Pyrex containers that have the same dimensions and were located in the same position in the MW oven as those of the test samples during the drying experiments. The MW power calibration was performed with water volumes covering the range from 25 to 125 mL. Absorbed power was calculated through the following expression based on the increase in water temperature:

$$P_o = m_w C_{pw} \frac{\Delta T}{\Delta t} \tag{16}$$

where m_w is the mass of liquid water (kg), Cp_w is the specific heat of water, ΔT is the increment of temperature, and Δt is the heating time.

A polynomial model was proposed to relate power P_o (W) with water content of the sample; Systat 10 Statistical software (SYSTAT, Inc., Evanston, IL) was used to estimate model parameters and to calculate their deviation.

The following relations were obtained:

$$\begin{aligned} P_o &= 102.8 + 6.31\,V & V &< 100\,\text{mL} \\ P_o &= 700 & V &\geq 100\,\text{mL} \end{aligned} \tag{17}$$

The values of P_o obtained with Eq. (17) were then used as input data in the solution of the mathematical model.

To avoid thermal degradation (scorching), the samples were irradiated with a cycled power of 50% (10 s on and 10 s off with the oven switch set at 1,000 W). In addition to lowering the incident MW power, this mode of operation made it possible to control the overpressure generated inside the foods and to prevent puffing and changes of volume. To establish drying kinetics, five independent runs with 1, 2, 3, 4, and 5 min of MW drying were performed under the same conditions. Moisture content of the samples was determined for the raw sample before drying and for the dry sample after each run by dehydration in a vacuum oven at 70°C and 65 kPa until constant mass was attained.[29]

Dehydration Experiments

With the aim of validating the numerical model, dehydration experiments on pears were run in a 2,450 MHz domestic MW oven with nominal power of 1,000 W. The drying tests were conducted in a batch mode. Pears (cv. Packham's Triumph) were bought at a local market and stored in a cold room at 4°C for one day. Before a drying trial, the pears were taken out and kept at room temperature for thermal equilibration.

The peeled pears were cut into slabs 1.5 cm thick ($1.5 \times 5.5 \times 5.5$ cm); the slabs were cut from the external region of the fruits to get the homogeneous material without its soft core and seeds. A sample was placed in the MW oven in a single layer on a plastic mesh support, which is transparent to MW radiation and allows energy and mass transfer through both faces of the samples. The average mass of slices was 38.53 g (1.96 s.d.), and the absorbed

RESULTS

Validation and Predictions of the Numerical Model

The mathematical model was validated against experimental data of temperature and water content. In all simulation runs of the mathematical model a time increment of 0.1 s was used and the simulation domain was divided into 15 space increments. Physical properties of pears used in the mathematical modeling are summarized in Table 1.

Figure 3 shows the predicted and experimental thermal histories of the surface and center of a pear slab during the representative test on MWD. The existence of two different stages assumed in the mathematical model can be observed: the heating stage until T_{eq} is reached and then the constant temperature period. A third period of over-heating of a dried sample was not observed, because the experiments were stopped before its occurrence. This third stage occurs when the energy needed for vaporization is less than the thermal energy converted from MW; local temperature then may rise above the boiling temperature of water. This continuous increase of temperature results in undesirable overheating and charring of dried food and must be avoided.[1] From Fig. 3 it is clear that Lambert's law predicts that during the first stage the center is the coldest point, whereas the surface is the hottest point, in accordance with the exponential decay of power absorption from the surface toward the interior of the food. With respect to numerical predictions good agreement is achieved, and deviations could be mainly attributed to inaccuracies in the sensor position inside the food (near the center).

Figure 4 presents the experimental and predicted moisture content values as a function of the process time. Two drying periods can be distinguished: (1) a heating period in
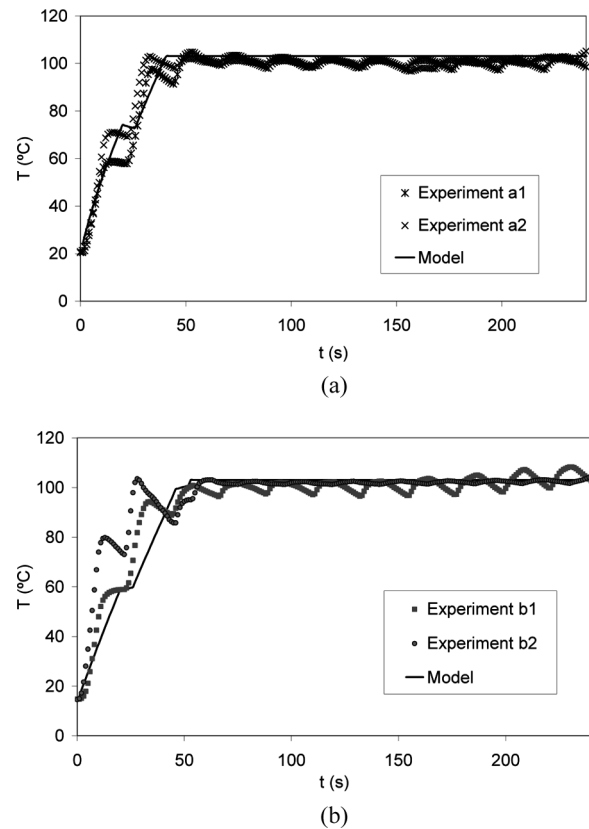

FIG. 3. Predicted (lines) and experimental (symbols) temperatures as a function of time: (a) surface; and (b) center.

which MW energy is converted into thermal energy within the wet materials and the temperature of the product increases with essentially no water evaporation; and (2)

TABLE 1
Thermal, transport and electromagnetic properties of pears

Property	Value for pear
Density ρ (kg/m³)	1,000[a]
Thermal conductivity k (W/[m °C])	0.595[b]
Specific heat C_p (J/[kg °C])	3,600[b]
Dielectric constant ε' (dimensionless)	$71.06 - 0.052\,T - 8.3\,10^{-4}\,T^2$ (fresh)[c]
Dielectric loss factor ε'' (dimensionless)	$20.95 - 0.25\,T + 1.4\,10^{-3}\,T^2$ (fresh)[c]
Attenuation factor α_d (1/m)	$1.4671 * MC\ (\%)$, (MC $\leq$ 22.4%), r² = 0.9991
	$40.932 - 0.0943 * MC\ (\%)$, (MC > 22.4%), r² = 0.9997[d]
Diffusion coefficient D_w (m²/s)	$2.6\,10^{-10e}$
Equilibrium water content C_{eq} (dry basis)	0.3657[f]

[a]Data from Sweat.[30]
[b]Data from Polley et al.[31]
[c]Data from Sipahioglu and Barringer.[32]
[d]Regression of experimental data obtained by Feng et al.[33]
[e]Data from Roman et al.[34]
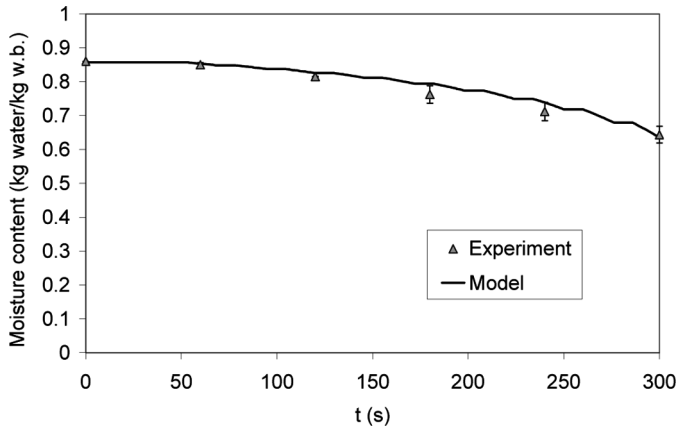[f]Data from Iglesias and Chirife.[35]

FIG. 4. Moisture content of the pear as a function of the dehydration time.

rapid drying period during which a stable temperature profile is established and MW energy is used for the vaporization of moisture. The weight loss in the first period (of about 55 s in this experiment) is very low; this validates the assumption of weak evaporation done in the mathematical model for Step 1. Later, a marked increase of drying rates is observed, allowing low final moisture content to be reached in 5 min.

Good accuracy of predictions can be observed (2.18% average absolute relative error between predicted and experimental values), in spite of the many assumptions made during the development of the model.

CONCLUSIONS

A relatively simple and easy-to-run model for the simultaneous prediction of temperature and water content profiles and weight loss during food drying in microwave ovens was developed. The food was considered as a system with physical properties that can change with material composition, structure, and temperature as well as with the characteristics of the electromagnetic field. Inner heat generation due to the electromagnetic field was considered using the approximation of Lambert's law, which implies an exponential decay of incident power with penetration depth. Two successive stages of drying were modeled: (1) initial heating followed by (2) intensive evaporation at food surface. Experimental runs of pear slices dehydration show the existence of both stages. Good agreement between experiment and simulation was achieved taking into account the simplifications made in the mathematical model: the use of Lambert's law to predict sample–radiation interaction and the fact that the model did not consider the complex mechanisms of mass transfer inside the fruit.

NOMENCLATURE

A Surface of the food (m^2)
C Concentration (kg/m^3)

C_p Specific heat capacity ($J/kg\,^\circ C$)
h Heat transfer coefficient ($W/[m^2\,^\circ C]$)
k Thermal conductivity ($W/[m\,^\circ C]$)
k_m Mass transfer coefficient (m/s)
L Half thickness (m)
L_{vap} Vaporization heat of water (J/kg)
MC Moisture content (%)
P Power generated by the absorption of MW (W)
P_o Power at the surface (W)
Q Accounts for the volumetric heat generation (W/m^3)
T Temperature ($^\circ C$)
t Time (s)
V Product volume (m^3)
x Position (m)

Greek Symbols

α Attenuation factor (1/m)
ε' Dielectric constant
ε'' Loss factor
λ Wavelength of radiation (m)
ρ Density (kg/m^3)

Subscripts

a Ambient
ave Average
d Dehydrated material
eq Equilibrium
ini Initial
w Water

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