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DETERMINATION OF HEAT SPEED IN POTATOES USING FINITE ELEMENT MODELING

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Abstract: This article presents a study of the reaction to a heat flow imposed on a raw potato of the Spunta variety. Its complicated molar characterization, where water occupies a high percentage, as well as proteins, starch, and fibers, makes the conventional constitutive law insufficient to respond to the temperature-time evolution, through finite element modeling and validation by numerical simulation. This work aims to find a correlation between all the mechanical and thermal parameters necessary for the normal flow to extract a meaningful relationship. This gives temperature velocity values in the unidirectional case of (0.01197 $K.s^{-1} \leq C$(temperature speed)$\leq$0.0187 K.s-1). To properly control the phenomenon, the time required for thermal homogenization is also determined in the longitudinal case and for an average length of 110mm of a potato tuber. The results show that after about 14 min at a distance of 55mm, we obtained stability between the extremes and the center for the studied texture.

Keywords: finite elements, potatoes, food, heat transfer, thermal velocity.

INTRODUCTION

Food crops are transformed in several ways. However, its internal texture does not react like an ordinary metal, considering the molecular structure as well as the duty cycle, among these food materials is the potato, which can be prepared in several forms, or form derivative products (HAFEZI *et al.*, 2015). This makes it go through thermal processes in which heat is transferred in several forms, including heating, cooling, and drying. This makes heat diffusion and velocity of propagation essential to the proper design of the equipment for these crops at different treatments (Chakraborty *et al.,* 2021; Ikegwu, 2021). Understanding these properties makes it possible to model heat transfers in complex systems and to predict thermal behavior (in the solid, fluid, and vicious state) (Bouhdjar *et al*, 2020). These predictions enable to perform the various heat transfer calculations used in the design of equipment, the process of storing and refrigerating, and estimating time for refrigerating, freezing, heating, or drying food (Lefort *et al*, 2003; Tansakul and Lumyong, 2008; Larwa, 2018). As these food properties are highly dependent on the chemical composition and temperature range of application, and as many types of agricultural food are available in many different molecular forms, it is almost impossible to give an exact model and thermal evaluation. Therefore, data must include the mass fractions of the main constituents present in the potatoes in this study and in general in agricultural materials (Murakami, 1997; Naumann *et al*, 2020; Chakraborty *et al.*, 2021). Thermal properties can be predicted using these composition data in conjunction with mathematical models and the thermal properties of the different food constituents, also based on several types of practice tests (Gosukonda *et al.,* 2017). The thermophysical properties of food are essential for calculating processing times and designing food storage and preservation equipment. For this, it is necessary to determine several foods' properties which depend strongly on the chemical composition and the thermal parameters which gives that provide the thermophysical models based on the proportionality of composition and according to the temperature to estimate the properties of foods. Several models have been developed, and the designer of food processing equipment is faced with the challenge of selecting suitable models (potatoes) (Betta *et al.*, 2009; Fricke and Becker, 2021; Lammari *et al.*, 2021).

MATERIAL AND METHODS

Theoretical model

Thermal conductivity is defined as the ability of a material to conduct heat. The theoretical methods are numerous and sometimes simple. However, we always try to standardize the models if possible because it is necessary to synchronize between the calculated and experimental results (in our case, the potato). Nevertheless, there are materials requiring test benches, which sometimes impose many difficulties that have to be solved. Thermal diffusion can be calculated indirectly, then, from thermal conductivity based on component weighting, density, and specific heat, it can also be determined directly from the solution of the heat transfer equation (Califano and Calvelo, 1991; Rahman *et al.*, 2012; Lammari *et al.*, 2020). Food components include water, protein, fat, carbohydrate, fiber, and ash. Choi and Okos in 1986 developed mathematical models to predict the thermal properties of these components as a function of temperature. Still, in some cases, the physical orientation of food components of biological origin has a highly variable character. The effect of changes in material composition on thermal conductivity values has been reported in these models (Fricke and Becker, 2001; Phinney *et al.*, 2017; Paternina *et al.*, 2022; Chakraborty *et al.*, 2021). The thermal properties of foods largely depend on the chemical composition and their reaction to temperature, potato does not come out of this concept available. The thermal conductivity (k) of foods can be predicted using these compositional data in conjunction with

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temperature-dependent mathematical models, and is estimated from the pure component of thermal conductivity ki, an important assumption used in this procedure. The estimate is that the contribution of each component to the thermal conductivity of the compound is proportional to the volume fraction Xvi, (Fricke and Becker, 2001; Farinu and Baik, 2007; Chuah *et al.*, 2008; Lammari *et al.*, 2021) Thermal conductivity was calculated based on the total of the contents of the composition multiplied by its thermal conductivity as shown in Eq1.

$$k = \sum (k_i Xvi) \qquad (1)$$

The thermal conductivities of the main constituents of the potato (W .m-1K-1) of pure water (kw), proteins (kp), lipids (kf), carbohydrates (kc), fiber (kfi) are calculated at temperature T°C, using the general equation (2) with the constants are well detailed for each component in Table.1 respectively (Srikiatden and Roberts, 2008; ABLANI, S.S.,2018; Salas-Valerio *et al.*, 2019) :

$$K\,i = A + B.T - T2.C \qquad (2)$$

Table 1.

Detailed constants for each component of equation 2

The Main Constituents Of The Potato: i	A	B	$C.10^{-6}$
pure water: w	0.57109	0.0017625	6.7306
Proteins :p	0.1788	0.0011958	2.7178
Lipids: f	0.1807	−0.0027604	1.7749
Carbohydrates:c	0.2.014	+0.0013874	4.3312
Fiber: fi	0.18331	0.0012479	3.1683

The volumetric parameter Xvi is proportional to each component of its mass presence Xi and its proportional density of this element ρi concerning the mixture density ρ (total) which constitutes the density of the potato and the physical parameters are calculated at room temperature in this case (Saenmuang *et al.*, 2017; Yin *et al.*, 2022) (Eq. 3).

$$Xvi = Xi\frac{\rho}{\rho_i} \qquad (3)$$

The density of each major potato component in kg/m3 is obtained by equations (4-5-6-7-8), respectively, for water (ρw), proteins (ρp), lipids (ρf), carbohydrates (ρc), fibers (ρfi):

$$\rho_w = 997.18 + T \times 0.0031439 - T^2 \times 0.0037574 \qquad (4)$$

$$\rho_p = 1323.9 - T \times 0.51814 \qquad (5)$$

$$\rho_f = 925.59 - T \times 0.41757 \qquad (6)$$

$$\rho_c = 1599.1 - T \times 0.31046 \qquad (7)$$

$$\rho_{fi} = 1311.5 - T \times 0.36589 \qquad (8)$$

We need a driving force to overcome resistance to transmit a thermal property. For any type of molecular transfer process (molecular motion, heat or thermal energy, and mass), the equation can be written as (transfer rate = driving force/ resistance). While the rate of thermal conduction through the wall is proportional to the heat transfer surface (A), the wall thickness (X) offers resistance to heat transfer. In addition, the capacity of the heat conductivity material must be taken into account (potato). This property of the material is called thermal conductivity (k), therefore, the resistance to heat transfer takes into account all these parameters, so the state of equilibrium is reached. The flux of heat (Q) through the body can be written by Eqs. 9 and 10 by equivalent substitution to the relation (1) (Yin *et al.*, 2022).

$$Q = -kA(T1 - T0)/X \qquad (9)$$

The equation in differential form is the Fourier law of heat conduction:

$$Qx = -kA\frac{dT}{dx} \qquad (10)$$

Considering a closed, homogeneous, and non-deformable solid system, occupying a volume(V) limited by a surface A. This system evolves over time as a result of energy exchanges in the form of heat with the exterior and/or internal production of thermal energy. The temperature distribution within the volume is not uniform and changes over time. The system is therefore not in thermodynamic equilibrium but in a state of heat flow. To establish the equation that governs the evolution of the temperature at each point of the volume, we will carry out an energy balance of the system. Plus, we will consider that the system is at rest and that there is no mechanical work involved because the system is undeformable (no volume variation) based on Ostrogradski's theorem for the surface integral (Taler and Ocłoń, 2014).

$$\iiint_V \rho c\frac{\partial T}{\partial t}dV = \iiint_V(\lambda\nabla T)dV + \iiint_V PdV \qquad (11)$$

This equilibrium constitutes the thermal equation in global form (integrated over the whole volume). It is valid for any volume element dV. A local heat equation can then be written, which, after solution, allows the temperature at any point in the system to be determined at any time.

We consider that the potato is solid, homogeneous, and deformable, and assume that the thermal conductivity of the material is constant, let's take the heat equation established earlier (Eq.12) (Pavlov *et al.*, 2017; Krishna Kumar *et al.*, 2018):

$$\rho c_p\frac{\partial T}{\partial t} = k\nabla^2 T + P \qquad (12)$$

Where P is the volumetric heat source (J.s^{-1}.m^{-3}), ρ is the density (kg.m^{-3}), c_p Is the specific heat capacity at constant pressure (J.kg^{-1}.K^{-1})), k is thermal conductivity (J.s^{-1}.m^{-1}.K^{-1}) noted although 1W=1 J.s^{-1}, T is the temperature (K) and t is time (s). The assumptions adopted in steady-state (permanent) ∂T/∂t=0 and the accumulation term are zero without heat dissipation. In the steady state, the balance of flows into and out of the medium is zero, which translates into the conservation of heat flow (∅) expressed by the following Eq.13:

$$\emptyset = \emptyset_E - \emptyset_S = \iint_S -\varphi.ndS \quad (13)$$

ds: elementary surface

To solve this problem, the FEM is a tool for analyzing complex structures since this method is based on the principle of using a nodal approximation by subdomains. On each subdomain, the function U(x)(a scalar (and not a vector) which only depends on the abscissa)is approximated by (Salas-Valerio *et al.*, 2019):

$$\mathrm{U(x)} = \sum_1^n N_i \ (x) U_i \quad (14)$$

Ni(x): represents the interpolation functions, Ui: represents the nodal displacements, n: represents the number of nodes of the element;

The complicated shape of the potato, and since the interpolation functions vary according to the type and geometry of the element and the number of nodes, in general, are chosen in the form of a polynomial sequence, in the appearance of one-dimensional problems. Therefore, it is necessary to set useful boundary conditions for a given time, translated into PDE, specifying the behavior of the solution at the field boundary. Three different types of boundary conditions are applied (Singh *et al.*, 2007, Dhall and Datta, 2011):

The temperature is imposed on a part Γ1 (Fig. 1) of the edge this first type of boundary condition (Dirichlet) supposes that the value is known by:

$$T = \bar{T} \quad sur\ \Gamma_1 \quad (15)$$

The heat flow is imposed on a part Γ2 (Fig. 1) of the border: is called the Neumann condition, and the derivative of the temperature at the border is known.

$$k_x \frac{\partial T}{\partial x} n_x + k_y \frac{\partial T}{\partial y} n_y = \bar{q} \qquad \Gamma_2 \quad (16)$$

This Robin's condition expresses that, on a part Γ3(Fig.3)of the boundary, the heat given up by the system is proportional to the difference between the temperature of the system and that of the external environment :

$$k_x \frac{\partial T}{\partial x} n_x + k_y \frac{\partial T}{\partial y} n_y = h(T_f - T) \quad \Gamma_3 \quad (17)$$

Where T represents the temperature, *Q(x)* is the heat generation rate which is generally an explicit function of k_x, and k_y Of the specified thermal conductivities where and are the principal directions of the conductivity tensor, $\bar{T}$ and $\bar{q}$ are the prescribed temperature and the given heat flux on the corresponding boundaries. Respectively, n_x and n_y are the director vectors of the exterior normal to the boundary surface. (h) is the convective heat transfer coefficient. (Tf) is the ambient temperature, Γ1, Γ2 and Γ3 are the boundary conditions to which the Dirichlet, Neumann, and Robin conditions are applied (Mitsoulis and Vlachopoulos, 1984).

Note that Γ1, Γ2 and Γ3 must constitute a partition of the boundary Γ, i.e.:

– At any point on the edge, a boundary condition is prescribed:

Γ = Γ1 ∪ Γ2 ∪ Γ3,

– A single boundary condition is prescribed at any point on the edge:

Γ1 ∩ Γ2 = Γ1 ∩ Γ3 = Γ2 ∩ Γ3 = ∅.

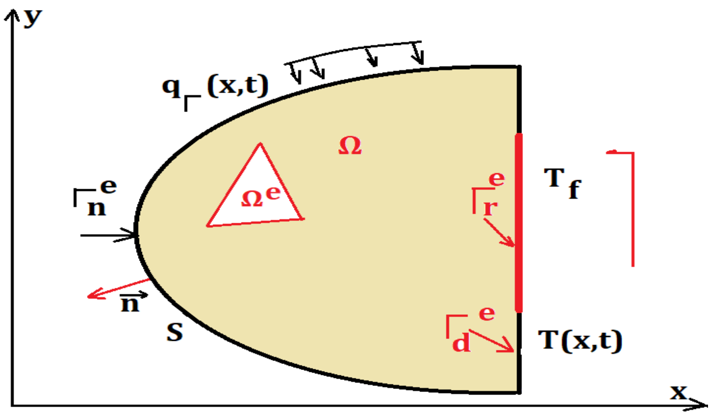

Fig. 1. Boundary condition with corresponding temperature profile.

The weak formulation associated with the heat conduction problem that is described in the model studied is obtained by multiplying the heat equation by a sufficiently regular test function w (or interpolation function: thermal), then, by integration over the whole domain and introducing the convective nature of the flow imposed on the part (Dhall and Datta, 2011; Taler and Ocłoń, 2014; Dash *et al.*, 2022; Yin *et al.*, 2022): The Galerkin method, which makes it possible to determine the nodal temperatures T(e,j [j=1,2 …n], the element domain Ω, Applying the above integral, Green's theorem, The left side is the integral over the element domain Ωe and the right-hand side denotes the integral over-element boundary Γ. Integrating by parts gives:

$$\int_\Omega \left[\frac{\partial w}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial w}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) - wQ(x,y)\right] dxdy - \oint_\Gamma w\left[\left(k\frac{\partial T}{\partial x}\right) n_x + \left(k\frac{\partial T}{\partial y}\right) n_y\right] dS = 0 \quad (23)\ (\text{Fig.1})$$

dS: elementary surface

* Note that the shape of the elements (triangle in this case) is the main source of the function and subsequently, it must be linearized.

Numerical simulation of heat transfer in potatoes

In Table 2 we have mentioned all the initial properties to model the heat transfer phenomena in a potato.

Table 2.

Properties of raw potatoes (Variety Spunta)
(Betta *et al.*, 2009; Lyng *et al.*, 2014 ; Krishna *et al.*, 2018; Lammari *et al.*, 2020)

Properties of raw potatoes	
Density (Kg.m^{-3}) 987 $\ll \rho \ll$1092	Facet temperature =46,5°C
The heat transfer coefficient h=7,81w.m^{-2}K^{-1}	Young Module E=4.4MPa
Thermal conductivity k=0.56 w.m^{-1}K^{-1}	Poisson's ratio μ (-) 0.42
thermal diffusivity (α) = 0.89 ± 0.01 × 10 $^{-6}$ m^2.s^{-1}	The temperature at T∞ = 100°C

To solve this problem, we want to model the heat transfers during the heating phase of the specimen. We propose to start with one-dimensional modeling. The solution to the heat equation can be written as follows (Mitsoulis and Vlachopoulos, 1984; Dash *et al*, 2022):

$$\rho c_P(T)\dot{T} - k\,\frac{\partial^2 T}{\partial t^2} = -(div\overrightarrow{q_r}\ ) \tag{18}$$

ρ is the density of the material, c_P is the mass heat capacity, k is the thermal conductivity, q_r is the flux density.

PDEs are grouped into three broad categories: parabolic, hyperbolic, and elliptical. To better understand what this means, we will see the case of partial differential equations of the second order relating to real functions. The application of the FEM method for solving heat conduction problems is presented for the two-dimensional case. Thus, this thickness is assumed to be measured in the plane perpendicular to the face. The basic FEM equations for two-dimensional elements are derived using the Galerkin method. The governing equation for heat conduction in solids (Singh *et al.*, 2007; Dhall and Datta, 2011; Krishna Kumar *et al*, 2018):

$$\boldsymbol{c_p}\frac{\partial \boldsymbol{T}}{\partial \boldsymbol{t}} = \frac{\partial}{\partial x}\left(\boldsymbol{k_x}\frac{\partial \boldsymbol{T}}{\partial x}\right) + \frac{\partial}{\partial y}\left(\boldsymbol{k_y}\frac{\partial \boldsymbol{T}}{\partial y}\right) + \boldsymbol{Q}(\boldsymbol{x},\boldsymbol{t}) \tag{19}$$

If the anisotropic thermal conductivities in the x and y directions are denoted $\boldsymbol{k_x}$ and $\boldsymbol{k_y}$ (Lammari *et al*, 2020).The initial conditions, needed to solve (25), are:$T(x, y, t)|_{t=0}$ $=T_0$ (x, y) in a closed domain Ω =∑ Ωe with boundary Γi.

RESULTS AND DISCUSSION

To carry out the simulation, choose the boundary conditions (temperature, displacement), after fixing the specimen, a temperature gradient is imposed on the surface studied to interpret its evolution as a function of time. In Fig. 2, the simulation of the model which is based on the real properties shows that the thermal homogenization time was 780s, with an imposed 1D temperature gradient of 46°C and thus an internal equilibrium of about 32.17°C (Fig. 2).

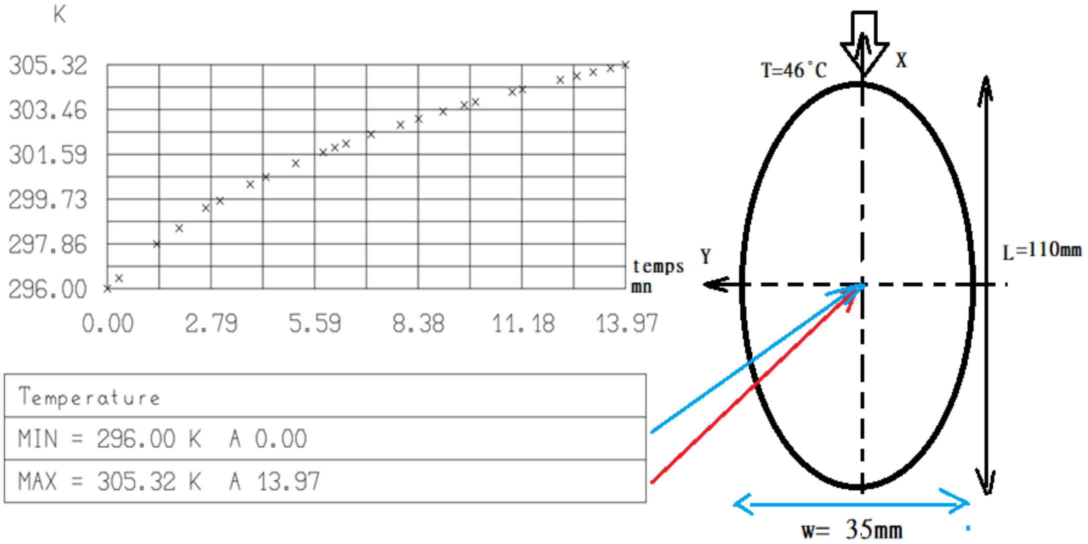

Fig. 2. Numerical modeling of temperature versus time (Y = 0) (Variety: Spunta).

The results given by the unidirectional modeling show that the heat celerity is c = 0.012K.s-^{1} observed in case the Spunta (medium) potato type remains under a temperature of 50°C; in summer or after harvesting, the temperature exceeds 33°C in 6 min. Thus, it is important to note that at t = 0s we can notice the harvest phase interior where the temperature is almost 23°C max. These values are used for the simulation.

To ensure that temperature circulates throughout the tuber, 2D flow (geometry) must be applied on all sides. Because while preparing meals or crisps, standardizing the distribution (Fig. 3) and indicating that the heating rate (Fig. 4) presents an objective of our study make these results more significant.

It remains to say that the propagation of the temperature in the case of 2D becomes more accelerated because of the imposed field of the simultaneous axes for the same geometry c=0.018K.s^{-1}.

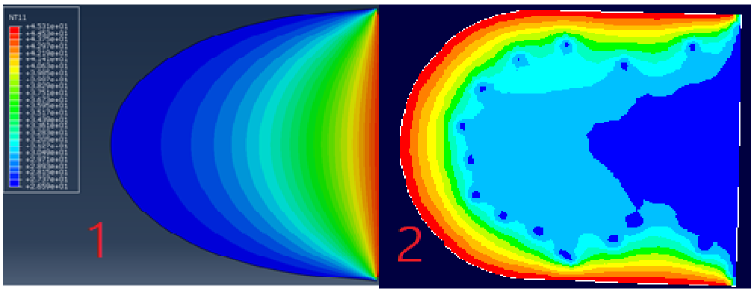

Fig. 3. Final temperature distribution (2d) after 1 hour.

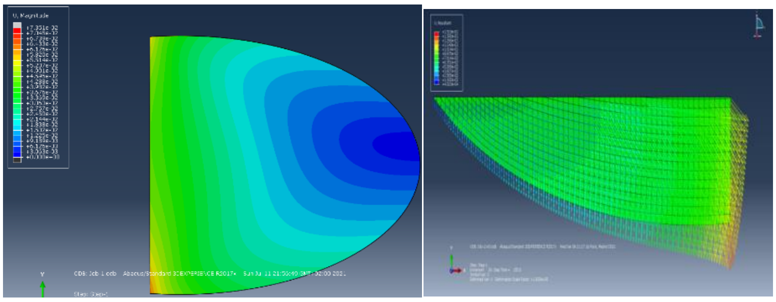

Fig. 4. Temperature speed in potato and direction of heat flow.

CONCLUSION

During its life cycle, the potato is exposed to various thermal stresses: convective conduction and radiation (harvesting phase; transport, storage, and industrial processing). But the convective phenomenon being the most important of all these cycles, we limited the range of thermal conductivity and proved that after 14 min by T = 50°C, raw potatoes (spunta) become thermally homogeneous by natural flow. Hence, this duration can be reduced in the case of an imposed or turbulent flow, it is the industrial case. The purpose of this study is to control and maintain the potato in good condition to guarantee its quality (taste and shape), to avoid the rapid aging of an important agricultural product optimize storage energy, and fix the time required at the rate of heat which is of importance.

AUTHORS CONTRIBUTIONS

Conceptualization, H.K.; methodology, S.B.K. and H.K.; data collection S.B.K.; data validation, L.L. and H.K.; data processing S.B.K. and H.K.; writing—original draft preparation, L.L.; writing—review and editing, S.B.K. and H.K.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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