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## The thermal, physical and mechanical properties of complex particle charged foodstuffs

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**Abstract :** The passage from a batch to a continuous process in order to sterilize heterogeneous products (viscous fluids with high concentration of fragile particles) remains an empirical and hazardous operation. We characterize the fundamental data: physical (rheology, density, dimension), mechanical (elasticity modulus), thermal (heat capacity, thermal and electrical conductivity, thermal diffusivity) properties of each phase (carrier fluids, particles) at the inlet and the outlet of conventional process.

**Key words:** characterization, foodstuffs, particle, mechanical and thermo-physical properties.

### INTRODUCTION

Food stores shelves confirm the increasing choice of prepared dishes. Due to their complex composition, these products are generally delicate to produce and stabilize, using a continuous thermal process. Heat treatment represents the most widely used-method and is standard industrial practice when sterilizing food products. Several heat treatments are available. The traditional technique used by the food industry is canning. Heat is applied to the outside of the can until sterilization is completed, which occurs the center has reached the required  $F_0$ . For foods containing particles, significant overheating should be applied to ensure full sterilization at the center of the can and of the particles. Continuous processing of heterogeneous liquid-particles food products with conventional or alternative technologies is being increasingly advocated as a substitute for batch sterilization. Food flows continuously throughout the heating, holding and cooking sections of the process. The sterilization temperature (130-140°C) may be achieved with a tubular heat exchanger (Direct Joule Effect and Indirect Joule Effect). Alternative technology may achieve a high temperature treatment in a shorter time (HTST). The expected advantages of a continuous process are an increase in production capacity, a reduction in power consumption, an improved treatment homogeneity and conservation of the integrity of particles. In continuous process, hydraulic and thermal phenomena will be closely associated. Two critical parameters are particle residence distribution time and a conservative heat transfer coefficient value  $h_p$  between the liquid and particle. Previous publications indicate that the major factors influencing particle velocity in a stream of the carrier fluid are viscosity, flow rate, relative (particle to fluid) density of solids, relative (particle to tube) size and the concentration of the solid phase in the fluid. Moreover, for the transport of particles, the main constraint is pressure drop for the sizing of pipes and pumps. In spite of efforts in understanding hydraulic transport phenomena, the modeling of pressure drop with flow rate for different particle concentrations and the prediction of particle behavior in ducts remain a very complex problem.

The Direct Joule Effect is a highly attractive process for the food-processing engineer, offering the use of HTST techniques for the sterilisation of particulate foods. In ohmic heating, heat is produced by the passage of an alternative electric current through a continuously flowing stream of food medium and inside the product. Physical factors, which affect the heating rate of food particles are shape, dimension, liquid and solid conductivities.

Indirect Joule Effect technology is a heating technology in which a stainless steel tube carrying a pumpable food product is connected to low-voltage, high-ampere electrical power and heated due to the resistance of the tube. Heat is transported to the fluid by convection as in a conventional heat exchanger.

From a scientific and industrial standpoint, it seems important to describe, understand and model heat treatment of heterogeneous food. The incidence of heating technologies (conventional heating, Direct Joule Effect or Indirect Joule Effect heat exchanger) appears fundamental in continuous process in which the knowledge of physical, mechanical, thermal and electrical properties of fluids and particles become necessary [1]. However, the properties of the foodstuffs themselves are absent from the literature. The present study aims to obtain these properties (process inlet, outlet) for two real food products: A, a meats mixture and B, a cooked dish, exclusively composed of large non-spherical particles with carrier fluids, which are highly viscous and exhibit non-Newtonian behavior. In this paper, we will focus on the materials

and methods we used before going on to present the obtained results. We will discuss physical, thermal and mechanical properties in order to evaluate the ability of continuous process to ensure heat treatment.

## MATERIALS AND METHODS:

### 1. Products

Product A was composed of meat particles in a carrier fluid (modified starch suspension). It was analysed before and after cooking in cans. Product B, a cooked dish was composed of beans (particles) and tomato sauce (carrier fluid). Experimental studies before cooking were performed with a model fluid (aqueous solution of Xanthan gum 0.6%w/w, sugar 22.6%w/w, salt 1.5%w/w), simulating the behavior of a cooked dish sauce. The model fluid was used to discuss the physical phenomena observed during the process and to carry out experiments on the variability of real products with a complex composition. Furthermore, dry bean processing requires an initial hydration stage (3 hours at 20°C) in order to facilitate a shorter cooking time. After hydration, these beans were blanched by immersion in boiling water at 90°C for 15 minutes, in order to ensure enzymatic inactivation. Product B analyses were performed before and after cooking in cans and in addition, characterizations of dry and hydrated beans were carried out.

### 2. Physical, mechanical and thermal properties

**Rheological properties:** The apparent viscosity of all solutions was determined using a rotational viscometer (Rheomat 30). The fluids were placed between two coaxial cylinders. A well-defined stress was imposed and the resulting strain measured. Rheological measurements were performed between 20-90°C. The precision was of  $\pm 1\%$  for apparent viscosity.

**Mechanical properties:** Particles texture was measured using an Instron test instrument attached to data acquisition control. Load cells of 1 kN and 100 N were used. The cutting edge employed was a 2.8 mm diameter rod. A 10x10 cm<sup>2</sup> aluminium plate with a thickness of 1.3 cm was supported on the Instron base and permitted the particle to be positioned correctly during the texture measurement. The stainless steel cutting edge was lowered at a speed of 10 mm.min<sup>-1</sup>. During the operation, the orientation of each particle was maintained by placing it on its flat side and cutting transversely through the centre. The cutting wedge was allowed to travel a distance of 5 mm before the movement was stopped. As the edge cut through the particle, the deformation process was recognised by the attached software as a graph of force versus displacement. The program identified the peak point of the curve, which was taken to be the maximum force required cutting through the particle. The experiment was repeated for 20 particles and the average deformation curve was used in the analysis. The precision for force was of  $\pm 0.1\%$ .

**Electrical conductivity:** Experiments were conducted in a static ohmic heater, which consisted of a polytetrafluoroethylene box with inner dimensions of 20 x 8 x 5 cm. At either end of the box were 40 cm<sup>2</sup> electrodes. The medium to be tested was placed between these. The system was fed from the 240V, 50 Hz mains supply via a variable transformer used to regulate voltage. A computer was used to record temperatures. Five thermocouples were placed to measure temperature in the liquid phase of suspension. The voltage applied and the current passing through the system were also recorded by the computer and used to calculate the electrical conductivity of the bulk system as a function of temperature. For this work, the mean heating rate was assessed from the time required to heat samples from 20°C to 90°C. The effect of particles concentration and temperature on electrical conductivity was studied. The precision was of  $\pm 2\%$  for electric current and potential and  $\pm 1^\circ\text{C}$  for thermocouple.

**Particle size distribution:** The particle size distribution was determined by image analysis of photographs. This method directly measures the dimensions of particles and was previously compared and validated with a standard method (vernier caliper). A minimum of 50 particles was sampled to determine the size distribution. The precision was of  $\pm 0.1\text{mm}$ .

**Density:** The fluids' density was measured using a densimeter (ANTON-PAAR type DNA 45). The principle of this apparatus is as follows: the fluid is placed in a gauged tube, which is put in oscillation. The instrument detects the frequency of the setting in resonance with the unit, which is proportional to the density of the fluid. A thermostatic bath permits the density to be determined at various temperatures and thus allows the obtention of the evolution of the density with temperature. The precision was  $\pm 0.0001 \text{ g.cm}^{-3}$ . The particle density was measured using a graduated test-tube ( $\pm 0.1\text{ml}$ ). Volume and mass variation enable their density to be calculated with a precision of  $\pm 0.01 \text{ g.cm}^{-3}$ .

**Thermal conductivity:** The TC Probe (Thermal Conductivity Probe) was developed based on a modified hot wire approach and is designed for testing flat solid materials and liquids at room temperature ( $20^\circ\text{C} \pm 2^\circ\text{C}$ ). The analysis of the design for the TC Probe began with the instrument for measuring the thermal conductivity of liquids. For the study of solids, the heat source had to be mounted on a backing rather than

embedded in the test sample, as had been done previously when testing liquids. Once a second material was introduced, the standard hot wire equations for two-dimensional conduction were complicated by the parameters of the two backing materials. A one-dimensional heat flow analysis was carried out in order to solve this problem. Testing with the TC Probe resulted in the parameters ( $\lambda, \rho, C_p$ ) of a material. The test time ranged from 10 to 120 seconds giving results with high repeatability of  $\pm 2\%$  and with a precision of  $\pm 10\%$ .

**Specific heat:** For specific heat measurements, the calorimeter used was a differential scanning calorimeter (SETARAM, type C80). This apparatus is provided with two measuring cells, one for air as a reference and one for the material to be characterised, placed in a calorimetric block. The heat flux exchanged between the cells and the block was measured using a fluxmeter. The difference in flux measured between the cells enabled us to determine the specific heat. The precision was of  $\pm 3\%$  for heat capacity.

Many physical data are adequately described by a normal distribution model noted  $f(x)$  and defined by two parameters: the average and the standard deviation. Normal distribution was validated with dimension, density, and mechanical properties.

## RESULTS & DISCUSSION:

### 1. Physical properties

#### □ Rheological properties and density of carrier fluids

Measurement of food viscosity is a vital area, not only as a means of monitoring the final product quality, but also for controlling intermediate processes. Rheological properties permit the flow nature (laminar, transition or turbulent) to be characterized by the calculation of the Reynolds number. In this study, we worked exclusively on laminar flow.

The rheological behavior of carrier fluids was studied at different temperatures (20-90°C). All the fluids used, presented a similar behavior. Results showed that an increase in the shear rate resulted in a decrease in apparent viscosity, suggesting pseudoplastic behavior (power law model). Viscosity decreased with temperature. The flow behavior indexes were between 0.1 and 0.5 and increased linearly with temperature, whereas consistency indices exhibited a power-law model with temperature.

Carrier fluid	n [-]	k [Pa.s <sup>n</sup> ]	$\rho$ [kg.m <sup>-3</sup> ]
Product A inlet	$0.2397 + 2.7 \times 10^{-3} \theta$	$416,43 \theta^{-0.97}$	$1033.0 - 0.705 \theta$
Product A outlet	$0,2174 + 2.8 \times 10^{-3} \theta$	$5912,7 \theta^{-1.53}$	$1045.9 - 0.338 \theta$
Product B inlet	$0.1458 + 7 \times 10^{-4} \theta$	$14.072 \theta^{-0.18}$	$1126.1 - 0.709 \theta$
Product B outlet	$0.4211 - 1.3 \times 10^{-3} \theta$	$18.456 \theta^{-0.39}$	$1068.6 - 0.389 \theta$

Table 1: Rheological behavior and the density of carrier fluids (products A and B, temperature from 20-90°C, inlet and outlet process).

#### □ Density and size distribution of particles

Three dimensions characterised the particles of products A and B: width, length and thickness. In the literature [2], particles are classified into three categories namely large ( $L > 1.1$  cm), medium ( $0.95 \leq L \leq 1.10$  cm) and small ( $L < 0.95$  cm). Table 2 confirms that all the particles studied are classified as large. Also, we observed that their dimensions changed during processing. They increased with moisture content for product B, resulting from a significant amount of absorbed water. In continuous process, dimension increase will limit the particulate concentration at process entrance due to a volume expansion during the process. A relationship between an increase in the heat transfer coefficient  $h_{fp}$  and an increase in particle size has been found by [3], whereas the opposite was observed by [4]. These observations show that the particle size intervenes primarily on  $h_{fp}$  by the modification of the flow.

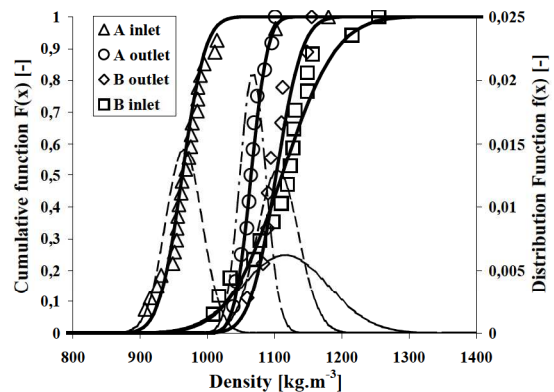
Relative density (particle to fluid) appears essential when characterizing the suspension homogeneity (decantation, flotation) and particle residence time distribution (RTD). Figure 2 shows that for particle in product A, density significantly increased during the process whereas for product B, it slightly decreased. For both the standard deviation decreased with cooking. For product B at the inlet, particle density ( $1116$  kg.m<sup>-3</sup>) was higher than fluid ( $1112$  kg.m<sup>-3</sup>) density, whereas, for product A inlet, it was the opposite. In the literature [5], particles with higher density ratios tend to settle on the bottom of the tube developing a stationary or moving bed of particles. In this study, the percentage of particles of product B at the inlet

detected at the bottom of the pipe would be 60% in static condition. It would be the same thing for the particles of product A, but the particles would move along the top of the tube. Note that for product A at the outlet, particle density ( $1068 \text{ kg.m}^{-3}$ ) became higher than fluid density ( $1039 \text{ kg.m}^{-3}$ ) forming a bed at the top of the pipe. This bed would reduce the effective flow diameter such that local velocities of fluid and particles would increase as they flow across the top of the particle bed. As particles are carried by the fluid, their residence time is directly related to the location of the particle within the liquid velocity flow profile. The particles would move slower in the tube probably due to the boundary layer or friction factor between the particles and the tube wall. This would increase the differences in the sterility of the particles or carrier fluid, especially when food contains diverse particle densities as in the case of product B (high standard deviation).

Product	$\rho$ [ $\text{kg.m}^{-3}$ ]	L [mm]	l [mm]	E [mm]
A inlet	971 (66)	19.4 (1.6)	10.8 (0.5)	7.8 (0.6)
A outlet	1068 (19)	20.7 (1.4)	10.1 (0.7)	9.3 (0.6)
Dry B	1181 (67)	15.6 (1.4)	7.9 (0.6)	5.9 (0.4)
Hydrated B	1057 (34)	20.4 (1.7)	9.7 (0.7)	7.0 (0.5)
Blanched B	1116 (64)	20.7 (1.2)	10.4 (0.8)	7.4 (0.6)
Cooked B	1104 (31)	21.1 (1.7)	10.7 (0.8)	8.5 (0.8)

Table 2: Dimension distribution of particles in products A and B at  $20^\circ\text{C}$  – mean value (standard deviation)-

Fig 2: Density distribution of particle in products A and B at  $20^\circ\text{C}$ .



## 2. Mechanical properties (Elastic modulus and admissible elastic limit)

In the literature, the magnitude of damage to the particles depends on their physical and mechanical properties [6]. Their mechanical properties were measured in one dimension, whereas products A and B are anisotropics. For all moisture contents, the compressive force on the particles increased with an increase in deformation. There was a decrease in the force after rupture occurred in the particles. The force required causing a given deformation decreased as the moisture content increased, as reported by [7]. This may be due to the fact that at higher moisture contents, the particles became softer and required less force. The particles were assumed to exhibit elastic behavior, obeying Hooke's law. Young's modulus is properly determined from the initial section of the stress-strain curve, at relatively low deformation. Thus, only the section of the deformation curve below the initial yield point is considered and the value obtained is referred to as the elastic modulus as reported by [8]. Elastic modulus was used to measure the textural changes of particles during thermal treatment. The two products present a similar behaviour (Figure 3) with a loss of elastic properties during process. The elastic modulus and strains are given in Table 3. The admissible elastic limit for the product A is higher than that for product B. Product A can be deformed at 72% of the initial state (inlet) and 36% (outlet), whereas product B can be deformed at 42% of the initial state (inlet), and 20% (outlet),

## 3. Thermal properties

### □ Electrical conductivity

The electrical conductivity is a key property in ohmic heating and in the estimation of heating rates. In highly conductive materials, a large current will flow. In highly resistive materials, there will be a negligible current. The effect of processing on the electrical conductivity of solid food pieces has been investigated by several authors [9, 10]. Figure 4 represents the evolution of electrical conductivity versus particle concentration and temperature. The general trend shows that electrical conductivity increased linearly with temperature ranges of 20 to  $80^\circ\text{C}$  and this was confirmed by [11,12]. For product B before cooking, electrical conductivity decreased linearly with particle concentration. For product A, it initially increased with increasing particles concentration and thereafter, a plateau was reached where no further change to the electrical conductivity value was observed. At this point, mass transfer between particles and liquid seemed to reach a balance. Lastly, the continuous contribution of particles reduced the ion mobility and generated a loss of the electric conductivity of the mixture. Major differences between products A and B may be explained by initial electrical conductivity ratios between the fluid and the particles. We observed that for product A, the electrical conductivity of particles is higher than for fluids whereas it was the opposite for product B. In practice, most vegetable solid particles exhibit lower electrical conductivities than

liquids. A combined effect of temperature and particle concentration on electrical conductivity was observed and regression equations were established. The general formulation of proposed models was  $\sigma = f_a(C) \theta + f_b(C)$  with  $f_a$  and  $f_b$  as polynomial functions. Overall, the models gave satisfactory predictions of the electrical conductivity.

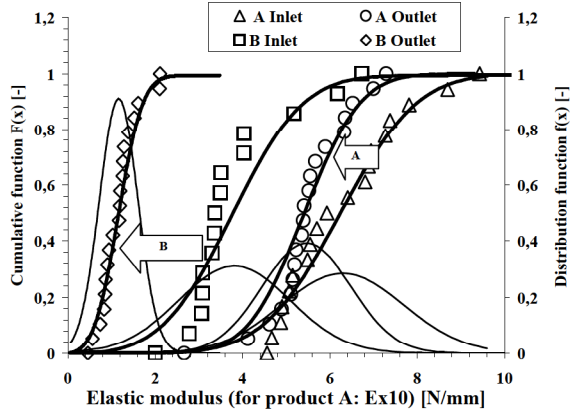


Fig 3: Elastic modulus distribution of particle A and B (inlet, outlet) at 20°C.

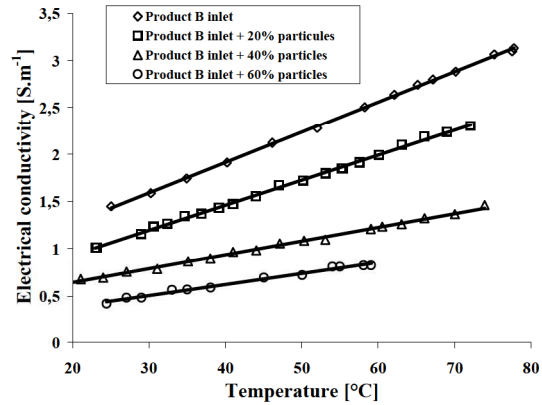


Fig 4: Electrical conductivity of product B (inlet) versus temperature and particles concentration.

□ Specific heat

The specific heat of product B at four moisture levels in the range of 11.57-67.4% and in the temperature range 20-80°C was found to lie between 1909-3400 J.kg<sup>-1</sup>.K<sup>-1</sup> and increased linearly with moisture content (Cp=25.703x<sub>H2O</sub>+1666.8). For product A, we observed that the specific heat of the inlet particle was lower than for those sterilized in agreement with the moisture content. Several empirical models useful in predicting the specific heat of foods have appeared in literature. For example, a model has been published [13] to predict specific heat as a function of water content, Cp=Cp<sub>0</sub>(1-X)+Cp<sub>w</sub>X. We used this model, but no satisfactory agreement could be found between the present data and the correlation.

		Thermal properties				Mechanical properties		
		X <sub>H2O</sub> [%]	Cp [J.kg <sup>-1</sup> .°C <sup>-1</sup> ]	λ [W.m <sup>-1</sup> .°C <sup>-1</sup> ]	ρ [kg.m <sup>-3</sup> ]	Dt [m <sup>2</sup> .s <sup>-1</sup> ]	E [Pa]	σ <sub>elas</sub> [Pa]
A	Pieces inlet	62.8	3272	0.29	970	9.1x10 <sup>-8</sup>	0.63	0.45
	Pieces outlet	71.7	3439	0.42	1068	1.2x10 <sup>-7</sup>	0.55	0.20
	Sauce inlet	96.4	4035	0.35	1012	8.6x10 <sup>-8</sup>	NR	NR
	Sauce outlet	91.4	3853	0.43	1039	1.1x10 <sup>-7</sup>	NR	NR
B	Dry beans	11.57	1909	NR	1181	NR	NR	NR
	Hydrated beans	53.2	3060	0.18	1057	5.6x10 <sup>-8</sup>	17.57	3.63
	Blanched beans	62.1	3240	0.22	1116	6.3x10 <sup>-8</sup>	3.82	1.62
	Cooked beans	67.4	3400	0.34	1104	9.1x10 <sup>-8</sup>	1.17	0.24
	Sauce inlet	81.1	3700	0.33	1108	8.2x10 <sup>-8</sup>	NR	NR
	Sauce outlet	86.6	3728	0.42	1062	1.1x10 <sup>-7</sup>	NR	NR

Table 3: Water content, specific heat, thermal conductivity, density and thermal diffusivity values for products A and B (inlet, outlet) at 20°C (NR : Not Realized).

□ Thermal conductivity

The thermal conductivity of foods varies with temperature during thermal processing due to the changes in texture and/ or composition [14]. Water content, specific heat, thermal conductivity, density and thermal diffusivity are given in Table 3. The thermal conductivity of particles of product B changed from 0.18 to 0.34 W.m<sup>-1</sup>.°C<sup>-1</sup>. It varied linearly with moisture content following the regression equation λ=0.0106x<sub>H2O</sub>-0.3968. For moisture contents higher than 30%, a linear relationship between thermal conductivity and the moisture fraction (w/w wet basis) was observed by [15]. In the literature, it was observed that the thermal diffusivity values of fruits and vegetables vary from 1 to 2x10<sup>-7</sup> m<sup>2</sup>.s<sup>-1</sup> and those of meat from 1.2 to 1.6x10<sup>-7</sup> m<sup>2</sup>.s<sup>-1</sup>. These values gave significantly higher values than those determined experimentally. Thermal diffusivity of products was also affected both by their water content and their temperature. [16] performed multiple regression analysis on 246 published values on thermal diffusivity of a variety of food products and obtained the following regression equation Dt=[0.05736x<sub>H2O</sub>+2.88x10<sup>-4</sup>(θ+273)]X10<sup>-6</sup>. No satisfactory

agreement could be found between the present data and this correlation. The difference may be attributed to the experimental method as well as to the product specificity.

### CONCLUSIONS AND FUTURE WORKS:

A complete set of physical, mechanical and thermal properties was obtained for particles and carrier fluids. The data highlights the heat and mass transfer occurring in the industrial process. Overall properties help to drive several recommendations, with regards to the continuous processing of suspension. First, particle dimension may increase during the process so that volume concentration at the outlet will be superior to that at the inlet to avoid blocking during the process. Secondly, mechanical properties will define the ability of particles to flow through a pipe with mechanical shocks between particles and with the wall. The mechanical resistance and elasticity appear to be major criteria. Thirdly, relative electric conductivity (mixture, particle, carrier fluid) leads to a decision as to whether the direct Joule effect to be considered as an interesting technology or not. Finally, most of the properties (mechanical, physical) evolve during the process and may be describe by normal distribution. As a practical consequence, these parameters may be used as a heat treatment tracer (Time temperature integrator). In continuous process, additional phenomena need to be taken into account: (i) the flow of heterogeneous suspensions (decantation, pipe orientation, concentration and Residence Time Distribution, (ii) heat exchanger technologies (conventional heat exchanger, Direct Joule Effect and Indirect Joule Effect) and heat transfer phenomena. In the future works, we will use these properties to compare a product treated by canning and a product treated by continuous heating.

### NOMENCLATURE

$\infty$	viscosity [Pa.s]	$\theta$	temperature [ $^{\circ}$ C]
k	consistency coefficient [Pa.s <sup>n</sup> ]	$X_{H_2O}$	moisture content [% (w/w)]
n	flow behavior index [-]	L	length [mm]
$\sigma$	electrical conductivity [S m <sup>-1</sup> ]	l	width [mm]
$\rho$	densiy [kg.m <sup>-3</sup> ]	e	thickness [mm]
$\lambda$	thermal conductivity [W.m <sup>-1</sup> . $^{\circ}$ C <sup>-1</sup> ]	Dt	thermal diffusivity [m <sup>2</sup> .s <sup>-1</sup> ]
Cp	specific heat [J.kg <sup>-1</sup> . $^{\circ}$ C <sup>-1</sup> ]	$h_{fp}$	heat transfer coefficient [W.m <sup>-2</sup> .K <sup>-1</sup> ]
		E	elastic modulus [Pa]
		$\varepsilon$	admissible elastic limit [-]
		$\sigma_{elas}$	elastic strain [Pa]

### REFERENCES

- PAN Z., SINGH R. P. Physical and thermal Properties of Ground Beef During Cooking. *Lebensm.-Wiss. u.-Technol.*, 34, 437-444, 2001.
- OGUNJIMI L.A.O., AVIARA N.A., AREGBESOLA O.A. Some engineering properties of locust bean seed. *Journal of Food Engineering* 55, 95-99, 2002.
- ZURITZ C.A., Mc COY S.C., SASTRY S.K. Convective Heat Transfer Coefficients for Irregular Particles Immersed in Non-Newtonian Fluid During Tube Flow. *Journal of Food Engineering*, 11, 159-174, 1990.
- ZITOUN K.B., SASTRY S.K.. Convective Heat Transfer Coefficient for Cubic Particles in Continuous Tube Flow Using the Moving Thermocouple Method. *Journal of Food Process Engineering*, 17, 229-241, 1994.
- GRABOWSKI S., RAMASWAMY H.S., Characterization of single particle tube-flow behaviour at elevated temperatures. *Journal of Food Process Engineering*, 18, 343-361, 1995.
- OJAYI O.A., CLARK B. High velocity impact of maize kernels. *Journal of Agricultural Engineering Research*, 67, 97-104, 1997.
- ABU-GHANNAM N. Modelling Textural Changes During the Hydratation Process of Red Beans. *Journal of Food Engineering*, 38, 341-352, 1998.
- SHITANDA D., NISHIYAMA Y., KOIDE S. Compressive strength properties of rough rice considering variation of contact area. *Journal of Food Engineering*, 53, 53-58, 2002.
- SASTRY S.K, SALENGKES S. Ohmic heating of solid-liquid mixtures: a comparison of mathematical models under worst-case heating conditions. *Journal of Food Engineering*, 21, 441-458, 1998.
- DE ALWIS A.A.P, HALDEN K., FRYER P.J. Shape and conductivity effects in the ohmic heating of foods. *Chem Eng Res Des*, 67, 159-167, 1989.
- PALANIAPPAN S., SASTRY S.K. Electrical conductivities of selected solid food during ohmic heating. *Journal of Food Process Engineering*, 14, 231-236, 1991.
- FRYER P., Zhang L. Electrical resistance heating of foods, *Trends in Food Science and technology*, 4, 364-369, 1993.
- ABHAYAWICK L., LAGUERRE J.C., TAUZIN V., DUQUEMOY A. Physical properties of three onion varieties as affected by the moisture content. *Journal of Food Engineering*, 55, 253-262, 2002.
- MENG G-T., MA C.-Y. Thermal properties of Phaseolus angularis (red bean) globulin. *Food Chemistry*, 73, 453-460, 2001.
- BIMBENET J.-J., LONCIN M. Bases du génie des procédés alimentaires, Paris: Ed. Masson, 248-250, 1995.
- MARTENS T., Mathematical model of heat processing in flat containers. Ph. D thesis. Katholieke Univ., Leuven, Belgium, 1980

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