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ABSTRACT

Since 1988, when the first experiments with the Instantaneous Controlled Pressure Drop (DIC) process were performed, a lot of investigations have been carried out concerning the structure expansion, processing kinetics (drying, extraction and sterilization) and the improvement of the functional and organoleptic properties of fresh and dried foods. In this study, two DIC technologies were used to expand the structure of green coffee beans. Two varieties of commercial Arabica coffee beans of different agricultural and geographical origins (Brazilian and Ethiopian) were inspected. The effect of initial moisture content (7–40% dry basis), type of heating in the DIC process (steam and microwaves), processing parameters like pressure (0.4–0.7 MPa) and heating time (20–200 s) on bean expansion were investigated. The expansion was evaluated as the ratio of the tapped density of raw beans to that of the treated material. The hydration capacity of the beans was also studied. The Response Surface Methodology was employed to optimize the processing parameters. After the steam DIC treatment, the maximum expansion ratio of the Brazilian beans (e = 1.74) was higher than that of the Ethiopian beans (e = 1.59). For Brazilian beans, the steam DIC treatment resulted in a higher value of expansion ratio than the MW DIC treatment (e = 1.39). Concerning hydration capacity, the steam DIC treatment gave values of 78.6% and 48.2% d.b. for the Ethiopian and Brazilian beans, respectively. It means almost two-fold increase in the hydration capacity using DIC treatment. The steam DIC treatment increased and accelerated in twice the weight loss of beans during roasting.

Industrial relevance: Preliminary experiments have shown that the structure expansion of green coffee beans significantly reduced the roasting time, amended the bean suitability to grinding and improved the kinetics and yield of caffeine and active compounds extraction. The industrial DIC processes can be distinguished by high quality of final products, energy saving and positive environmental impact. Due to the fragile structure of coffee beans, a batch process should be applied. Industrial plant can be designed as a tower plant with several compartments separated by guillotine valves where the material falls down by gravity force or a carrousel or a linear plant with filling, DIC treatment and discharging operations. The ABCAR DIC Process Company (La Rochelle, France) develops plants with a capacity of 50 kg/h to 8 ton/h of dry coffee beans. Despite the promising experimental results concerning microwave DIC technology, the industrial applications are so far limited to the steam DIC treatment due to technical reasons.

1. Introduction

Coffee is cultivated in about 80 tropical countries, but the world's top producers are Brazil, Colombia, Ethiopia and Vietnam. There are at least 20 species in the genus *Coffea*, but only two of them, Arabica (*Coffea arabica*) and Robusta (*Coffea canephora*), are consumed throughout the world.

Coffee is composed of more than 900 components (Grattini, 1993). The major ingredient in coffee is sugars (49%), followed by fats (19%), water (11.6%), proteins (11%), minerals, vitamins and acids (7%), no nutritious components (1.5%) and free amino acids (0.8%). The chemical composition of coffee varies according to the botanical variety, climate conditions, maturation grade and the technological process used.

The quality of coffee is determined in the first place by its aroma (Franca, Mendonça, & Oliveira, 2005; Farah, Monteiro, Calado, Franca, & Trugo, 2006). The quality of the beans depends on plant genetics, the soil and the climate. Along with the roasting process, these factors have an important effect on the differences in taste between the many varieties of coffee (Illy, 2002). Roasting is generally conducted by heating the beans at a temperature of between 185 and 240 °C for 90 s to 40 min. Several parameters can be used as indicators to determine the degree of roasting, such as: flavour, aroma, colour, bean's temperature, pH, chemical composition, bean pop, mass loss, gas composition and volume (Hernández, Heyd, Irles, Valdovinos, & Trystram, 2007). The characteristic of flavour and aroma results from the combination of the compounds produced by the reactions

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that occur during roasting (Oosterveld, Harmsen, Voragen, & Schols, 2003).

A lot of information is available concerning the optimization of the roasting parameters to maximize the aroma and flavour, but information concerning the effect of the physical properties of the raw beans on the roasting results is scarce. The impact of roasting conditions on microstructure of roasted beans was studied by Schenker, Handschin, Frey, Perren and Escher (2000). The pore structure controls mass transfer during roasting. It is evident that any improvement of the beans' physical properties prior to roasting will improve the final coffee quality (Sarrazin, Le Quéré, Gretsch, & Liardon, 2000).

The Instantaneous Controlled Pressure Drop (DIC) process seems to be a good means to modify the structure of raw beans to obtain a better quality of roasted coffee. This process has proven its ability to expand the structure of different products (Rezzoug, Maache-Rezzoug, Mazoyer, Jeannin, & Allaf, 2000; Haddad, Louka, Gadouleau, Juhel, & Allaf, 2001). Louka and Allaf (2002) improved the drying kinetics of expanded potatoes. Expanded structure of green beans can make the caffeine more available for supercritical fluid extraction used for coffee decaffeination (Brunner, 2005). It can also have a favourable effect on the evolution of carbon dioxide and vapour during roasting (Geiger, Perren, Kuenzli, & Escher, 2005).

Instantaneous controlled pressure-drop consists in heating wet material in an autoclave for a short period of time with saturated steam or microwaves, followed by a rapid expansion to a final pressure lower than 10 kPa. The vapour that is produced from the superheated liquid mechanically strains the material. This stress creates a porous structure, breaks the cell walls and also destroys microorganisms. The exposure of material to a high temperature is limited to a short heating period, after which the temperature decreases rapidly during the expansion and adiabatic auto-vaporization. Hence DIC is suitable for the treatment of thermo-sensitive materials.

The aim of this paper is to present DIC process based on two different sources of product heating. Saturated vapour was used in the first process as the heating medium. The electromagnetic energy (microwaves) was applied as the bulk heat source in the second DIC process. The effect of the DIC processes on the structure expansion ratio of green coffee beans was studied. This investigation was confirmed with the measurement of hydration capacity and structure visualization using a scanning electron microscope of the DIC treated beans. The response surface methodology was applied in order to estimate the optimum DIC parameters (pressure, heating time and initial moisture content). The effect of the modified bean structure on the degree of roasting (expressed in % weight loss) was also studied.

2. Experimental part

2.1. Experimental set-up

Two different DIC set-ups were used. Coffee beans were heated using saturated vapour in a steam DIC and using microwaves in a MW DIC.

The steam DIC set-up is shown in Fig. 1. It consists of an autoclave (1), a reservoir under a vacuum (2), a water ring vacuum pump (3) and a trap (4). The 18 L autoclave was separated from the 1600 L reservoir by a butterfly valve (V2) with a diameter of 180 mm. This valve was driven pneumatically. Saturated vapour (S1) was supplied through the valve (V1) into the autoclave. The autoclave double jacket was heated by saturated vapour (S2). The autoclave was equipped by a vent (V3). The reservoir was cooled by tap water (W1) circulating in a double jacket. The autoclave and reservoir were equipped with manometers and pressure transducers. Several thermocouples were mounted in the autoclave for temperature measurements of treated material and steam. Pressures and temperatures were recorded by a PC computer. The treated material was enclosed in one perforated steel container with a diameter of 175 mm. The height of the bean layer was about 20 mm. Condensate was removed from the reservoir through the trap (4) equipped with a system of valves.

The DIC process involves several steps. A typical temperature and pressure history of the steam DIC process is shown in Fig. 2. A sample was placed in the autoclave at atmospheric pressure (a) and the autoclave was closed. By opening of the valve (V2) an initial vacuum was created (b), which made the material more accessible for steam. After closing (V2), saturated steam was injected into the autoclave (c) and a selected pressure (0.4–0.7 MPa) and corresponding temperature (143.6°–165 °C) was maintained manually during the heating period (d) by the valve (V1). After this period, an abrupt pressure drop

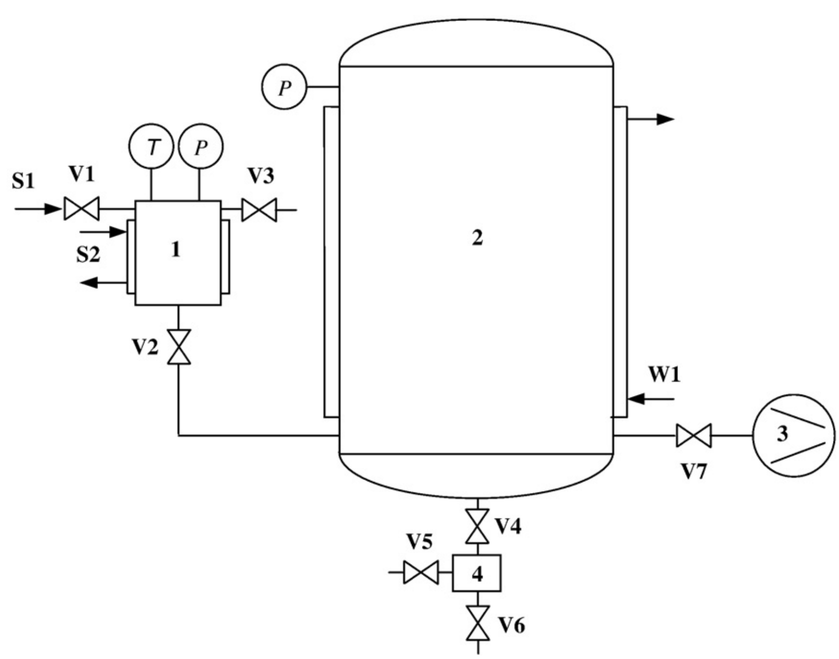

Fig. 1. Steam DIC set-up. 1 — autoclave, 2 — vacuum tank, 3 — vacuum pump, 4 — trap, V1–V7 — valves, S1, S2 — saturated vapour, W1 — cooling water, P — pressure gauge, T — thermocouples.

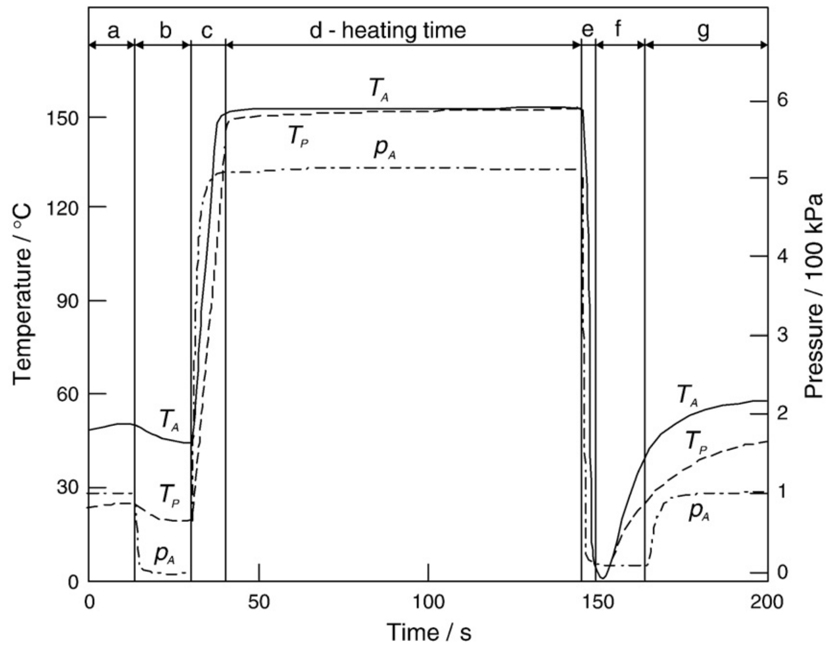

Fig. 2. Temperature and pressure history of steam DIC. p_A pressure in autoclave, T_A temperature in autoclave, T_P temperature of product, (a) sample at atmospheric pressure; (b) initial vacuum; (c) saturated steam injection to reach the selected pressure; (d) constant temperature corresponding to saturated steam pressure; (e) abrupt pressure drop towards vacuum; (f) vacuum; (g) releasing to the atmospheric pressure.

towards a vacuum (about −0.5 MPa/s) was carried out (e) by rapid opening (less than 0.2 s) of the valve (V2). This abrupt adiabatic pressure drop provoked auto-vaporization of superheated liquid contained in the material, instantaneous cooling, structure swelling and even rupture of the cell walls. The vacuum lasted for a short time (f). Finally, atmospheric pressure was restored in the autoclave by the vent (V3) and the material was recovered (g). The pressure in the reservoir (2) was almost constant and equal to 4 kPa. The processing parameters were heating time (d), pressure in the autoclave during the heating period and moisture content of the beans. The moisture content was adjusted by soaking the dry beans in water.

The MW DIC set-up is shown in Fig. 3. The material was heated in a Pyrex tube (1) which was placed in a multimode cavity (2). The tube was closed by a pneumatically moved piston 3. A pressure safety valve (*SV*) kept the pressure at a constant level during the whole period of microwave-heating. The tube (1) was connected with an expansion chamber (5) through a valve (4). The vapour was condensed in a U tube (6) with a double jacket cooled by tap water. A reservoir under a vacuum (8) was connected to the condenser through a series of filters (7). A vacuum pump (9) installed a pressure of about 1 kPa. Microwaves with a frequency of 2.45 GHz were generated by a magnetron (10) with a maximum power of 6 kW. They were transmitted by means of two wave-guides equipped with circulators (11) and automatic impedance adapters (12) into the cavity (2). The Pyrex tube had an inside diameter of 42 mm and a length of 300 mm. The maximum allowable pressure in the tube was 1 MPa. The volumes of the tube, expansion chamber and reservoir were 0.5, 9 and 300 L, respectively.

The MW DIC treatment was as follow. Material was loaded in the tube (1) through the upper orifice and the tube was closed by the piston (3). A pressure of 0.6 MPa was installed in the tube using compressed air (A1) and held constant. The microwaves with energy 600 W were applied on the material for a selected period. The temperature of the material in the tube during DIC cycle was not measured due to several technical reasons. After the heating period, the valve (4) was rapidly opened and the material was projected into the expansion chamber (5). The final pressure in the system was 5 kPa. The material was recuperated from this chamber by means of an opening at the bottom. The processing parameters were heating time and moisture content of the beans.

2.2. Methods of analysis

The tapped density of beans was calculated from the volume measured using a graduated 100 cm^3 cylinder. A sample with a known mass (about 5 g) was put into the cylinder and covered with

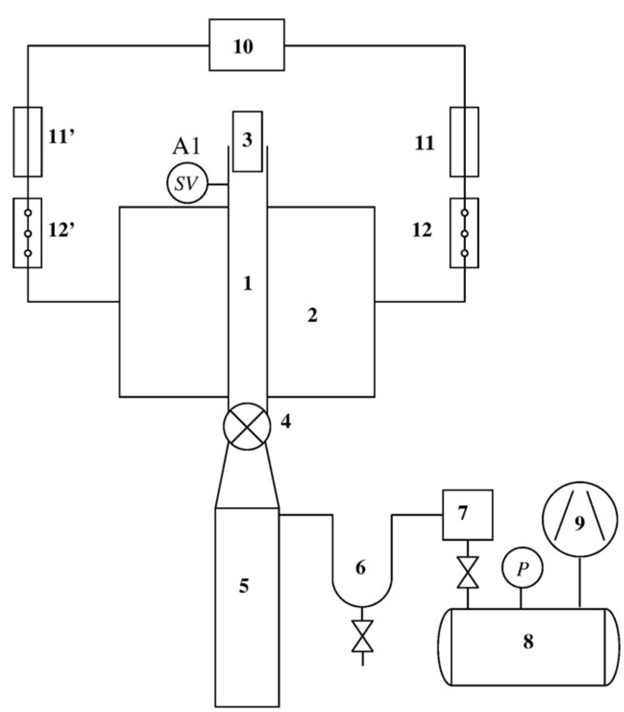

Fig. 3. Microwave DIC set-up. 1 — Pyrex tube (heating chamber), 2 — multimode cavity, 3 — piston, 4 — spherical valve, 5 — expansion chamber, 6 — condenser, 7 — filters, 8 — vacuum tank, 9 — vacuum pump, 10 — magnetron, 11, 11′ — circulators, 12, 12′ — impedance adapters, A1 — pressure air, *SV* — safety valve, *P* — pressure gauge.

Table 1
Physical characteristics of the raw coffee beans

Physical property	Brazilian beans	Ethiopian beans
Approximate size ($h\times l\times w$) mm	3.6×9×7	3.8×7.5×6.3
Colour *	Deep green	Green
Tapped density ρ kg/m^3	1200±5**	1180±5
Moisture content m % d.b.	7±0.2	11±0.2
Hydration capacity h in % d.b. after 30 min immersion.	32.4±0.2	40.8±0.2

* naked eye observation, ** 95% confidence interval for the mean.

sand (ρ=1.59 g/cm^3). The sand was then tamped for one minute on an Autotap Quanta Chrome vibrator operating at 230 rpm. The total volume and mass were then measured. The expansion ratio, e, is equal to the density of raw beans divided by the density of treated beans.

Hydration capacity was determined by immersion of treated beans in distilled water at room temperature. Samples were weighed at several intervals (1, 2, 3, 4, 5, 10, 20, 30, 40, 50 and 60 min). Hydration capacity, h, was expressed as the water mass after 30 min of immersion divided by the dry mass.

Degree of roasting was indicated by total weight loss (W_T) which is expressed as the percentage of dry weight loss of coffee beans as follows:

$$W_T(\%) = 100(W_I - W)/W_I, \tag{1}$$

where W_I and W are the weight of coffee samples before and after roasting.

Roasting was performed using a laboratory air circulating oven (Air Concept FirLABO AC 60, France) at a constant temperature of 215 °C during 2, 15 and 29 min in order to simulate light, medium and dark roasting (Oosterveld et al., 2003, Sarrazin et al., 2000). About 40 g of non-treated and DIC treated coffee beans were placed on stainless steel nets in a single layer. For each sampling step, two nets were withdrawn from the oven and cooled with compressed air to stop the pyrolysis reactions. Roasted coffee samples were stored in sealed containers at ambient temperature for a maximum period of 24 h before the analysis of weight loss.

Moisture content, m, was expressed as a percentage of a dry weight basis. The initial moisture content of raw beans was determined by the oven method following the ISO 6673-1983 (E) standard. The moisture content of hydrated samples was measured by means of a Mettler Toledo LJ 16 moisture analyser at 105 °C.

To observe structural changes in the beans, scanning electron micrographs were taken using a Philips Quanta 200 ESEM/FEG scanning electron microscope working under a pressure of 110 Pa and with an accelerating voltage of 20 kV.

2.3. Samples

Two brands of commercial grade Arabica raw coffee beans were investigated in this work. Coffee beans of Brazilian (Sofedis production, Boulanger) and Ethiopian origin were purchased from local markets. The physical properties of the beans are shown in Table 1.

2.4. Experimental design

The saturated steam pressure, processing (heating) time and initial moisture content of the material were the variable parameters of the steam DIC process used with the Brazilian beans. Response surface methodology was used to optimize these parameters. This methodology is commonly used for the experimental design (Varnalis, Brennan, MacDougall, & Gilmour, 2004; Rezzoug et al., 2000). Statgraphics Plus software was used for experimental design and data treatment. After preliminary experiments, a full central composite design with the three variables and eight replicates at the central point, i.e. a total of 22 experiments, was employed to evaluate the effect of steam DIC treatment on the expansion ratio and hydration capacity of Brazilian coffee beans. The experimental design is presented in Table 2.

The experimental design for steam DIC treatments of Ethiopian beans were carried out at two initial moisture contents level (m=11 and 28% d.b.). The experimental design with three replicates at the central point was generated by varying the steam pressure and heating time (Table 3).

The MW DIC process was only used with the Brazilian beans. The investigated parameters were initial moisture content and heating time, while the pressure was held constant at 0.6 MPa. The experimental design with 11 points is shown in Table 4.

3. Results and discussion

The Brazilian beans were treated by steam DIC according to the experimental design. The results, i.e. the expansion ratio and hydration capacity after 30 min of immersion, are shown in Table 2. The effect of the processing parameters on the expansion ratio is shown in Fig. 4. The expansion ratio increased with increasing pressure and initial

Table 2
Experimental design and results for steam DIC treatment of Brazilian coffee beans

No.	p (MPa)	m (% d.b.)	t (s)	ρ (kg/m^3)	h (% d.b.)	e
1	**0.55**	**18.5**	**75**	**890**	**42.4**	**1.35**
2	0.55	29.4	75	750	58.4	1.60
3	0.46	12	101	910	47.2	1.32
4	0.46	25	101	860	46.6	1.40
5	0.46	25	49	1060	44.7	1.13
6	**0.55**	**18.5**	**75**	**890**	**54.4**	**1.35**
7	0.55	18.5	119	870	43.43	1.38
8	**0.55**	**18.5**	**75**	**900**	**56.9**	**1.33**
9	0.55	7.6	75	940	47.9	1.28
10	0.4	18.5	75	890	47.5	1.35
11	0.46	12	49	910	51.5	1.32
12	**0.55**	**18.5**	**75**	**870**	**41.9**	**1.38**
13	0.64	12	101	900	47.9	1.33
14	0.64	25	101	810	51.9	1.48
15	**0.55**	**18.5**	**75**	**890**	**46.9**	**1.35**
16	**0.55**	**18.5**	**75**	**880**	**47.9**	**1.36**
17	**0.55**	**18.5**	**75**	**870**	**46.4**	**1.38**
18	0.55	18.5	31	1090	59.6	1.10
19	**0.55**	**18.5**	**75**	**890**	**46.4**	**1.35**
20	0.7	18.5	75	870	49.4	1.38
21	0.64	25	49	900	52.8	1.33
22	0.64	12	49	940	41.3	1.28

The central point is in bold.

Table 3
Experimental design and results for steam DIC treatment of Ethiopian coffee beans (m=11% and 28% d.b.)

No.	p (MPa)	t (s)	ρ (kg/m^3)		h (%)		e	
			28%	11%	28%	11%	28%	11%
1	**0.6**	**70**	**760**	**790**	**79.6**	**51.9**	**1.55**	**1.49**
2	0.67	91	748	760	85.5	59.7	1.58	1.55
3	0.6	40.3	794	870	73.6	56.0	1.49	1.36
4	0.5	70	771	810	79.4	56.9	1.53	1.46
5	0.53	91	767	780	77.9	59.8	1.54	1.51
6	0.67	49	765	810	80.5	58.2	1.54	1.46
7	**0.6**	**70**	**756**	**790**	**80.1**	**55.7**	**1.56**	**1.49**
8	0.6	99.7	743	780	82.2	58.7	1.59	1.51
9	0.53	49	823	840	76.0	58.7	1.43	1.40
10	0.7	70	774	800	72.0	51.4	1.52	1.48
11	**0.6**	**70**	**765**	**790**	**78.2**	**55.7**	**1.54**	**1.49**

The central point is in bold.

Table 4
Experimental design and results for MW DIC treatment of Brazilian coffee beans

No.	m (% d.b.)	t (s)	ρ (kg/m^3)	h (% d.b.)	e
1	27.5	19.4	990	57.9	1.21
2	33	43	960	54.1	1.25
3	**27.5**	**100**	**960**	**43.1**	**1.25**
4	27.5	180.6	850	50.7	1.41
5	35	100	1000	48.5	1.20
6	33	157	950	46.2	1.26
7	22	157	950	45.3	1.26
8	**27.5**	**100**	**870**	**51.6**	**1.38**
9	22	43	1100	41.7	1.09
10	**27.5**	**100**	**900**	**44.4**	**1.33**
11	20	100	1100	46.7	1.09

The central point is in bold.

moisture content. The dependence on time assumed a maximum. The response surface is described by the relation

$$e = 1.529 - 0.401p - 0.0714m + 0.00976t - 0.271p^2 + 0.000581m^2 - 0.0000675t^2 + 0.0662pm - 0.00374pt + 0.000274mt$$

The significance of the parameters is shown in Fig. 4c. The vertical line on the Pareto chart determines the effects that are statistically significant at the 95% confidence level. The standardized effect is the estimated effect divided by its standard error. Hence a low standardized effect can mean either a low effect of the parameter or a large experimental error. Processing time, t^2, m and $m\ t$ had a significant effect. The effect of pm, m^2 and p was lower. No effect was observed of $p\ t$ and p^2 on the expansion ratio. Time had a positive effect whereas t^2 had a negative influence. This explains the maximum of the time dependence shown in Fig. 4b. The response surface for expansion ratio indicated a maximum of 1.74 for p=0 7 MPa, m=29.4% d.b. and t=1 12s. This means that the tapped density of the treated coffee was 1.74 times lower than that of the raw material.

The standardised effect of all parameters on the hydration capacity of Brazilian beans treated by steam DIC was not significant at the 85% confidence level. Therefore a mean value was only calculated from the hydration capacity data. It is important to note that the mean value of the treated beans (48.8% d.b.) was much higher than that of the non-treated beans (32.4% d.b.).

Initial moisture content and the time of exposure to microwaves were varied in the processing of Brazilian beans using MW DIC. The experimental plan and results are given in Table 4. The variation of the

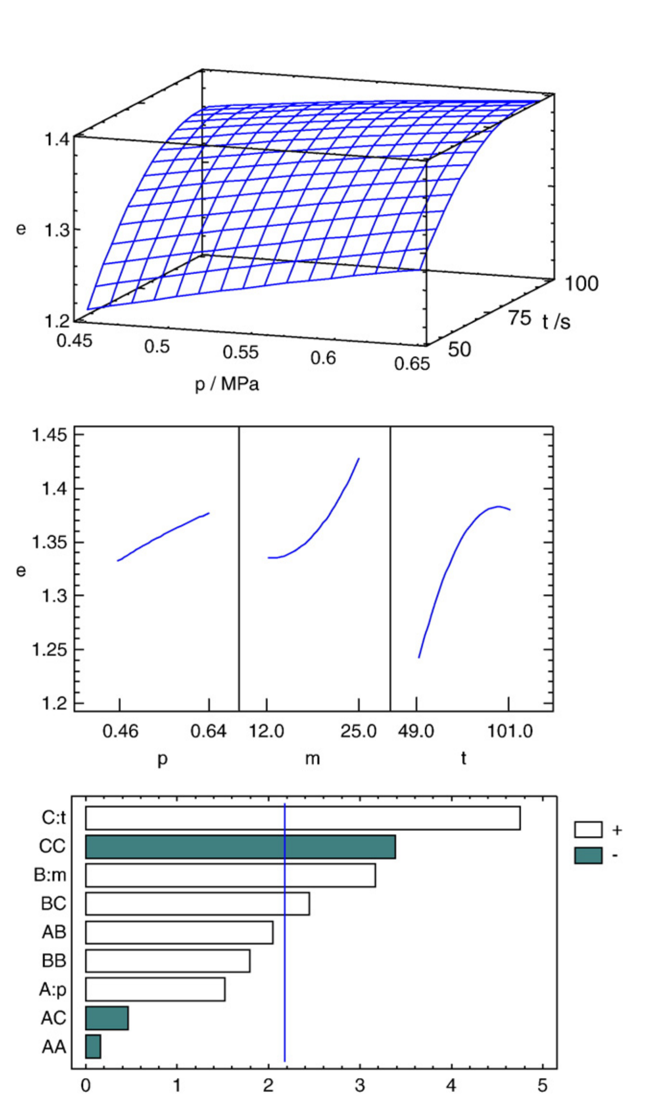

Fig. 4. Expansion ratio of Brazilian beans treated with steam DIC. a) response surface (m=18.5% d.b.); b) main effect of parameters; c) standardized effects.

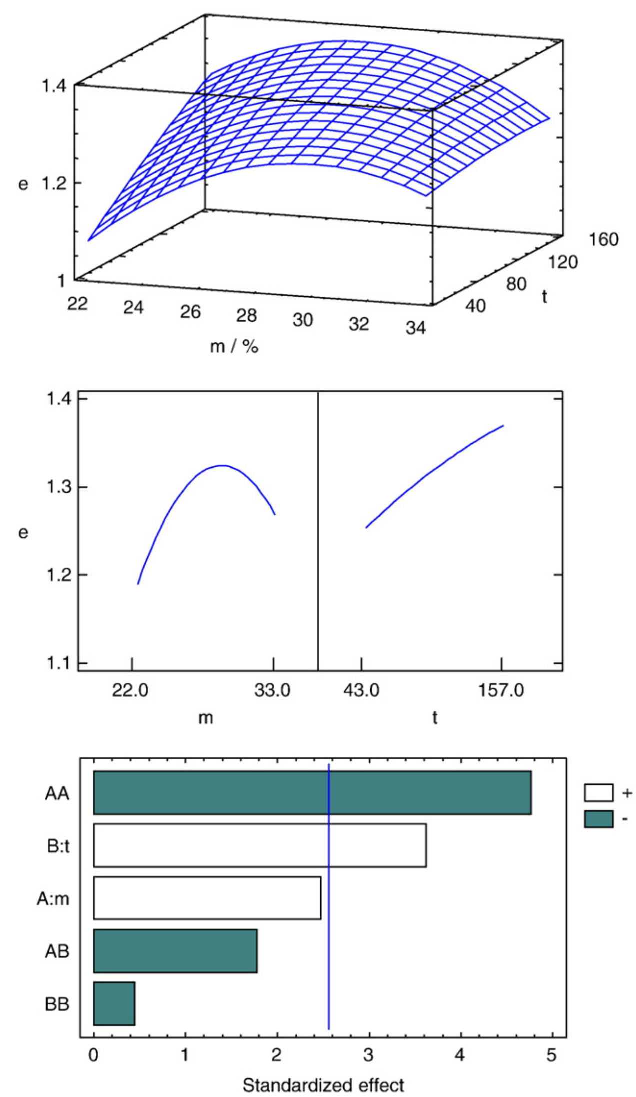

Fig. 5. Expansion ratio of Brazilian beans treated with microwave DIC. a) response surface; b) main effect of parameters; c) standardized effects.

expansion ratio is shown in Fig. 5. The equation of the response surface has a form

$$e = -1.61 + 0.184m + 0.005t - 0.003m^2 + 0.0000025t^2 - 0.000128mt$$

The initial moisture content, its square and time were found to be significant parameters. The expansion ratio increased with time, whereas the dependence on the initial moisture content assumed a maximum. A maximum expansion ratio of 1.39 was found on the surface response for m=27% d.b. and t=181 s. As in the case of steam DIC treatment, only a weak correlation was found between hydration capacity and processing parameters. The mean value of hydration capacity (48.2% d.b.) was similar to that obtained with steam DIC.

The steam DIC treatment gave a higher expansion ratio of Brazilian beans than MW treatment. It can be due to the effect of steam heating on the bean structure. In the case of steam DIC, the air was evacuated at the beginning of the treatment so the beans were in direct contact with saturated vapour. Louka and Allaf (2002) showed that the initial vacuum significantly increases the heat transfer between the steam and material. The MW treatment started with pressurisation by air and partial the pressure of the vapour evolved by microwave heating was lower than in the steam DIC. Another reason for the smaller expansion ratio can be the non-uniformity of material temperature due to non-homogeneity of electromagnetic field (Klima, 2006). A hydration capacity of about 48% d.b. after soaking for 30 min in water at 23 °C confirmed that both treatments increase the bean porosity. It can be supposed that the acquired porous structure will improve downstream processes like caffeine extraction and roasting.

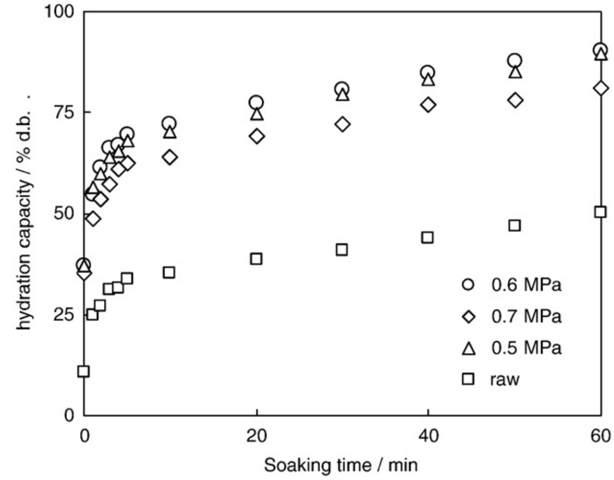

Fig. 7. Hydration capacity as a function of soaking time of Ethiopian beans (m=28% d.b.) treated with steam DIC for 70 s.

The Ethiopian beans were treated only with steam DIC. The effect of time and pressure was investigated for two initial moisture contents (see Table 3). The response surface of the expansion ratio is presented in Fig. 6 for an initial moisture content of 28%. This surface was described by the equation

$$e = -0.379 + 4.67p + 0.0113t - 3.0p^2 - 0.0000171t^2 - 0.00119pt$$

The expansion ratio increased with time and assumed a maximum of the dependence on pressure. Maximal value of 1.59 was found for p=0.58 MPa and t=99.7 s. The hydration capacity as a function of soaking time is shown in Fig. 7 for m=28%. At a pressure of 0.6 MPa, the hydration capacity assumed maximum values. The values of this capacity for 0.7 MPa were lower than for 0.5 MPa. The hydration capacity ratio, i.e. the hydration capacity of treated beans divided by the hydration capacity of raw beans, is shown in Fig. 8 as a function of the expansion ratio. The hydration capacity was found to correlate with the expansion ratio (R^2=0.95). With DIC treatment, the value h for treated beans was twice as high as that of raw beans. This means

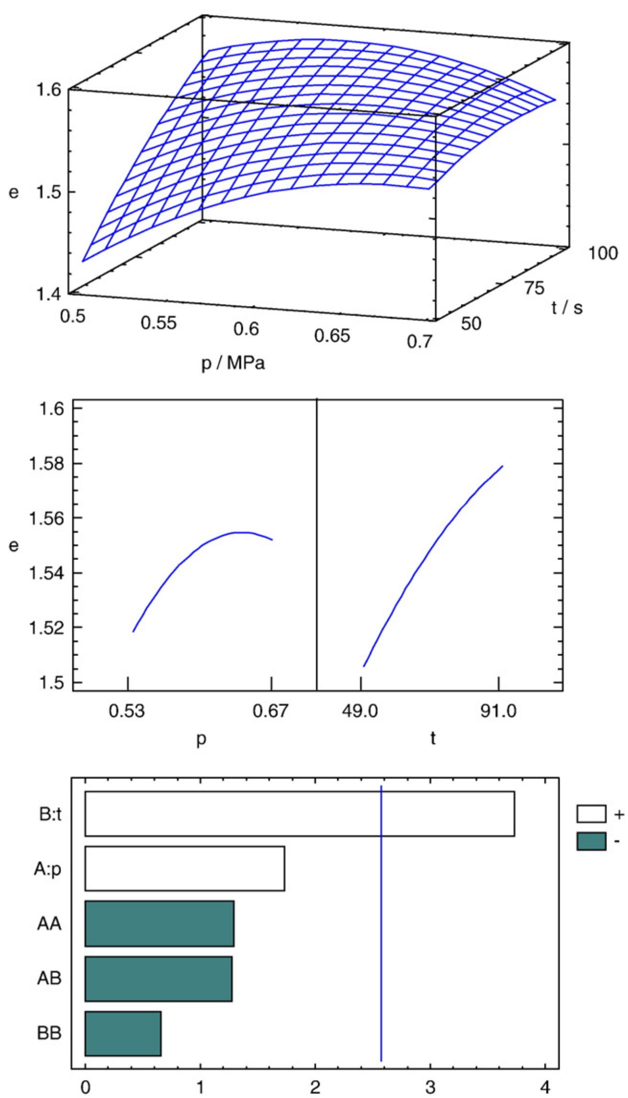

Fig. 6. Expansion ratio of Ethiopian beans (m=28% d.b.) treated with steam DIC. a) response surface; b) main effect of parameters; c) standardized effects.

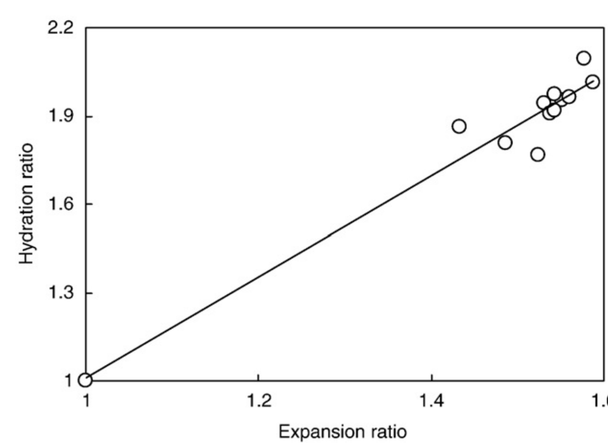

Fig. 8. Hydration capacity ratio as a function of expansion ratio of Ethiopian beans (m=28% d.b.) treated with steam DIC.

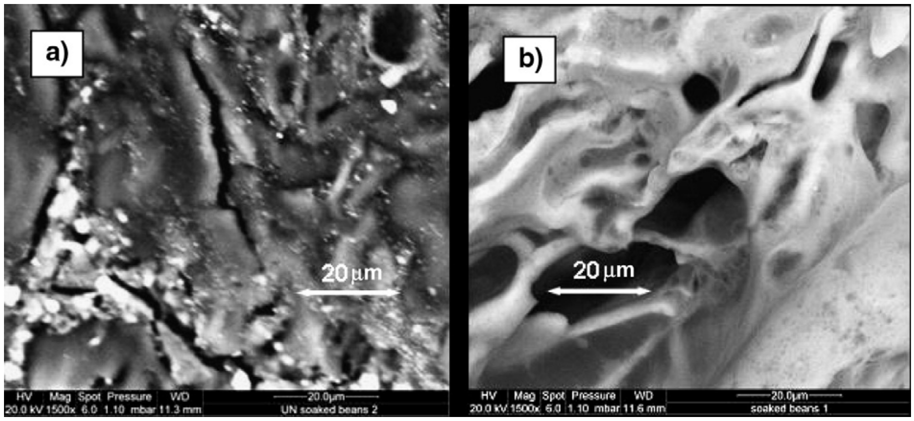

Fig. 9. Micrographs of cross-sections of Ethiopian coffee beans. a) raw bean; b) bean treated with steam DIC, m=28% d.b., p=0.5 MPa, t=35 s.

that the DIC treatment greatly increased the bean's porosity and made the structure more accessible to solvents.

The effect of pressure and time on the tapped density of Ethiopian beans with an initial moisture content of 11% was similar to that reported for 28%. However, the maximum expansion ratio was not so high (1.52 vs. 1.59) and the mean value for hydration capacity was much lower (56.6% vs. 78.6% d.b.).

There are differences between Brazilian and Ethiopian beans in both expansion ratio and hydration capacity. The difference is especially remarkable for hydration capacity. Steam DIC treatment for 70 s (resulted in) gave values of 78.6% and 48.2% d.b. for the Ethiopian and Brazilian beans, respectively. The maximum expansion ratio of the Ethiopian beans (e=1.59) was lower than that of Brazilian beans (e=1.74). The DIC parameters (and their quadratic effect) were also specifics for both beans. A more detailed study of the chemical composition of both beans is necessary.

The structure of beans was studied by electron scanning microscopy. The micrographs of cross-sections of Ethiopian coffee beans cut along the longitudinal axis are shown in Fig. 9. Dark regions represent cavities or pores. The structure of raw bean is compact, with several small pores. Well-defined pores with a diameter of about 10 µm were created by the DIC treatment. Using mercury porosimetry, pores with dimensions of between 5 and 50 µm were found in the soy beans treated with the steam DIC process (Rochová, Sovová, Sobolík & Allaf, 2008).

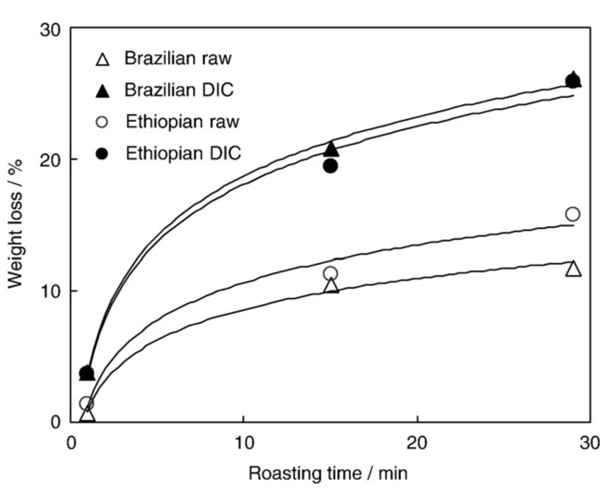

Fig. 10. Weight loss during roasting at 215 °C of Brazilian and Ethiopian beans non-treated and treated by steam DIC at optimum parameters concerning expansion ratio. The lines are the best data fit by logarithmic curves.

Steam pressure had a positive effect on expansion ratio in all the experiments. The temperature of saturated steam is defined by the pressure. The amount of generated vapour depends on the temperature difference of the material before and after pressure-drop. The higher the steam pressure at a given final pressure, the more vapour is generated by self-vaporization and the higher the expansion ratio. The expansion of the structure also depends on the rheological behaviour of the material, namely the temperature and moisture content dependence of the viscosity and the temperature of glass transition. The major components of the cell walls of coffee beans are polysaccharides. These biopolymers, like mannan, arabinogalactan and cellulose, are softened and partially melted during the heating period. Certain heating time is needed for obtaining a uniform temperature in material, equal to the steam temperature. The achievement of viscoelasticity which are essential for the structure modifications requires also certain heating time. They are subjected to the elongational flow induced by the vapour released in the material. The expanded viscoplastic structure is then cooled as a result of the pressure drop and solidified. The presence of water in the flowers is also necessary for the production of vapour during auto-vaporization. The higher the initial moisture content, the more important is the vapour quantity evaporated during the pressure drop and thus the higher is the expansion ratio. The negative effect of quadratic p, t and m signifies that an excessive increasing in p, t and m results the partial or total disintegration of the structure and therefore the decreasing in expansion ratio.

Pittia, Rosa and Lerici (2001) described the high yield roasting as a process where the heat exchange occurs very fast in order to obtain higher volume expansion of the beans owing to a faster pressure increase within the beans. This type of process was claimed to produce a highly porous structure in the bean cell tissues and this should determine a higher extraction yield than traditionally roasted coffee during brewing of ground coffee. By the intervention of DIC process, the bean structure can be modified in a controlled way which could affect the extraction yield of the coffee. The effect of the steam DIC treatment on weight loss of beans during roasting is shown in Fig. 10. The DIC treatment at optimum parameters which gave the highest expansion ratio (for Brazilian beans p=0.7 MPa, t=112 s, m=29.4% d.b., and for Ethiopian beans p=0.58 MPa, t=99.7 s, m=28% d.b.) resulted in twice weight loss in comparison to the raw beans.

4. Conclusions

The present study demonstrated the effect of DIC treatment on the structure of coffee beans. Both systems of heating, i.e. steam and microwaves, expanded the structure and increased the hydration capacity of raw coffee beans. The expansion ratio correlated well with processing parameters like heating time, initial moisture content and saturated steam pressure. At the given conditions, steam DIC had a more pronounced effect on expansion than microwave DIC. The expansion of Brazilian beans was more marked than that of the Ethiopian beans. The hydration capacity of treated beans was about twice as high as that of raw beans. No significant correlation of hydration capacity with the processing parameters was found. The only exception was the steam DIC treatment of Ethiopian beans, where the hydration capacity increased with the expansion ratio. DIC treatment increased and accelerated also the weight loss during roasting. The effect of the DIC treatment on the extraction yield of coffee beans should be studied.

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