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EFFECTS OF AIR PARAMETERS ON CHANGES IN TEMPERATURE INSIDE ROASTED COCOA BEANS*

Wiesława Krysiak, Lidia Motyl-Patelska

Institute of Chemical Technology of Food, Technical University of Łódź
ul. Stefanowskiego 4/10, 90-924 Łódź
e-mail: krysia@snack.p.lodz.pl

A b s t r a c t. Cocoa beans of the Ivory Coast variety were roasted convectively at different temperatures (110, 135 and 150°C), air flow rates (v of 0.5, 1 and 1.5 m s^{-1}) and relative air humidities (*RH* of 0.9-0.3 and 5%). Temperature of selected parts of beans (on their surface, of the layer between the kernel and shell, and inside the kernel) was measured throughout roasting. It was found that in the initial stage of roasting (10-15 min) all the air parameters strongly affected the values of temperature and its profile in all examined parts of beans. In the final stage of roasting, the difference between the temperature of shell and kernel was approximately 2°C, independently from the air parameters.

K e y w o r d s: cocoa bean, roasting, air humidity, temperature of roasted cocoa beans

INTRODUCTION

Roasting is the principal technological unit operation during cocoa processing. Physicochemical reactions occurring inside the beans at elevated temperature change the aroma, colour and texture of cocoa beans [1,6,11-13,15,16,18].

Convective roasting is most commonly applied for thermal processing of cocoa, also in Poland. During this process cocoa beans are brought, for 15-45 min, to a temperature of 130-150°C [9,10,16,17,20]. Also cocoa mill and pulp are roasted [3,4,16,17].

Roasting parameters determine the character of chemical and physical processes occurring inside beans, and thus the quality of ultimate products [7,10,16,18]. Roasting conditions depend on the variety and quality of cocoa, on the cultivation conditions, on-farm (primary) processing after harvesting [5,9,16,19], construction

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and dimensions of roasters, the manner of heating gas supply, the method of shifting of roasted material in a roasting chamber, and on the size of roasted material particles [4,10,16,17].

A significant difference between temperatures of shells and kernels of cocoa beans, approaching 10-12°C, is a disadvantage of the traditional method of whole cocoa beans roasting [3,4,16] (data on process conditions were not included in the cited reports). Such a large gradient of temperature results in heterogenous distribution of generated aroma and taste compounds in roasted material, as well as in insufficient or excessive roast level of different parts of cocoa beans [16]. Excessive time of roasting at high temperature negatively affects the aroma of cocoa, makes it bitter, and generates acroleine which is a product of degradation of triglycerides contained in lipid fraction. Too high temperature of roasting favours the formation of certain substances (e.g. dimethylpyrasine) which are responsible for burnt aroma of cocoa [16,20]. Insufficient roast level does not eliminate all undesired volatile organic acids and water, which hampers further processing. Its another disadvantage is relatively high content of remaining water-soluble tannins, which imparts an unpleasant bitter taste to cocoa [16,20].

Benz [2], who estimated the difference in temperatures of cocoa beans shell and kernel, presented detailed characteristics of raw cocoa beans prior to their debacterization in Buhler reactor (at 120°C) and on its completion. According to this author, the difference between temperatures of kernel and shell approached 30°C, but he did not determine other air parameters except its temperature. Jinap and Dimick [5], who found that upon roasting at 150°C the difference in temperature between shell and kernel ranged from 20 to 2°C, depending on the stage of roasting, also measured only air temperature.

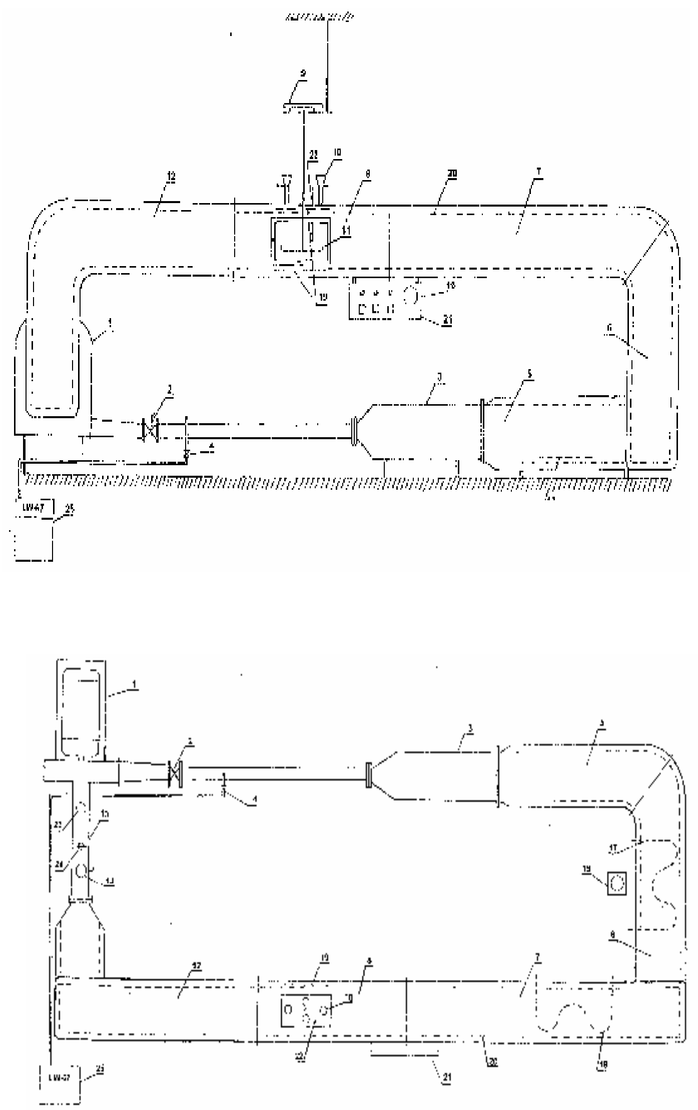
Because of the paucity of reports on the influence of the three principal hot air parameters, i.e. its temperature, rate of flow and relative humidity, on temperature profile inside cocoa beans upon their roasting, we attempted to find the correlation between these quantities.

MATERIALS AND METHODS

Selected cocoa beans (18-24 mm in diameter) of the Ivory Coast variety, derived from Ivory Coast, was the raw material used throughout the studies.

Convective roasting of cocoa beans was conducted in a tunnel with forced air circulation, shown in Figure 1. Parameters of air were as follows:

- temperature of 110, 135, and 150°C,
- rate of flow of 0.5; 1; and 1.5 m s^{-1},
- relative humidity of 0.3-0.9 and 5%.



a)

b)

Fig. 1. Schematic diagram of a tunnel for thermal processing of cocoa beans: a) front viev, b) top viev. 1 – fan, 2 – throttle, 3- heater, 4 – steam supply inlet with a regulating valve, 5 – section of air parameters control, 6 and 7 – sections for equalising air velocity profiles, 8 – measuring section, 9 – balance, 10 – bean batching funnels, 11 – plate, 12 – section of air removing, 13 –recirculated pipe, 14 – air offtaking pipe, 15 and 16 – autotransformers, 17-19 – additional heaters, 20 – insulation, 21 – control panel, 22 – temperature probe (sensor), 23 – pipe with fresh air inlet valve, 24 – valve for air recirculation control, 25 – steam generator

Portions (200 g) of raw cocoa beans were placed on a plate (through a funnel-shaped inlet, which resulted in their uniform monolayer) after stabilizing the roasting conditions inside the roasting chamber.

Prior to cocoa beans loading, the following parameters were determined:

- temperature of air in front of and behind the plate,
- air flow rate,
- relative humidity of air (if the process was conducted at elevated humidity),
- atmospheric pressure,
- temperature on the surface of a single cocoa bean,
- temperature of the interspace between the hull and kernel of a single cocoa bean.

The initial mass of the sample was measured immediately after placing a sample of cocoa beans on the plate inside the roaster. After determined time intervals, e.g. every 2, 5, 10, 20 min, measurements of the mass of roasted cocoa beans, air temperature, temperature of selected parts of a cocoa bean (surface, the layer between shell and kernel, and inside the kernel), air flow rate and its inlet relative humidity, were carried out. Roasting was carried out untill the ultimate water content inside cocoa beans approached approximately 2%. On completion of roasting, the material was taken out of the roasting chamber and cooled for 6-10 min to around 30-35^{o}C using air with temperature of approximately 20^{o}C. Roasted and cooled whole cocoa beans and their separated shells and kernels were analyzed for water content by thermogravimetric method according to the standard PN-A-76101:1998.

Temperature of air and selected parts of cocoa beans was measured with an accuracy of ±1^{o}C using a YC-262 YCY-meter equipped with a NiCr-NiAl probe. Air flow rate was estimated with an accuracy of ±0.05 m s^{-1} using a coupled THERM 2285-2B meter equipped with a 9915 S120 probe.

Relative humidity of „dry" air was calculated using the following formula:

$$RH = 100 \cdot \frac{RH' \cdot P}{0{,}622 \cdot (P_{sat})_{110^0 C} + RH' \cdot (P_{sat})_{110^0 C}}$$

where: RH – relative air humidity (%), RH` – absolute air humidity at 20°C kg H_2O (kg dry air)$^{-1}$; 8729·10^{6} kg H_2O (kg dry air)$^{-1}$, P – pressure of saturated steam (Pa); 101·10^{3} Pa, $(P_{nas})_{110°C}$ – steam pressure at 110°C (Pa), according to „Engineer manual – Sugar industry", 1973 p.52; 143.3·10^{3} Pa .

Air humidity was elevated using saturated steam produced in the steam generator (Fig. 1). Humidity of this air was measured with an accuracy of ±0.5% using a coupled THERM 2285-2B meter equipped with a FHA636-HR2 probe.

Triplicate samples of cocoa beans were roasted in given conditions. Results displayed in figures and tables are means ± standard deviation (the latter did not exceed 3-4%).

RESULTS AND DISCUSSION

Effect of air temperature on changes in temperature inside cocoa beans upon roasting

Figures 2 and 3 exemplify the dependence of temperature of selected parts of cocoa bean on air temperature when roasting was conducted at air temperature of 110 or 135°C, at fixed air flow rate of 1 m s^{-1} and relative humidity of 0.9-0.4% (”dry” air).

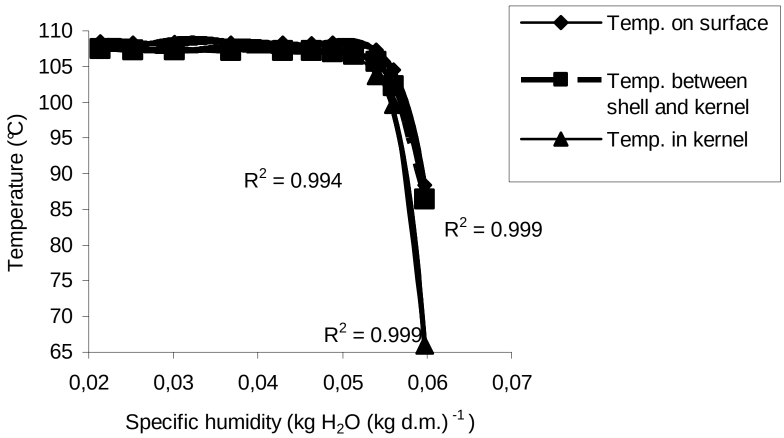


Fig. 2. Changes in temperature of selected parts of cocoa bean roasted for 70 min at 110°C (air flow rate of 1 m s^{-1} and relative air humidity of 0.9%)

Based on results shown in Figures 2 and 3 it was found that for the constant air flow rate of 1 m s^{-1}, the rate of increase in temperature of the selected parts of beans depended on air temperature. This finding was consistent with earlier reports on relationships between air temperature, roasting time and physicochemical properties of roasted cocoa [3,5,7,10,16].

Our experiments showed that air temperature affected the temperatures of cocoa bean kernel and the layer between kernel and shell. It was observed that at higher air temperatures, the difference between temperatures of kernel and the adjacent layer was greater prior to a drop in the specific humidity to 0.05 kgH_2O (kg d.m.)$^{-1}$ of cocoa beans. During further stages of roasting, this temperature gradient was reduced, but the higher was the air temperature the greater were the differences in temperature of the examined parts of cocoa beans (Fig. 2 and 3, Tab. 1). This shape of curves indicated that at higher temperatures of roasting, i.e. at 135 and 150°C, the empty gap between kernel and shell was formed faster. This phenomenon is advantageous because it facilitates shell removal. Furthermore, quicker formation of the empty gap hampers migration of lipids to the shell, which is very desirable because of lesser losses of valuable cocoa lipids [8].

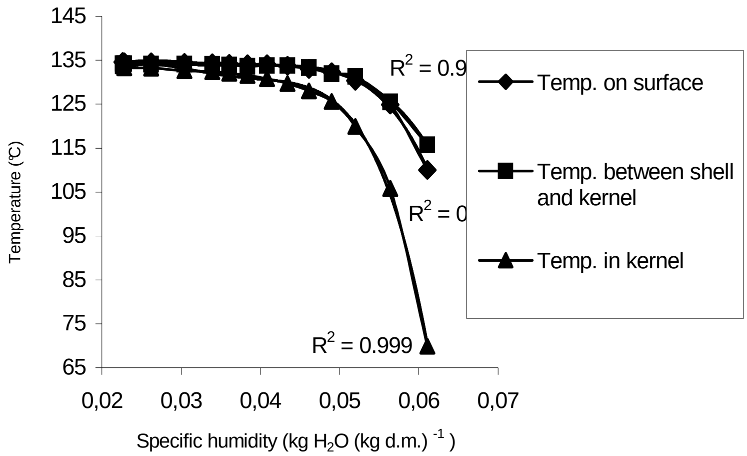


Fig. 3. Changes in temperature of selected parts of cocoa beans roasted for 35 min at 135°C (air flow rate of 1 m s^{-1} and relative air humidity of 0.4%).

Table 1. Differences between the temperature of air used to roast cocoa beans and (a) temperature of their surface (T_1), (b) temperature of the layer between shell and kernel (T_2), and (c) temperature of the kernel (T_3)

Process parameters		Temperature		
Air flow rate (m s^{-1})	Time of roasting (min)	T_1 (°C)	T_2 (°C)	T_3 (°C)
Temperature of 110°C; *RH* of 0.9%				
0.5	0.08	19.7	36.2	55.0
	10	2.2	4.1	5.8
	30	1.1	2.7	3.4
	80	0.9	2.3	2.6
	100	0.3	1.8	2.2
1.0	0.08	23.5	18.6	32.5
	10	2.7	3.8	4.1
	30	1.7	2.8	2.7
	70	1.5	2.5	2.5
1.5	0.08	19.8	28.0	52.8
	10	1.7	3.5	4.9
	30	1.5	2.7	3.1
	70	0.5	1.8	1.8

Table 1. Cont.

	Temperature of 135°C; *RH* of 0.4%			
0.5	0.08	36.2	43.9	76.3
	10	2.9	3.9	8.2
	30	1.1	2.1	3.2
	50	1.0	2.0	2.7
1.0	0.08	19.3	25.0	65.2
	10	1.3	2.5	5.3
	30	0.3	2.0	2.3
	35	0.2	1.8	1.7
1.5	0.08	36.9	42.6	54.2
	10	0.6	2.8	3.1
	30	0.4	2.5	2.2
	35	0.2	2.1	1.8
	Temperature of 150°C; *RH* of 0.35%			
0.5	0.08	33.9	47.7	80.2
	10	1.6	4.6	7.9
	20	0.5	2.5	3.8
	25	0.5	2.2	3.2
1.0	0.08	39.8	56.8	68.6
	10	4.6	4.5	5.2
	20	2.1	2.2	2.3
1.5	0.08	39.2	39.1	61.0
	10	2.0	3.8	4.8
	20	1.1	2.4	2.4

Effect of air flow rate on changes in temperature inside cocoa beans upon roasting

Effects of different air flow rates on temperatures of the kernel and the layer between kernel and shell were estimated at three different air temperatures and the air humidities range of 0.9-0.35% (“dry” air). Relationships between these quantities for air temperature of 135°C, its humidity of 0.4%, and three different flow rates are presented in Figures 4 and 5.

Presented curves provide evidence that air flow rate also had a strong impact on the rate of increase in temperature of both examined parts of the cocoa bean. Like in case of temperature, also a rise in the rate of air flow markedly increased the temperature of the examined parts of cocoa beans, particularly in the early stage of roasting. When the specific humidity of cocoa beans reached 0.055 kgH_2O (kg d.m.)$^{-1}$, the effect of air flow rate on the rate of increase in temperature of examined bean parts was negligible, particularly in the case of the kernel (Fig. 4, 5).

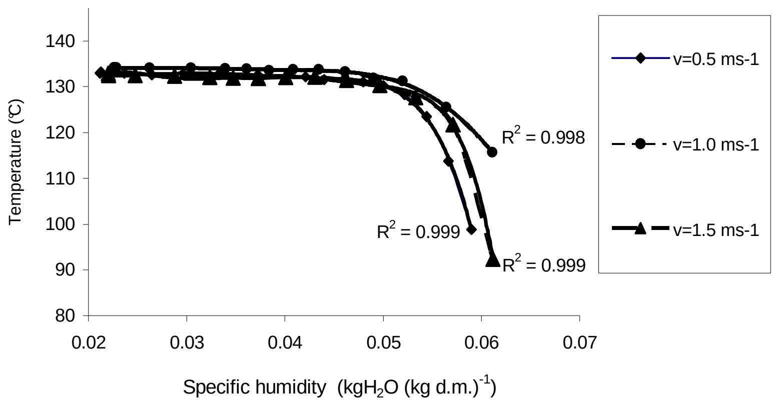


Fig. 4. Changes in temperature between the kernel and shell in cocoa beans roasted at T = 135°C; RH = 0.4%

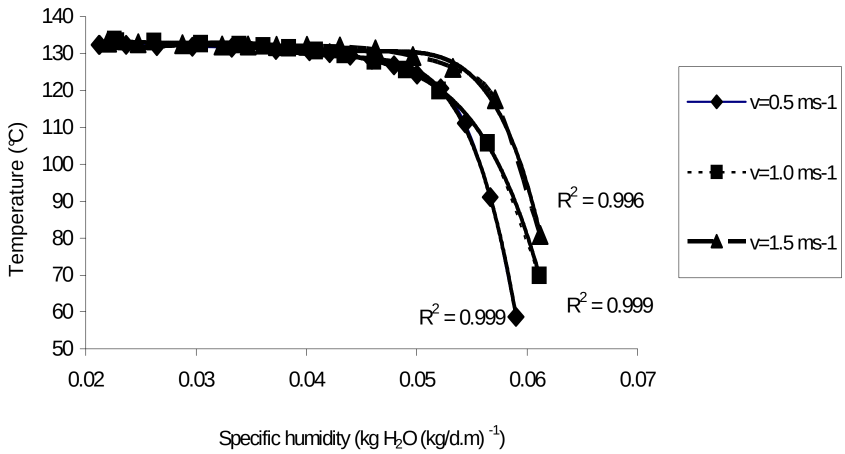


Fig. 5. Changes in temperature in the kernel in cocoa beans roasted at T = 135°C; RH = 0.4%

Estimation of the relationship between air flow rates and differences between temperatures of the kernel and the layer between the kernel and shell was also of importance because it could facilitate determination of the moment when empty gap between the kernel and shell is formed.

Table 1 displays results of measurements of differences in temperatures of hot air, the surface of beans being roasted, the layer between shell and kernel, and kernel. In Table 1, T_1 is the difference in temperatures of air used for roasting and surface of beans upon roasting, T_2 is the difference in temperatures of air used for roasting and the layer between shell and kernel, and T_3 is the difference in temperatures of air and a kernel of cocoa bean.

It was found (based on relatively high differences in measured temperatures) that at air flow rate of 0.5 m s^{-1} in the initial stage of roasting (up to 10 min) the rise in temperature of both the kernel and the layer between the latter and shell was relatively slow, independently from the temperature of roasting. In further steps of roasting these differences in temperatures continued to decrease, and in the final stage they were at the level of 2^{o}C (±0.3^{o}C), independently from the temperature and air flow rate. Our results are consistent with that of Jinap and Dimick [5].

A similar relationship was also observed for air flow rates of 1 and 1.5 m s^{-1}, however, at these rates the differences in examined temperatures were lesser in the early stage of roasting, but in the final step they were of the same range as for air flow rate of 0.5 m s^{-1}.

Data collected in Table 1 show that differences in T_3 and T_2 were very small when cocoa was roasted at 110^{o}C, independently from the air flow rate. It provides evidence that there was no empty gap between kernel and shell. When cocoa was processed at 135 and 150^{o}C, these differences were significantly higher, which suggested that the empty gap was formed relatively quickly. The latter process is termed the „baloon effect" [4,17].

Results collected in Table 1 and in Figure 4 and 5 indicate that independently from the air temperature, cocoa roasting at air flow rate above 1 m s^{-1} is groundless.

Influence of relative air humidity on changes in temperature inside cocoa beans upon roasting

The third examined parameter, i.e. the relative air humidity, is also one of the most important roasting parameters. Earlier investigations showed that elevated *RH* had a beneficial effect on debacterization of cocoa beans [2, 4, 6]. Enhanced air humidity can be achieved by means of using for roasting so-called circulating air which contains some moisture [16].

Figures 6-9 exemplify temperature profiles of the examined parts of cocoa beans upon their roasting in the atmosphere of air with different levels of humidity (*RH* of 0.97-0.30% and 5%). Presented curves prove that independently from the air temperature and the part of cocoa bean (kernel, shell), in the initial part of the process (up to 10-15 min) conducted at elevated *RH*, humidity is easily adsorbed by beans. This process was intensified at higher air temperatures. Furthermore, the temperature of kernel was slightly (by 2-3^{o}C) increased when *RH* was 5%. Arguably, it resulted from slightly longer time of roasting as compared to that of roasting in "dry" air.

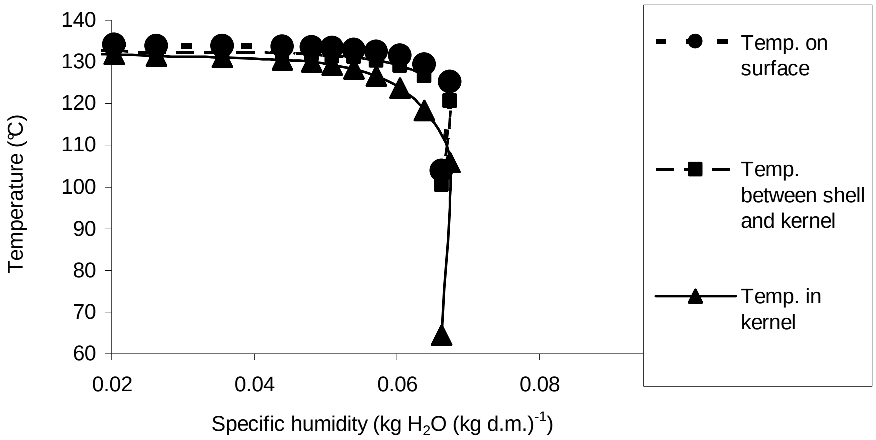


Fig. 6. Changes in temperature of selected parts of cocoa bean roasted for 50 min at 135°C (air flow rate of 1 m s^{-1} and relative air humidity of 5%)

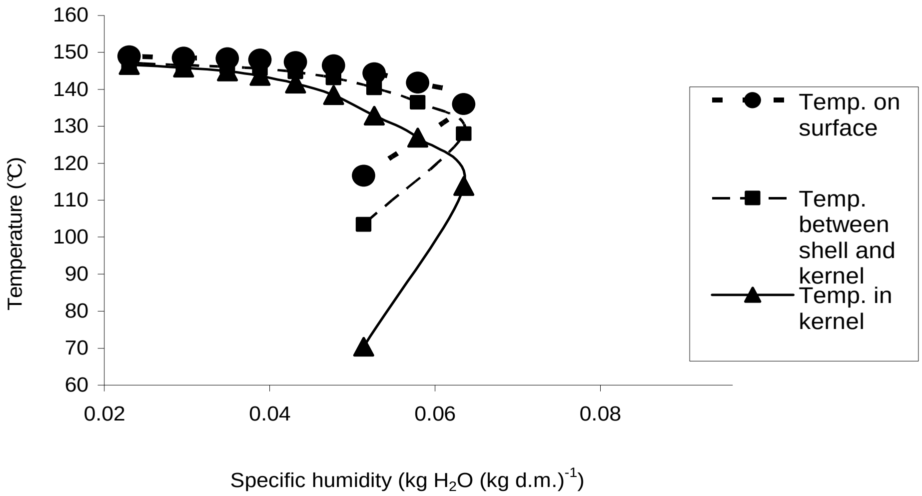


Fig. 7. Changes in temperature of selected parts of cocoa bean roasted for 20min at 150°C (air flow rate of 1 m s^{-1} and relative air humidity of 5%).

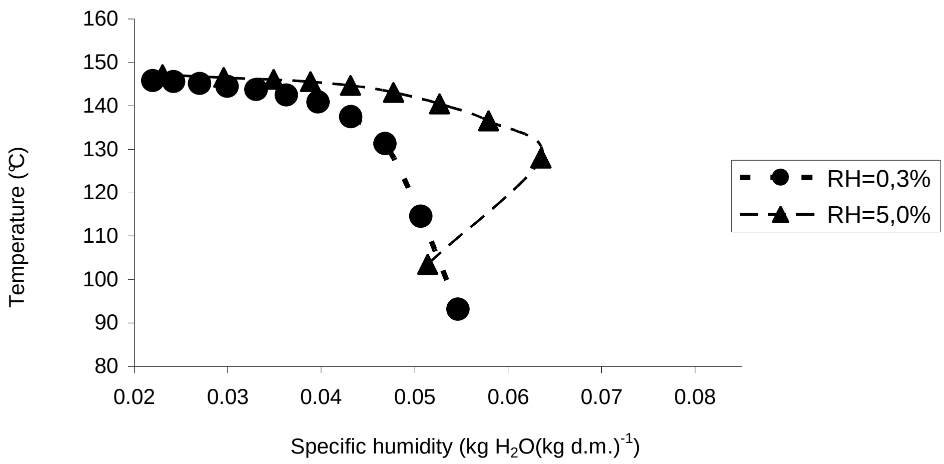


Fig. 8. Changes in temperature between the kernel and shell in cocoa beans roasted at $T = 150^{o}$C; $v = 1$ m s^{-1}

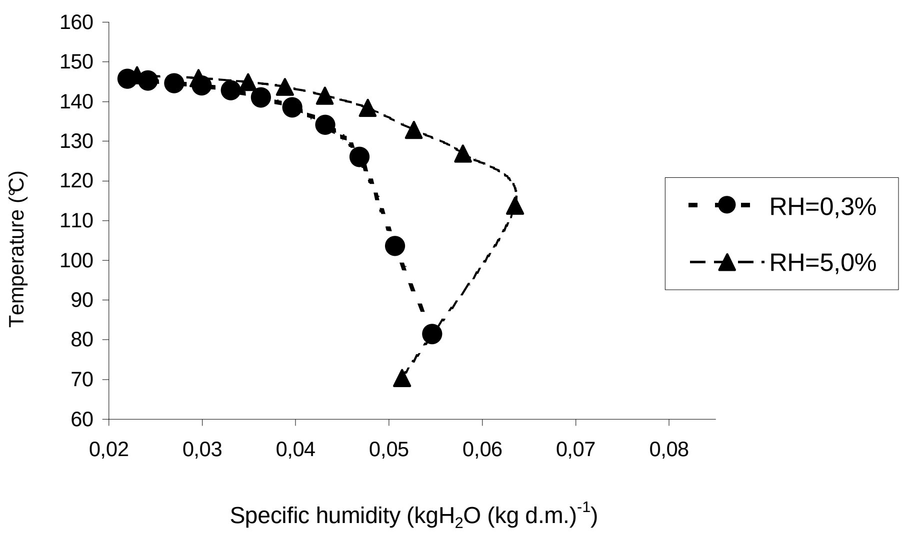


Fig. 9. Changes in temperature in the kernel in cocoa beans roasted at $T = 150^{o}$C; $v = 1$ m s^{-1}

Tabela 2. Differences between the temperature of air used to roast cocoa beans and (a) temperature of their surface (T_1), (b) temperature of the layer between shell and kernel (T_2), and (c) temperature of the kernel (T_3)

Process parameters		Temperature		
Humidity (%)	Time of roasting (min)	T_1 (°C)	T_2 (°C)	T_3 (°C)
Temperature of 110°C; *v* of 1 m s^{-1}				
0.9	0.08	23.5	18.6	32.5
	10	2,7	3.8	4.1
	30	1.7	2.8	2.7
	70	1.5	2.5	2.5
5.0	0.08	26.5	24.5	54.8
	10	1.7	2.6	3.7
	30	0.6	1.7	1.8
	80	0.2	1.3	1.1
	100	0.1	1.2	1.0
Temperature of 135°C; *v* of 1 m s^{-1}				
0.4	0.08	19.3	25.0	65.2
	10	1.3	2.5	5.3
	30	0.3	2.0	2.3
	35	0.2	1.8	1.7
5.0	0.08	31.1	34.5	70.6
	10	2.1	3.8	6.7
	30	1.2	2.7	3.6
	50	0.8	2.4	2.9
Temperature of 150°C; *v* of 1 m s^{-1}				
0.35	0.08	39.8	56.8	68.6
	10	4.6	4.5	5.2
	20	2.1	2.2	2.3
5.0	0.08	33.4	46.5	79.6
	10	2.7	5.3	8.5
	15	0.9	2.3	2.4
	20	0.8	2.1	2.2

Studies on the influence of the relative air humidity on differences in temperature of air and that of the kernel and the layer between the kernel and the shell showed that during the first 10 min of roasting at 135 and 150°C, and *RH* of 5%, both T_3 and T_2 values and the difference between them were higher. In the final part of the process, the difference between these temperatures dropped to 2°C and was independent from humidity and temperature of air. At 110°C and *RH* of 5% this difference was the smallest (approximately 1°C, Tab. 2), which presumably resulted from the very long time of roasting.

The increased air humidity had a beneficial impact on the "baloon effect". Air temperature of 110°C had a weaker effect on the formation of the empty gap between shell and kernel independently from air humidity, which can be concluded based on small differences in temperatures of both these parts of cocoa bean (Tab. 2). At the latter temperature, air humidity declines so the shell can absorb less water and its swelling is retarded. At this relatively low temperature, both water removal from cocoa beans and tearing the shell apart from the kernel slow down. At 135 and 150°C, and *RH* of 5%, shells are rapidly separated from kernels because the fibre contained in shells swells intensively due to enhanced water content, and the relatively high temperature of roasting favours rapid evaporation of water from the processed material.

CONCLUSIONS

Results of presented studies provide evidence that:

1. Air temperature has a strong impact on the rate of increase in temperature of principal parts of cocoa beans upon their roasting. Before the specific humidity of roasted cocoa dropped to 0.05 kgH_2O (kg d.m.)$^{-1}$, the difference between temperatures of kernel and shell was greater at higher roasting temperatures.
2. Increments in temperatures of the examined parts of cocoa beans were the smallest for air flow rate of 0.5 m s^{-1}, independently from air temperature.
3. Roasting at air flow of 1.5 m s^{-1} was found to be groundless, independently from air temperatures, because at this air flow rate increments of temperatures of examined parts of cocoa beans were not substantially larger than that at air flow of 1 m s^{-1}. The latter value of air flow rate was found to be the most adequate (of the three examined values of v) for roasting of cocoa beans.

- At 135-150°C roasting of cocoa beans should be carried out at elevated air humidity (*RH* of 5%).
- Independently from the parameters of air, the ultimate difference between air temperature and that of the kernel and the layer between the latter and the shell of cocoa bean reached 2°C.

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WPŁYW PARAMETRÓW POWIETRZA NA ZMIANĘ TEMPERATURY W PRAŻONYM ZIARNIE KAKAOWYM

Wiesława Krysiak, Lidia Motyl-Patelska

Instytut Chemicznej Technologii Żywności, Politechnika Łódź
ul. Stefanowskiego 4/10, 90-924 Łódź
e-mail: krysia@snack.p.lodz.pl

S t r e s z c z e n i e. Ziarno kakaowe odmiany Ivory Coast prażono metodą konwekcyjną w zmiennych warunkach temperatury (110, 135 i 150°C), prędkości (v = 0,5, 1 i 1,5 m·s^{-1}) i wilgotności względnej powietrza (RH = 0,9-0,3 oraz 5%). W trakcie procesu prażenia w poszczególnych częściach ziarna (na powierzchni, w przestrzeni między jądrem a łuską i w jądrze) mierzono temperaturę. Stwierdzono, że wszystkie parametry powietrza w początkowym okresie procesu prażenia (10-15 min) istotnie wpływają zarówno na wysokość, jak i na kształtowanie się profilu temperatury we wszystkich częściach ziarna. Niezależnie od stosowanych parametrów powietrza, w końcowym etapie procesu obserwuje się różnice między temperaturami osiąganymi przez jądro i łuskę na poziomie 2^{0}C.

S ł o w a k l u c z o w e: ziarno kakaowe, prażenie, wilgotne powietrze, temperatura prażonego ziarna