**EFFECT OF THE AMOUNT OF STEAM DURING BAKING ON BREAD CRUST
FEATURES AND WATER DIFFUSION**

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Abstract

Surface mechanical properties in fresh bread and during storage are greatly affected by the water plasticizing effect. However, the incidence of steaming during baking on the crust mechanical properties remains still unclear. The impact of the amount of steam (100, 200 and 400 ml) during baking on the crust features and water diffusivity was investigated. The amount of steam significantly ($p < 0.05$) affected the crust colour, glossiness and mechanical properties. An increase in the amount of steam led to reduced colour, failure force and failure firmness, whereas increased glossiness. Water vapour transfer rate and water vapour permeability of the bread crust significantly decreased when increasing the amount of steam applied during baking. Crust microstructure studies carried out by scanning electron microscopy and X-ray microtomography confirmed that the amount of steam greatly affected the surface starch gelatinization and also the protein-starch network.

1. Introduction

Wheat bread is one of the most commonly consumed food products in the world. Fresh bread usually presents an appealing brownish, crispy and crunchy crust besides pleasant aroma. In bakery products, crust quality attributes as crispy texture and colour are the most important attributes for consumer's perception. Jefferson et al. (2005) defined the crust as the part of bread near its surface, where the density is significantly higher than elsewhere, which is formed during the final baking.

Baking is an important stage in bread making; because it implies many physical and chemical changes, e.g. evaporation of water; formation of crumb structure; volume expansion; protein denaturation, starch gelatinization. In this final stage of the bread making process, the temperature in oven chamber and amount of steaming are essentially to give bread with main characteristics as open gas cell structure, expansion volume, and a crust envelop. Steaming is applied at the beginning of the baking process to improve crust texture and colour (Ahrné et al., 2007). Steam is responsible of preserving the extensibility of the surface of the dough during the oven-spring phase and giving a nice gloss of the crust (Chang, 2006), improving crust colour, and promoting heat penetration into the loaf interior (Ahrné et al., 2007). Dried oven conditions will yield rapid evaporation of water from the dough exposed surface, causing premature formation of a dry inelastic shell on the bread surface. As a consequence, the oven spring is restricted, which increases the risk of tearing of the surface of the crust in the finished bread (Hui et al., 2006). Conversely, it is expected that excessive moisture in the oven atmosphere will favour the expansion during baking (oven rise) (Le-Bail et al., 2011) but no definitive scientific information is available.

Instrumental measurements of bread crust texture provide force-displacement plots that are related to the surface structure. Mechanical surface properties have been mainly associated to water migration from the crumb to the crust (Luyten et al., 2004). Water transport through

crumb to the crust is complex and it may occur that water evaporates at one end of a pore and condenses at the other end. Water vapour diffuses through the interconnected pores towards the surface, under the influence of the gradient of water vapour concentration. In fact, liquid water gradient is formed and ensures the diffusive transfer of water from the core to the surface (Luyten et al., 2004). Diffusion and solubilisation of molecules through the material matrix are clearly dependent on the permeability of the product. Water vapour permeability (WVP) is defined as the rate of water vapour transmission per area unit of flat material or thickness unit under specified temperature and humidity conditions. The most common method used for the determination of WVP on films or edible packaging is the “cup method” based on the gravimetric technique (Debeaufort, et al., 1998). However, the reliability of this method in brittle materials is questioned.

The objective of this research was to evaluate the influence of the amount of steaming (100, 200 and 400 ml used in a baking chamber, which will correspond to 0.33 l/m³, 0.66 l/m³ and 1.33 l/m³, respectively) on the physicochemical and mechanical properties of bread crust. Special emphasis was put on assessing water vapour transmission rate and water vapour permeability in crust features during the post baking storage. The effect of steaming on the crust microstructure was investigated by scanning electron microscopy and X-ray microtomography.

2. Experimental

2.1. Materials

Commercial wheat flour was supplied by Paulic Minotiers SA (France). The flour had the following properties: 14.51% d.m. moisture content, 11.30% d.m protein, 0.51 % d.m. ash content, Zeleny index 33 ml, alveograph parameters $W=243 \times 10^{-4}$ J and $P/L=0.95$.

2.2. Bread making procedure

Dough was prepared on a flour weight basis, for 100 g flour, 63 g water, 2 g compressed baker's yeast (l'Hirondelle, France), 2 g table salt (Cérebos, France). Ingredients were mixed in a SP10 spiral mixer (VMI, Montaigu, France) for 4 min at 100 rpm and 4 min at 200 rpm, and rested for 20 min while covered with a plastic film to avoid drying. Dough was divided (75 g) and moulded in a divider-moulder (Bongard, Holtzheim, France), then dough pieces were rolled mechanically in MB230 moulder (L'Artisanne, France). Nine dough pieces were placed on aluminium trays (size 40 cm x 60 cm) and proofed at 25° C and 95% relative humidity in a fermentation cabinet (ARG68 HENGEL, France). Nine dough pieces were placed on aluminium trays (size 40 cm x 60 cm) and proofed at 25° C and 95% relative humidity up to three dough volume increase (versus the initial volume of the dough) in a fermentation cabinet (ARG68 HENGEL, France). Next, dough pieces were baked in an electrical deck oven (MIWE CO 1.1208-Germany) with a surface of 1.02 m² (0.85 x 1.2 m). All baking was performed at fixed oven temperature of 230° C for 18 min. The steam injection was programmed to 100, 200 and 400 ml, which will correspond to 0.33 l/m³, 0.66 l/m³ and 1.33 l/m³, respectively. From hereafter, millilitres will be used to refer to the different amount of steam applied at the beginning of the baking process. The selection of the amount of steaming applied was based on results of previous study where the impact of steaming on the kinetics of heating of crispy rolls was assessed (Le-Bail et al., 2011). After baking, breads were allowed to cool down for 1h at room temperature. Four sets of each sample were performed in separate days. Fresh loaves were tested for colour and crust mechanical properties one hour after baking. Bread crust was used for further water vapour transmission rate and water permeability determinations.

2.3. Chemical and physical analyses

Color parameters and glossiness of bread crust were measured using a CM-3500d spectrophotometer (Minolta, Co. Japan) after standardization with a white calibration plate ($L^* = 93.4$, $a^* = -1.8$, $b^* = 4.4$). The colour was recorded using CIE- $L^* a^* b^*$ uniform colour space (CIE-Lab), where L^* indicates lightness, a^* indicates hue on a green (-) to red (+) axis, and b^* indicates hue on a blue (-) to yellow (+) axis.

Glossiness is an indication of the degree to which the coated surface simulates a perfect mirror in its capacity to reflect incident light (Yang and Zhang, 2004). The value L^* was determined between specular component included (SCI) and specular component excluded (SCE) measurements using CM-3500d spectrophotometer (Minolta, Co. Japan). Crust glossiness was calculated as the subtraction of L^* (SCE) and L^* (SCI) values.

2.4. Water vapour permeability (WVP) determination

Water vapour permeability of the crust was determined according to the method ASTM E96 (ASTM, 1980). First, the crust was separated from the bread one hour after cooling using a razor blade. The crust was sealed to a cup partially filled with distilled (100% RH; 2.38×10^3 Pa of vapour pressure at 20°C) leaving an air gap beneath the crust. Sealing was carried out with gaffer tape of grade that met packaging certification standards (ASTM D5486). The test cup was then placed into a chamber (VC 7018 Vötsch, Industrietechnik, Germany) with controlled temperature and relative humidity at 61.2% RH and 20°C, respectively. Changes in the weight over time were monitored to determine the steady state flux of water vapour through the crust. The cups were weighed every day during five days. The thickness of the crust (Table 1) was measured using a micrometer, and the area of crust exposed in the test cup was 3.14 cm². Three replicates were determined for each measurement.

2.5. Water vapour transmission rate (WVTR) calculations

Water vapour transmission rate (WVTR) was determined using Eq. (1) (ASTM E96 method, 1980). The slope of the weight versus time plot was divided by the effective crust area (3.14 cm²) to obtain the WVTR.

$$WVTR = \frac{\text{Slope}}{\text{Crust area}} \quad \text{Eq (1)}$$

Water vapour permeability (WVP) correction method

Water vapour permeability was calculated by determining mass transfer through the stagnant air layer in the test cup (Bird et al., 1960; Krochta, 1992). Equation (2) enables calculation of the corrected water vapour partial pressure at the crust inner surface (P2).

$$WVTR = \frac{P * D * Ln[(P - P2)/(P - P1)]}{R * T * \Delta z} \quad \text{Eq (2) (McHugh et al., 1993)}$$

Where:

P= Total pressure

D= Diffusivity of water through air at 20° C (2.53×10⁻⁵)

R= Gas law constant (8.32 Pa m³ mol⁻¹ K⁻¹)

T= Absolute temperature 293.25 K

Δz=Mean stagnant air gap height (z_{original}+z_{final})/2 (m)

P1= Water vapour partial pressure at solution surface (Pa)

P2= Corrected water vapour partial pressure at crust inner surface in cup (Pa).

Water vapour permeance could then be calculated using Equation (3). The corrected partial pressure at the inner surface of the crust; P2 was employed in Eq. (3) to calculate true water vapour permeance.

$$\text{Permeance} = \frac{WVTR}{P2 - P3} \left(\frac{g}{m^2 s Pa} \right) \quad (\text{gmm/m}^2 \text{s Pa}) \quad \text{Eq(3)}$$

Where:

P3= Water vapour partial pressure at crust outer surface in the cabinet. Equation (4) could then be used to calculate true WVP of the crust; by multiplying the cored permeance and average crust thickness. The thickness of the crust was measured using a flat parallel surface micrometer with 1p.m resolution. This procedure, using Eq. (2), (3) and (4), was defined as the WVP Correction Method.

$$Permeability = Permeance * Thickness \quad Eq(4)$$

2.6. Puncture tests

Fresh breads after one hour cooling were puncture tested at a deformation speed of 100 mm/min using a 4mm diameter cylindrical probe. This speed was chosen because low puncturing rate allows penetrate successively cell walls of the brittle cellular materials (Vickers and Bourne, 1976). Experiments were performed using a texture analyzer (Lloyd Instrument LR5K, Southampton, UK). The peak force and the peak deformation point of the crust were calculated by punching the samples at five different points on the bread crust: looking down on the top surface, punching was at the midpoint and 2 cm from that point at 12, 3, 6, and 9 o'clock. Three different samples were used, which gave 15 measurements and the average value was calculated. Preliminary studies were run to confirm that peak force values responded to crust failure by following the crust rupture over 6-hours period after baking. Data confirmed that puncture test carried out in this type of bread within two hours after baking give information about stiff crust and not toughness. The failure force was calculated as the peak force observed according to studies by Jackman and Stanley (1992). The failure deformation, defined as the deformation at the peak point and the failure firmness, defined as the average slope of load displacement curve from zero to the point of rupture or failure (Shafiee et al., 2008), were also determined.

2.7. Scanning electron microscopy (SEM) and x-ray microtomography

The structure of the crust was observed with environmental SEM at 15 kV (ZEISS). The environmental microscopy permits to observe the sample without any treatment usually done for most SEM protocol (Drying + gold plating). Observation of the sample was done from a “fresh” piece of crust. The sample is placed on a temperature controlled sample holder. The temperature of the sample is adjusted as well as the partial vapour pressure of water above the sample to prevent dehydration.

In addition, X-ray microtomography was used, since it seems to be a very powerful tool in the study of materials microstructure, it is non destructive and provides understanding of the physical structure of the product from an engineering perspective (Frisullo et al., 2009). The characterization of the cellular crust structure by X-ray microtomography was performed using the Skyscan 1174 (Skyscan, Belgium). The crust sample was placed on a plate; 10 mm thickness was evaluated starting from the outer crust surface. The source and the detector were fixed, while the sample was rotated during measurement. Power settings of 50kV and a CCD camera of 12 bits 1280 x 1024 pixels were used. A set of flat cross-section images was obtained for each sample after tomographical reconstruction (NRecon software, Skyscan) of projection images acquired under different rotations (0.7 degree steps) over 180 degrees. The size of the gas cells or porosity was analyzed from X-ray microtomography images obtained at a magnification factor of 20x (1 pixel = 13.5 μm), the volume analysed was 10 x 6 x 1.5 mm^3 . Porosity was determined from the pixel ratio (solid domain versus void domain).

2.8. Statistical analysis

All determinations were carried out in triplicate. The results presented are averages of all available replicates. For each parameter, a one way analysis of variance (ANOVA) was

applied using Statgraphics Plus V 7.1 (Statistical Graphics Corporation, UK), to assess significant differences ($p < 0.05$).

3. Results and discussion

3.1. Effect of the amount of steaming on the physico-chemical properties of crust

The impact of different amount of steaming applied during baking on the physico-chemical properties of crust was evaluated (Table 1). The surface colour of bread is an important quality for consumers acceptance. The steam is commonly used during the initial stages of baking to improve crust brightness. The steaming conditions induced significant differences ($p < 0.05$) in the crust colour parameters. The lightness (L^*) increased with the steaming amount, observing significantly higher values with the highest amount of steaming (400 ml), also these samples had the highest yellowish colour (b^*). The reddish colour was observed with the lowest amount of steaming (100 ml). Therefore, crust browning during baking is significantly affected by the steaming amount during baking. In fact, Xue & Walker (2003) reported that cakes baked in highly humid air showed higher crust lightness.

Glossiness was also affected significantly ($p < 0.05$) by the amount of steaming used during baking. There was an increase of the glossiness on the crust when increases the steam (Table 1). The breads baked with the lowest steam amount (100 ml) gave an opaque crust, whereas the breads baked with 400 ml steam displayed a glossy crust. This effect could be attributed to the level of gelatinized starch granules on the crust, because the glossy appearance is due to the water vapour from steaming, which allows the formation of a starch paste that will gelatinize, form dextrins and finally caramelize to give both colour and gloss (Cauvain and Young, 2007).

236 The loss of water through each sample stored in the chamber was plotted as function of time
237 (Fig. 1), thus exhibiting significantly different plots according to the steam amount used for
238 baking. In the breads baked with the lowest steam level (100 ml), the crust had a greater rate
239 of weight loss (slope) during storage. When higher amounts of steam were used the
240 differences were reduced. The slope of the curve in the linear region was used to calculate the
241 water vapour transfer rate (WVTR) and water vapour permeability (Table 1). Differences in
242 WVTR were found as a result of the amount of steaming used during baking. In consequence
243 greater WVTR was obtained with lower amount of steam, which could be expected, taking
244 into account that lower amount of steam limits the starch gelatinization and gelification
245 yielding a more porous network comprised of protein, intact granules and partially gelatinized
246 starch granules. When a dried solid polymer material like starch is brought into contact with
247 water, the water diffuses into polymer and diffusion will increase dramatically with increasing
248 water activity (Luyten et al., 2004). In the breads baked with the highest steam level (400 ml),
249 the crust showed the lowest weight loss after storage (Fig. 1), and in consequence, the lowest
250 WVTR, thus the resulting crust network appears to decrease the rate of water diffusion.

251 The water vapour permeability (WVP) results reported in Table 1 showed significant ($p < 0.05$)
252 changes with the amount of steam. There was a steady decrease in WVP of the crust when
253 increasing the amount of steam used during baking. Likely, the amount of steam modifies the
254 heat penetration into the loaf from the surface to the inner parts, which will affect the crust
255 thickness. In fact, low steaming produced thinner crust that favoured the water diffusion,
256 whereas 200 and 400 ml of steam led to thicker crust that retains more moisture inside the
257 loaf. Besides during baking there exists a concentration gradient of water vapour between the
258 product surface and air. Therefore, water vapour is transferred through mass convection
259 (Zhou and Therdthai, 2008). Changes in WVP values have been associated to structural

changes in the polymeric matrix due to modification in the density of the network (Carvalho and Grosso, 2004).

WVP correction method was also applied to obtain corrected WVP using experimental WVTR data (Eq. 2, 3 and 4). For the WVP values without correction, it is assumed that the resistance to water vapour transport of the air gap between the crust and the surface of the liquid inside the cup is negligible. Conversely, correction method considers the water vapour partial pressure gradient in the air gap, where the driving force will be $P_2 - P_3$. The corrected WVP values of the crust are displayed in Table 1. The corrected values of WVP were much lower than those without any correction. Thus in the case of breads it is important to consider the resistance to water vapour transport of the air gap between the crust and the liquid when calculating the water vapour permeability. This result agrees with McHugh et al (1993), who reported that films based on hydrophilic polymers like proteins or polysaccharides are very sensitive to the moisture content diffusion and the air gap could drive to erroneous values. An increase of the amount of steam used in the baking decreased the corrected WVP.

3.2. Effect of the amount of steam on crust mechanical properties

Crust mechanical properties were measured by a puncture test (Jackman and Stanley, 1992), being dependent on the crust hardness and also on its microstructure. These parameters have been selected for characterizing crust of bread. Lately, high values of failure deformation have been related to stiffer crust structure due to the presence of thick crusts (Altamirano-Fortoul and Rosell, 2011). The effect of steaming on mechanical properties of the crust is shown in Table 1. The failure force was significantly ($p < 0.05$) affected. The increase of the amount of steaming used during baking caused an increase in the failure force, lower value has been observed for lower steaming (100 ml). Therefore, lower values in failure force indicate soft crust, whereas high force suggests more brittle and rigid crust. In addition, the failure

deformation decreased significantly ($p<0.05$) with the increase of the amount steaming. This may be explained by the distribution and size of starch granules, due to varied moisture content across the crust, which affect the mechanical properties of the cell walls of cereal-base food (Attenburrow et al., 1989).

The failure firmness augmented significantly ($p<0.05$) with the increase of the amount of steam (Table 1), probably due to the changes induced in the starch on the crust surface by the steam. The firmness is caused mainly by the formation of cross-links between partially solubilized starch and gluten proteins (Martin et al., 1991).

3.3. Effect of the amount of steaming on crust microstructure

Microstructure was studied in order to explain the effect of different amounts of steam used during baking on the mechanical properties of the crust, because the morphology of the crust in crispy foods determines the fracture behaviour (Luyten et al., 2004). Scanning electron microscopy (SEM) was applied to the crust surface. The micrographs of the morphology of the top and side crust sections are presented in Fig. 2 and 3. Bread baked with 100 ml of steam (Fig. 2a,b) showed a continuous sheet of clearly visible starch granules with homogeneous distribution, whereas, in the side or inner section (Fig. 3a) it was observed starch granules with lenticular shape, besides starch granules that preserved their integrity.

Bread baked with 200 ml of steam revealed a less compact structure (Fig. 2c), also the starch granules were less spherical due to its swelling occurred during gelatinization (Fig. 2d), thus the amount of steaming used during baking resulted in a different starch structure. In the side section crust showed some swollen starch granules and these were surrounded by protein matrix (Fig. 3b). When 400 ml of steam were used, some deformed starch structure could be envisaged integrated in a gelled structure (Fig. 2e,f); the crust had smoother and uneven structure compared to the lower steam levels tested. The side section of this crust showed less

intact starch granules on its surface, which were embedded in a very smooth film resulted from the gelatinization of the starch (Fig. 3c).

3D-images of the crust of breads baked with different amounts of steam obtained by X-ray microtomography are presented on Fig. 4. Different cell structures were observed depending on the amount of steam applied. Breads baked with 100 ml of steam showed more homogeneous and spherical crust cellular structure, the volume of the matrix being rendered in grey levels (Fig. 4a). Very thin crust was observed at the surface. Breads baked with 200 ml of steam presented more heterogeneous cellular structure and cell size distribution, the previously spherical bubbles became elongated and a population of bigger bubbles coexisted with smaller ones mainly located towards the surface (Fig. 4b). A denser zone was observed close to the surface indicating thicker crust. When much steam was applied during baking (samples with 400 ml), bubbles were more elongated, with a deformed appearance, it seems that their resistance to expansion was exceeded and protein-starch matrix network was disturbed and broken in several places (Fig. 4c). Thickness of the dense zone greatly increased.

The evaluation of the local porosity has been calculated from X-rays microtomography images (Fig. 5). It appeared that baking with 100 ml of steam resulted in higher porosity than in the case of 200 ml and 400 ml. The higher porosity observed for 100 ml steamed samples is in agreement with the moisture permeability results observed for crust in comparison to values obtained for higher amount of steam. Indeed, higher porosity combined with thinner outer crust is supposed to favour moisture diffusion in comparison to a denser domain (lower porosity) such as those observed for 200 and 400 ml. Therefore, microstructure analysis confirmed that the amount of steaming used during baking greatly modifies the crust

structure, affecting the bubbles shape and size, the proteins-starch network and surface density.

4. Conclusion

Crust properties greatly determine the perception of the fresh bread, especially crispness. Those properties are significantly affected by the amount of steam applied during the baking process, particularly colour and glossiness, thickness, microstructure and texture properties. Low amounts of steam give thinner crusts with high vapour transmission rate and permeability. Thus, lower permeability attributed to the crust can be directly related to porosity, which acted as a barrier affecting this property. On the other hand, it is necessary to apply the right amount of steam to obtain brittle and firm crusts in the fresh bread. Based on present results, it seems that a medium to low amount of steam results in a thinner crust, which in turn is more permeable to moisture during storage. Therefore, it is expected that such crust will remain brittle for longer time during storage after baking.

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413 **Table 1.** Crust physicochemical and mechanical properties obtained from bread baked with different amount of steaming (100 ml, 200 ml and
 414 400 ml corresponded to 0.33 l/m³, 0.66 l/m³ and 1.33 l/m³, respectively).

	Amount of steaming (ml)		
	100	200	400
Color parameter values :			
<i>L</i> *	60.05±0.98 a	61.11±0.47 a	64.71±0.34 b
<i>a</i> *	13.04±0.65 b	8.24±0.51 a	7.83±0.34 a
<i>b</i> *	32.72±0.67 a	33.62±0.69 b	34.84±0.62 c
Glossiness	0.32 ± 0.01 a	0.51 ± 0.01 b	0.60 ± 0.01 c
WVTR (g/m ² s)	1.11E-03 ± 8.91E-06 c	7.76E-04 ± 3.43E-05 b	6.24E-04 ± 1.27E-05 a
WVP (gmm/m ² sPa)	7.34E-07 ± 5.91E-09 c	5.49E-07 ± 2.43E-08 b	4.65E-07 ± 9.43E-09 a
WVP correction (gmm/m ² sPa)	1.88E-06 ± 1.51E-08 c	1.41E-06 ± 6.21E-08 b	1.20E-06 ± 2.42E-08 a
Crust thickness (mm)	0.90 ± 0.01 a	1.00 ± 0.01 b	1.00 ± 0.01 b
Failure Force (N)	4.20 ± 0.23 a	4.70 ± 0.04 b	5.73 ± 0.20 c
Failure Deformation (mm)	17.70 ± 1.04 b	16.57 ± 1.26 b	15.43 ± 3.23 a
Failure Firmness (N/mm)	1.45 ± 0.19 a	1.90 ± 0.34 b	2.30 ± 0.03 c

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417 Means sharing the same letter within a raw were not significantly different (p<0.05)

418 WVTR: water vapour transmission rate

419 WVP: water vapour permeability.

420

FIGURE CAPTIONS

Fig. 1. The effect of amount of steam on the water vapour transfer rate (WVTR) as weight loss during the experimental time.

Fig. 2. Scanning electron micrographs of top crust section at different magnifications. Top crust section in the left side (a, c, e) using a magnification of 250x and top crust section in the right side (b, d, f) using adjusted magnification to show the starch granules. Pictures corresponded to: 100 ml of steam (a, b), 200 ml of steam (c, d), 400 ml of steam (e, f). Arrows show starch granules (S).

Fig. 3. Scanning electron micrographs of side crust section using a magnification of 1000x. Pictures correspond to 100 ml (a), 200 ml (b), 300 ml (c). The arrows indicate the location of the crust outer surface, which appears to be thicker for the high steaming.

Fig. 4. Effect of amount of steaming on the crust microstructure by X-ray microtomography. 3D surface rendering of 100 vertical cross sections of images obtained at a magnification of 20x (1 pixel = 13.5 μm), volume size = 10 x 6 x 1.5 mm³: a) 100 ml of steam, b) 200 ml of steam and c) 400 ml of steam.

Fig. 5. Crust porosity expressed as percentage (calculated from X-ray microtomography images) in function of the distance from the outer crust surface.

Fig. 1

Fig. 2

a)

b)

c)

d)

e)

f)

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457 Fig. 3
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465 c)
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470 Fig. 4
471 a)

472 b)
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474 c)
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Fig. 5