Defatting and Dehydration of Meat Products during Heating in Steam Convection Oven

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Abstract
In this study, we investigated the effects of steam on the reduction in fat and/or water content during the heating of foods. Experiments were performed at 250°C with steam and without steam by using three types of heating equipments; the equipments had different heat transfer coefficients and rates of increase of gas humidity. Sausage and raw pork pate were used as model sample materials. During roasting with steam, the amounts of weight loss and fat loss were greater in the raw pork pate than in the sausage because the amount of protein shrinkage in the pork pate was greater than that in the sausage.

Key words
Defatting, Dehydration, Protein Denaturation, Convective Heat Transfer Coefficient, Gas Humidity

1. Introduction
Steam convection ovens can heat a large amount of food by using not only air but also steam that is generated in a small boiler. Therefore, these ovens have been used for mass cooking, e.g. in food service facilities. Ovens that use steam have also begun to be used for domestic cooking in recent years. The use of steam for heating has been investigated in the field of food technology, e.g. for cooking [1, 2], drying [3, 4], sterilization [5–7], brewing [8], and heating by using Aqua-gas [9, 10]. We have investigated the change in gas humidity in a steam convection oven chamber, and have found that the gas humidity is not constant during cooking when heating is carried out without supplying steam. The gas humidity increases during cooking because of the evaporation of moisture from the food. The gas humidity in the chamber is influenced by the kind of foods being cooked, cooking pattern, and amount of food cooked. The gas humidity also influences the cooking performance. It has been suggested that during cooking, it is important to adjust not only the temperature but also the gas humidity [11].

When cooking with steam convection ovens, the steam serves to control the food moisture content, improve taste, and reduce the heating time, thus improving the efficiency of such ovens. In our previous research, it was reported that the cooking performance was influenced by the humidity (steam mole fraction) in the chamber, for example, the heating time, final appearance of the food, and the decrease in the food mass differed depending on the presence/absence of steam [12, 13]. In another previous study, we examined the effect of defatting on sausage; we used 10 ovens (3 steam convection ovens and 7 domestic cooking ovens) and examined the effect of humidity in the oven chamber on defatting of foods. The rate of increase of gas humidity and the maximal gas humidity in the chamber varied among the ovens, especially between the two types of ovens. The effect of furthering defatting was seen in the case of heating being accompanied by steam supply in the steam convection oven (called combi-mode). However, in the case of the domestic cooking oven, we could not observe any effect, because the rate of increase of gas humidity and the maximal gas humidity were low [14]. From these researches, we know that the effect of defatting is strongly influenced by the heating characteristics of ovens, such as the humidity and changes in the humidity, the flow velocity in the oven chamber, and the heat sensitivity of meat products. There are many studies on protein denaturation, including theoretical studies [15–18]. However, they have not clarified the defatting mechanism in meat products with/without steam.

In this study, we investigated the effect of steam on the reduction in fat and water content during the heating of meat products. Sausage (heat-treated) and raw pork pate (not heat-treated) were used as model sample materials. Experiments were performed with steam and without steam using three types of equipments; the equipments had different gas flow velocities (convective heat transfer coefficient) and rates of increase of gas humidity. Changes in the gas humidity in the chamber were estimated from changes in the surface temperature of spherical wet gauze.

2. Experimental Methods

2.1 Experimental equipment
In this study, experiments were performed with three types of equipments. Table 1 shows the characteristics of the equipments. One of them was an experimental apparatus (referred to as E) and the other two were steam convection ovens (referred to as L and Y).

A schematic diagram of equipment E is shown in Fig.1. This equipment can be used to regulate the humidity of drying media such as room air and superheated steam at atmospheric pressure. In addition to a boiler (1) and a reboiler (2) for steam generation, a blower (4) for hot air generation, electric heaters (6, 8, 10), flowmeters (5, 9), a strainer section (12), a test section (13), and an exhaust blower (14) for balancing the static pressure inside and outside the test section were used. The dry-bulb temperature of the heating media upstream of the test section is controlled by the heaters. The gas flow velocity in the test section is measured by using a flowmeter (9) and is set to approximately 1 m/s. The dimensions of the test section, which is a rectangular duct, are 140 mm × 140 mm × 200 mm (length); the top surface and both the sides of the test section are covered with double glass for heat insulation and observation of the samples during heating. The bottom of the test section has a 100 mm × 80 mm
opening. The samples are inserted into the test section through this opening, and they are exposed to the heating media immediately after the start of heating.

The steam convection ovens (L and Y) shown in Fig.2 are commercial batch-type ovens, and these were partly converted into experimental models. These ovens have a small boiler and a convection heater. Steam is supplied from the boiler to the oven chamber and the convection heater increases the gas flow temperature in the chamber to the specified value. In this study, a maximum of two heater increases the gas flow temperature in the chamber to the specified value. In this study, a maximum of two samples were introduced simultaneously in the oven chamber and heating commenced immediately after closing the door. When samples were introduced into the chamber, some amount of the air in the room also entered the chamber. The gas flow velocity was measured by a flowmeter (KANOMAX, 6332D) in air at room temperature.

The gas flow velocity differed among the three equipments, as shown in Table 1. The equipments were temperature flowmeter (KANOMAX, 6332D) in air at room chamber, some amount of the air in the room also entered closing the door. When samples were introduced into the chamber and heating commenced immediately after samples were introduced simultaneously in the oven the specified value. In this study, a maximum of two heater increases the gas flow temperature in the chamber to the specified value. In this study, a maximum of two samples were introduced simultaneously in the oven chamber and heating commenced immediately after closing the door. When samples were introduced into the chamber, some amount of the air in the room also entered the chamber. The gas flow velocity was measured by a flowmeter (KANOMAX, 6332D) in air at room temperature.

The gas flow velocity differed among the three equipments, as shown in Table 1. The equipments were preheated.

2.2 Sample material
The food samples were sausage and pork pate. The sausage was a commercial one (Ajinoshuen, Marudai Food Co., Ltd.), and its diameter was about 55 mm. It was cut so as to have a thickness of 15 mm (about 40 g). A block of thin pork fillet was minced by a mincer, and lard (20% of total weight) and salt (0.5% of total weight) were added. After kneading well, this pork pate was divided into 40 g tubular samples (diameter \(d = 54\) mm). All samples were used after refrigeration to ensure that they had the same temperature (8°C). The fat and water content of the sausage samples were about 20% and 60%, respectively, which were equivalent to those of the pork pate. These values were confirmed by JFRL (Japan Food Research Laboratories). A major difference between a sausage and pork pate is in the condition of the protein. The protein in the sausage is denatured since sausage is a heat-treated product.

2.3 Measurement methods
The samples were heated on a shelf made of wires; the shelf was positioned on a heat insulator (Fig.3). A kitchen paper on an aluminium foil dried at 105°C was placed under the sample to collect the drops of water and fat from the food samples.

![Fig.3 Food sample](image)

The mass \(m\) and diameter \(d\) of samples were measured before \(m_0, d_0\) and after heating \(m_1, d_1\). The largest and smallest values of the diameter and thickness were measured for each sample. During heating, the inner temperature of the sample \(T\) was measured by a K-type thermocouple inserted close to the center from a side of the sample. The mass of the kitchen paper was measured before and after heating \(k_0, k_1\). The masses of the kitchen paper after drying at 105°C for different durations ranging from 3 h to 1 night were also measured \(k_2\). The amounts of fat loss \(\Delta k\), weight loss \(\Delta m\), and dehydration \(\Delta y\) were calculated by Eqs.(1)–(3) below. The heating times were 180, 300, 480, 600, and 900 s, and the number of repetitions of the experiment ranged from 1 to 4. For a specific sample, the fat loss calculated by Eq.(1) was verified to be equal to the amount of fat removed from the sample. The percentages of weight loss \(W\), fat loss \(F\), and diameter shrinkage \(D\) were defined as in Eqs.(4)–(6).

\[
\Delta k = k_2 - k_0
\]  
\[
\Delta m = m_0 - m_1
\]  
\[
\Delta y = \Delta m - \Delta k
\]  
\[
F = \frac{\Delta k}{m_0} \times 100
\]  
\[
W = \frac{\Delta m}{m_0} \times 100
\]
\[ D = \frac{d_2 - d_1}{d_0} \times 100 \] (6)

2.4 Experimental conditions

2.4.1 Humidity change measurement methods

The surface \( (T_{sf}) \) and core \( (T_{co}) \) temperatures of the wet gauze sphere (diameter \( d = 22 \) mm), shown in Fig. 4, were measured to determine the gas humidity in the chambers of the three equipments. The gas humidity was determined by Eqs.(7) and (8) [19,20]. It was assumed that the adiabatic saturated temperature \( T_{sat} \) \( [\degree C] \) was equal to \( T_{ad} \) \( [\degree C] \). K-type thermocouples (\( d = 0.2 \) mm) were positioned to be in contact with the inner surface of one piece of gauze and to be in the vicinity of the center of the gauze sphere. The wet gauze sphere was placed at the center of each chamber, and temperature changes during heating were measured. When the gas humidity was 100% (steam mole fraction \( x = 1 \)), \( T_{ad} \) equals 100°C at atmosphere pressure. Another wet gauze sphere (Fig. 4 (b)) with the same diameter was inserted in the chamber when the temperatures of the previously inserted gauze sphere were being measured. The mass of this gauze sphere was measured before and after heating. The heat transfer coefficient \( h \) \( [W/(m^2 \cdot K)] \) of each equipments was calculated for the different masses and temperatures of the gauze [21], as shown in Table 2.

\[
x = \frac{1.005(T_{gas} - T_{co}) - M_{H_2O}P_{v,ad}}{M_{air}P_T} \gamma_{T_{ad}} \]
\[
(1.005 - 1.846) \frac{M_{H_2O}}{M_{air}}(T_{gas} - T_{co}) - \frac{M_{H_2O}}{M_{air}}P_T \gamma_{T_{ad}} = \frac{P_{v,ad}}{10^{(-7.0746 + 1.65746(1 - d/d_{22}))}}
\] (7)

\[
P_{v,ad} = 10^{(-7.0746 + 1.65746(1 - d/d_{22}))}
\] (8)

Here, the variables are defined as follows:
- \( M_{H_2O} \): molecular weight of \( H_2O (= 0.018015 \text{ kg/mol}) \)
- \( M_{air} \): molecular weight of air \( (= 0.02896 \text{ kg/mol}) \)
- \( P_T \): total pressure \( (= 101.325 \text{ kPa}) \)
- \( P_{v,ad} \): saturated vapour pressure
- \( \gamma_T \): evaporating latent heat at \( T \)
- \( P_{v,ad} \): saturated vapour pressure
- \( P_T \): total pressure

Fig. 5 shows the changes in the gas temperature \( T_{gas} \) and surface temperature \( T_{sf} \) of the wet spherical gauze. The \( T_{ad} \) values of EA, LA, and Y A reached 54, 61, and 58 \( (x = 0.04, 0.12, 0.07) \), respectively.

In the case of ES, when heating was carried out in steam flow (superheated steam), the change in \( T_{ad} \) was very small. Consequently, the samples were exposed to pure steam without any air \( (x = 1) \) immediately after heating commenced. On the other hand, a finite time was required for the gas humidity in the chamber to be restored to 100% \( (x = 1) \), and it took about 90 s for \( T_{ad} \) to reach approximately 100°C in the case of LS and YS (the steam convection ovens) when heating was accompanied by steam supply (Table 2).

2.4.2 Experimental conditions

Table 2 lists the experimental conditions and includes the measurement results obtained by using the wet gauze. The conditions are labeled in the rightmost column.

3. Experimental Results

3.1 Heating the sausage and pork pate

3.1.1 Temperature changes

The changes in the temperatures of the sausage and pork pate are shown in Fig. 6. In the case of equipment E, the rate of temperature increase in the case of heating with steam \( (ES\bullet) \) significantly differed from that without steam \( (EA\bullet) \); the equipments had a low gas flow velocity and a low heat transfer coefficient. The equipment showed a high rate of increase of humidity under ES, indicating that the sample was subjected to high humidity \( (x = 1) \) immediately after the beginning of heating. Subsequently, the material temperature increased significantly because of steam condensation. For equipment Y, which had a high gas flow velocity and a high heat transfer coefficient, the difference in the rate of increase of temperature between the two cases \( (YA\bullet, YS\bullet) \) was small. The presence of steam was effective to fasten the temperature rising, under low gas flow velocity rate especially because steam condensation was effective to fasten the temperature rising.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Gas temperature ( T_{gas} ) (^{[\degree C]} )</th>
<th>Steam supply</th>
<th>Time for restoring gas humidity to 100% ([\text{s}])</th>
<th>Maximal gas humidity ( x ) ([\text{%}])</th>
<th>Heat transfer coefficient ([W/(m^2 \cdot K)]) ((d = 22 \text{ mm}))</th>
<th>Label</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>240</td>
<td>Steam only</td>
<td>0</td>
<td>1.0</td>
<td>24</td>
<td>ES</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Room air only</td>
<td>–</td>
<td>0.04</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td></td>
<td>Supplied</td>
<td>90</td>
<td>1.0</td>
<td>34</td>
<td>LS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>–</td>
<td>0</td>
<td>0.12</td>
<td>34</td>
<td>LA</td>
</tr>
<tr>
<td>Y</td>
<td></td>
<td>Supplied</td>
<td>86</td>
<td>0.85</td>
<td>62</td>
<td>YS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>–</td>
<td>0</td>
<td>0.07</td>
<td>62</td>
<td>YA</td>
</tr>
</tbody>
</table>

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3.1.2 Fat loss and weight loss

We compared the percentages of fat loss (F) and weight loss (W) of the sausage with those for the pork pate (Figs.7 and 8). A comparison of Figs.7 (a) and 8 (a) with Figs.7 (b) and 8 (b) shows that the moisture and fat content of raw sausage samples were almost equal to those of raw pork pate samples, whereas the W and F values of the raw pork pate were greater than those of the heat-treated sausage. Most of the fat loss of the pork pate occurred in the early stage of heating, up to 600 s, and the loss after 600 s was very small. However, the weight loss was constantly up to the final stage of heating. Compared with the fat loss of the sausage, the weight loss was large. It occurred no droplet but the drying. The fat loss and weight loss of the pork pate increased when heating was carried out with steam in equipments E (○) and L (▲) which had a low gas flow velocity and a low heat transfer coefficient.

3.1.3 Visual observation and diameter shrinkage

Fig.9 shows the percentage of diameter shrinkage (D). Fig.10 shows some photographs of the pork pate for the conditions EA and ES, for which the diameter shrinkage was large. The change in the size of the sausage was small, about 4%, while the diameter of the pork pate rapidly decreased in the initial stage of heating, except for the condition of heating without steam in equipment E (EA○). This difference between the two materials was the result of protein denaturation during heating. Protein denaturation caused the shrinkage of the materials. D for ES (□) and LS (▲) was larger than that for EA (○) and LA (▲). The reason for this observation is considered to be follows: steam condensation occurred and the sample temperature rose; this led to the denaturation of protein, which result in the shrinkage.

3.2 Defatting (pork pate)

To determine the defatting mechanism, the defatting of the pork pate was analyzed because the pork pate showed a high percentage of fat loss. Figs.11 and 12 show the rate of fat loss $\Delta k/\Delta t$ (kg/s) and the dehydration rate $\Delta y/\Delta t$ (kg/s) of the pork pate sample, respectively. The rate of fat loss was high in the initial stage of heating and decreased with increasing time in all conditions. The rate of fat loss decreased to nearly zero at around 600 s (about $10 \times 10^6$ kg/s) because of dehydration caused by drying. Drying was carried on after denaturation almost completed.

Next, we examined the correlation between the fat loss and the weight loss in the pork pate (Fig.13). The fat and water content of the sample decreased simultaneously, which is reflected by the curves coinciding. The curves in Fig.13 are convex upward. When the curves are compared with the broken line that represents the value of $20/(20+60)$ for the initial ratio of fat to fat and water (maximal weight loss), the rate of fat loss is found to be greater than the dehydration rate up to around $W = 22\%$. 
The relationship between the fat loss and the weight
Protein shrinkage is enhanced if steam is supplied to
s
s
s
ferent salt content, grind
%  
ES
G'
LA YA
kg/s
LA YA
LS YS
Heating with steam was effective in increasing the rate
ES
Shrinkage
kg/s
゚
LS YS
%
During roasting, weight loss and fat loss were greater
extrusion along with condensed vapor. However, it should
sausage.
reduction in the viscosity of lard caused the defatting of the
resulting in reduced water retentivity. Further the drying of
lard decreases. Therefore, the lard is extruded (Fig.15).

Fig.11 Rate of fat loss
(pork pate)
Fig.12 Dehydration rate
(pork pate)

Fig.13 Percentage of fat loss (F) and percentage of weight loss (W)

When the heat transfer coefficient was low, the rate of
fat loss clearly increased because of protein shrinkage
caused by the rapid increase in temperature with steam
condensation in the initial heating stage.

Heating meat leads to the denaturation of meat protein,
which in turn causes a color change, reduced water retentivity, and protein shrinkage [22]. The denaturation
temperature of meat protein is about 65–80°C [23]. The
water stored in the net-like structure of the protein is
extruded, and therefore, water retentivity is reduced [24].
The connective tissue membrane that encloses adipose
tissue is damaged, and the temperature reaches the melting
point of adipose (the melting point of lard is 33–46°C [25])
with the result that the adipose melt and the adipose are
extruded. Fig.14 shows the viscosity of pork pate (lard:
20%) and 100% lard (tested at UBM Co., Ltd.). The
viscosity of pork pate decreases with the increase in temperature. At
temperatures above 40°C, lard melts and becomes a liquid;
melted lard cannot be measured because it has very low
viscosity. The viscosity of pork pate decreases with the
softening of lard from 5°C to 50°C; the viscosity increases
at higher temperatures because of protein denaturation.

When the temperature rises, the protein denatures. This
results in the shrinkage of the protein, and the viscosity of
lard decreases. Therefore, the lard is extruded (Fig.15).
The protein in the sausage was already denatured,
resulting in reduced water retentivity. Further the drying of
the sausage led to the shrinkage. It is thought that the
reduction in the viscosity of lard caused the defatting of the
sausage.

In the case of heating with steam, fat loss is caused by
extrusion along with condensed vapor. However, it should
be clarified that the key factor responsible for fat loss is
extrusion resulting from protein denaturation.

There are differences among foods, e.g. with regard to
the fat and moisture content, shape, and effects of
temperature on the physical properties. Even if the same
material is used (e.g. pork pate), different results will be
obtained for samples with different salt content, grind
ratios, etc. The results presented in this paper are not
necessarily applicable to all foods. The intention of heating
can be many, e.g., to defat and to cook to an adequate level
without decreasing the fat and moisture content. It is
possible to achieve the intended objectives by changing the
heating method or conditions. Therefore, it is important to
improve our understanding of effect of heat on foodstuffs.

4. Conclusion
The effects of steam on the fat and/or water content during
the heating of foods were investigated. Experiments were
performed at 250°C with steam and without steam by
using three types of equipments; the equipments had
different heat transfer coefficients and rates of increase of
gas humidity. Sausage and raw pork pate were used as
model sample materials. The following results were
obtained:

1. Heating with steam was effective in increasing the rate
of temperature increase for a low heat transfer
coefficient. High rate of increase of gas humidity was
so effective.
2. During roasting, weight loss and fat loss were greater
in the pork pate than in the sausage.
3. In the case of the pork pate, shrinkage caused by
protein denaturation accelerated the fat loss.
4. Protein shrinkage is enhanced if steam is supplied to
the chamber, especially when heating is carried out for
a low heat transfer coefficient.
5. The relationship between the fat loss and the weight
loss of pork pate is valid in all conditions. The
defatting process proceeds at a greater speed than the
dehydrating process up to a weight loss of 22%.
**Nomenclature**

- $F$: percentage of fat loss, %
- $D$: percentage of shrinkage, %
- $d$: diameter of sample, m
- $k$: kitchen paper mass, kg
- $M$: molecular weight, kg/mol
- $m$: mass of sample, kg
- $P_1$: total pressure, kPa
- $p_v$: vapour pressure, kPa
- $T$: temperature, °C
- $t$: time, s
- $W$: percentage of weight loss, %
- $x$: steam mole fraction
- $y$: mass of water contained in sample, kg
- $\gamma$: evaporating latent heat at $T$[°C], kJ/kg

**Subscripts**

- $ad$: adiabatic
- $air$: air
- $co$: core
- $gas$: flow gas
- $H_2O$: steam
- $sat$: saturated
- $sf$: surface
- $0$: before heating
- $1$: after heating
- $2$: after heating and drying

**References**