11th International Congress on Engineering and Food (ICEF11)

Fundamentals-based quality prediction: Texture development during drying and related processes

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Abstract

Using Young’s modulus as a measure for texture, a framework for predicting the effective modulus of a solid food material is developed and extended to four moisture removal processes—frying, drying, microwave heating and baking. The effective modulus is predicted using mechanical analysis from local modulus values that depend on transient moisture and temperature. For two different processes of drying and frying, the development of modulus can be predicted from the same dependence of moisture and temperature. These predictions compared well with experimentally measured modulus. The prediction framework is then extended to the processes of baking and microwave heating. The moisture and temperature information needed for prediction of modulus is in turn obtained from multiphase porous media based models of the processes, thus making physics-based texture prediction possible from process and product parameters. Texture development during the four moisture removal processes are compared with each other and the effect of oven temperature and sample size is discussed.

Keywords: multiphase transport; drying; frying; texture

1. Introduction

The manuscript is organized as follows. The process model formulation for drying, baking, and microwave heating of potato strips is developed. Experiments to measure Young’s Modulus as a function of the drying time of the potato strips are described. Results for temperature, moisture, and Young’s Modulus development with time during drying are shown from computation and compared with experimental results for various drying temperatures. Predictions of texture are extended to the processes of baking, frying and microwave heating and the four processes are compared side by side.

Although texture development in foods is a widely studied subject [1], it is typically studied empirically. Completely empirical models of texture, which are often used to study food texture, can be

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useful for specific situations and for applications such as automated process control, but they do not provide much understanding of the fundamental mechanisms involved. Investigations using such models are frequently limited to a particular food under study so that the results cannot be generalized. A framework for a quantitative, first-principle-based understanding of food quality should make science-based decision-making and problem solving for food product and process developers easier. Such a framework should also prove to be useful in an education environment. For example, texture development in processes that can provide alternatives to deep frying (and thus be more desirable from a health standpoint) can be better understood so that such processes can be developed in a more predictable manner.

2. Materials & Methods

The framework involves multiphase porous-media based process-model that provides temperature and moisture fields throughout the domain of the food sample [2,3]. Relationship between Young’s Modulus of the food material and its moisture and temperature content is experimentally determined. Once the temperature and moisture fields are predicted from the process model, the local Young’s Modulus values in the food sample can be estimated. A stress-strain analysis is then performed, in which the food material is then subjected to fixed uniaxial compression strain (small) to obtain the resulting. The ratio between the predicted stress and the applied strain is then defined as the effective Young’s Modulus of the material. Since the temperature and moisture fields vary with the process duration, the effective Young’s Modulus also varies.

Mathematically, the net rate of change of Young’s Modulus is the sum of changes due to temperature and moisture expressed as:

$$\frac{dE}{dt} = \frac{\partial E}{\partial M} \frac{dM}{dt} + \frac{\partial E}{\partial T} \frac{dT}{dt}$$

where M and T are the local (at a location) values of moisture content and temperature, respectively. Experimental determination of temperature and moisture dependence of Young’s Modulus ($\partial E/\partial T$ and $\partial E/\partial M$, respectively) is discussed elsewhere [4]. Rates of change of temperature and moisture ($dT/dt$ and $dM/dt$, respectively) are obtained from the process model.

The governing equations for a process model are first solved to obtain time-dependent temperature and moisture spatial profiles for the duration of the process. A commercially available finite element software, COMSOL Multiphysics 3.5a (COMSOL Inc, Burlington, MA), was used to solve the equations. The plane-stress (small deformation) analysis is then performed using COMSOL to predict the effective Young’s Modulus as a function of time.

To verify model predictions of temperature, moisture content and Young’s Modulus during drying, experimental data were obtained for all three. Drying was then carried out at temperatures of 120°C, 130°C and 140°C in a hot air oven (VWR International oven, Model 1415M, Sheldon Manufacturing Inc., Cornelius, OR) for a period of 60 min each. Ten readings for Young’s Modulus at several time steps were taken for each temperature. The higher temperatures ensured that the potato samples reached their gelatinization temperatures and a significant temperature effect was captured.

All samples that had been once used for measurement of either moisture or Young’s Modulus were discarded. This work was replicated three times to enhance confidence and check variability. This experiment provided data on the dependence of Young’s Modulus on moisture content at constant temperature.

Experiments were performed to capture Young’s Modulus of the material during the drying process. Young’s Modulus of the sample was measured using compression tests in a Q800-0666-DMA Analyzer during the processes of constant temperature drying and heating in water. The strain rate of the probe was
1.0%, which is within the elastic range in the case of the potato samples [5]. Young’s Modulus was determined using the compression test at each stage of drying (at several levels of moisture). This was done by applying a constant strain on the material for 30 seconds and measuring the corresponding stress generated from which Young’s Modulus was obtained.

3. Results & Discussion

Temperature, moisture, and texture (Young’s Modulus) development during drying are predicted and compared with experimental results. The effects of drying temperature and sample size on development of Young’s Modulus are predicted. Finally, the framework for texture prediction is extended to baking, microwave heating, and frying, and comparative development of Young’s Modulus in the four processes is investigated.

3.1 Temperature, moisture and texture (Young’s Modulus) development with time for drying

The moisture and temperature dependence of Young’s Modulus, shown in Fig. 1 and Table 1 respectively, are used to compute effective Young’s Modulus.

Table 1. Temperature dependence of Young’s Modulus, in terms of first-order reaction rate constant, \( k_f \), and activation energy, \( E_a \), at two temperatures [4]

<table>
<thead>
<tr>
<th>Temperature</th>
<th>( k_f ) (min.)</th>
<th>( E_a ) (kJ/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>85°C</td>
<td>0.372</td>
<td>53.95</td>
</tr>
<tr>
<td>95°C</td>
<td>0.5575</td>
<td>92.83</td>
</tr>
<tr>
<td></td>
<td>0.6579</td>
<td>70.93</td>
</tr>
</tbody>
</table>

Fig. 1. Moisture dependence of Young’s Modulus [4]. The points are measurements and the solid line shows the data used as input parameters in mechanical analysis

Figure 2 shows the variation of core temperature, average moisture content, and effective Young’s Modulus with time for the process of drying. Moisture loss is faster at higher drying air temperatures.
Thus, as shown in Fig. 3a, Young’s Modulus increases faster with time for higher drying air temperatures. The same final value for Young’s Modulus is predicted for all drying air temperatures since the final moisture content is the same.

3.2 Texture development during drying: effect of sample size

Figure 4a shows how Young’s Modulus changes with time for variations in sample size. As the sample size increases, the fraction of its moisture lost per unit time decreases. Volume increases much faster with greater sample size than surface area through which moisture loss occurs. For a larger sample, the crust that forms due to moisture loss at the surface is thinner compared with the size of the sample. This leads to reduced effective modulus of the sample (since the inside is always soft with a lower modulus value) for a larger size for the same duration of heating.
Fig. 3. (a) Change in Young’s Modulus with time for various drying temperatures; (b) Time to reach the same value of Young’s modulus for various drying temperatures

Fig. 4. (a) Change in Young’s Modulus with time for various sample sizes; (b) Time to reach the same value of Young’s modulus for various sample sizes
3.3 Comparative texture development in four processes

The framework for texture (Young’s Modulus) prediction, developed and verified in the previous sections for drying, would be more useful if it could be extended to prediction of texture in other processes. Note that the framework has already been used successfully for frying [4]. To demonstrate the more general applicability of the framework, it is extended to two other processes: baking and microwave heating. Process models for baking and microwave heating have been discussed elsewhere [6, 7]. Figure 5 compares effective Young’s Modulus development over time for all four processes side by side. The process with the fastest moisture loss (frying) produces the fastest texture development. It is also instructive to compare the spatial variation of temperature and moisture at a given time for all four processes (not shown here). These figures show that for a duration of 200 s of each of these processes, frying achieves the lowest moisture, the highest temperature, and the desired level of texture. As baking and drying are slower processes, there is still a significant amount of moisture left. As expected, since frying produces the fastest moisture loss, it takes the least time to develop the desired texture followed by microwave heating, drying, and baking.

Fig. 5. Comparative development of texture (Young’s Modulus) during four different processes

4. Conclusion

Change in effective Young’s Modulus during drying of a potato sample was predicted starting from a physics-based model of the process and experimentally observed temperature and moisture dependence on local modulus. Change in the moisture content of the material had the most dominant effect on Young’s Modulus. Thus, at higher temperatures, where the moisture loss was faster, predicted Young’s Modulus showed the fastest increase. In a larger sample, modulus development is slower since the fraction of moisture lost per unit time decreases. For a given final modulus value, the required drying time increases linearly with any decrease in drying air temperature and increase in sample size. The physics-based prediction of Young’s Modulus (measure of texture), proven here for drying and in past work for frying, is extended to baking and microwave heating. Comparative modulus development in four processes (baking, drying, microwave heating and frying) is observed to follow that order, i.e., frying produces the fastest increase in modulus and baking the slowest. This order follows the order of moisture
loss, since frying has the fastest moisture loss and baking the slowest. The framework of texture (Young’s Modulus) prediction thus developed and applied to four processes is considered generally applicable to other moisture removal processes and therefore can be used to predict texture for a wide variety and combination of processes.

References


Presented at ICEF11 (May 22-26, 2011 – Athens, Greece) as paper EPF1210.