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Effects of salt on the expansion of starchy snacks: a multiscale analysis

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Abstract

We investigate the effect of salt on the expansion of starchy snacks during frying by means of a multiscale simulation model. This model has been developed earlier for starchy snacks without salt. The simulation results are analysed by means of the supplemented state diagram. We have found that the optimal expansion for salty snacks occurs at the same conditions as for snacks without salt. This occurs namely, at the moisture content where the 4 bar boiling line intersects the critical isoviscosity line of 1 MPa.s. Salt is shown to influence both the boiling line and the critical isoviscosity line, via change of the glass transition. The optimal moisture content for salty snacks is lower compared to that of unsalted snacks without salt. We view our findings are of importance for reformulations of starchy snacks with lower salt levels. Furthermore, the presented tools of the multiscale simulations and supplemented state diagram can generally be used for reformulation problems in structured foods.

INTRODUCTION

A significant part of food consists of expanded snacks, which are based on starch. These snacks have a porous structure, which is formed via bubble expansion, when water from the starch dough is evaporated during intense heating of the dough. Until recently, there has been little quantitative understanding of this expansion process [19, 28]. In our recent research we have advanced this understanding for a particular class of snacks, namely indirectly expanded snacks [30, 28, 29]. These snacks are mixed via extrusion, and subsequently dried into a self-stable form (pellets). Later, the dried pellets are expanded via frying, hot air, or microwave heating. We have focussed the research on frying, which is the common method of expansion,

as is also done for the traditional Asian snack keropok. More background on these types of snacks one finds in the reviews [19, 28].

In our research we have made two important steps, which have enabled us to obtain a quantitative description of the expansion process. The first important step comprises of the understanding of the thermodynamics of starch/water mixtures [30]. Via the Flory-Huggins-Free-Volume (FHFV) theory we have been able to predict the complete phase/state diagram of the mixture (also known as the supplemented state diagram). The second important step is the construction of a multiscale simulation model, which describes the development of steam bubbles in an relatively dry amorphous starch matrix during frying [29]. As stated earlier [19, 31, 28], the supplemented state diagram of starch/water mixtures is vital for understanding the expansion process. With help of the supplemented state diagram we have been able to explain the optimum in the degree of expansion as a function of moisture [29].

The expansion of starchy snacks is only possible if the starch matrix can enter the boiling state. Furthermore, at the advent of bubble expansion, the starch matrix needs to be in the rubbery state such that it can yield in response to the pressure build up in the steam bubble. Because the relatively dry starch matrix is still highly viscous, the expansion takes only place at elevated pressure, i.e. about 4 bars. This means that in the analysis of the expansion process with the supplemented state diagram, we have to use the boiling line at 4 bars [29]. As follows from the FHFV theory the boiling line at elevated temperatures runs parallel to the boiling line at 1 bar.

Previously, it is thought that expansion is immediately possible if the starch matrix exits the glassy state [19]. However, we have found that the starch matrix yields at a lower viscosity. At the glass transition the matrix viscosity is about 10^{13} Pa.s. Via the multiscale simulation model, we have found that the matrix will yield only at viscosities below the critical value of $\eta_{cr} = 10^6$ Pa.s. Hence, in the analysis via the supplemented state diagram we have to use the isoviscosity line of η_{cr} instead of the glass transition line [29]. It is good to recognize that the glass transition is also an isoviscosity line, with a viscosity of 10^{13} Pa.s. Near the glass transition, viscosity can be described theoretically with Williams-Landel-Ferry (WLF) theory. From this theory follows that isoviscosity lines run parallel to the glass transition. A similar situation exists for the collapse phenomenon during freeze-drying or spray-drying. The collapse temperature runs also parallel to the glass transition, and is 10-20 degrees above the glass transition. Therefore it has been advised to include isoviscosity lines in the state diagram for spray drying of dairy products [32].

The optimum of expansion in amorphous starch/water mixtures occurs at the moisture content where the boiling line of 4 bar intersects with the isoviscosity line of η_{cr} [29]. This comprises a slight adjustment of the earlier hypothesis by Kokini and coworkers, who said that optimal expansion occurs

at the intersection of the 1 bar boiling line, and the glass transition line [4].

In the previous paper describing the multiscale model of bubble expansion in snacks, we have assumed that the matrix does not contain any salts. In reality snacks contain a significant amount of salt, $NaCl$, which can be upto 3% of its total weight. In the recent years concerns are raised about the high levels of salt in food, as this can lead to elevated blood pressures and cardiovascular diseases. Next to its effect on taste, salt also effects the thermodynamics of food materials, and possibly also other material properties like the glass transition. Hence, it is often not immediately evident how to change the food formulation if the salt level is lowered.

The objective of this paper is to investigate the effect of salt on the expansion of starchy snacks, and particularly how the moisture content for optimal expansion changes with salt content. We will use the previously developed multiscale simulation model, but with the thermodynamics and material properties adjusted for the presence of salt in the matrix.

The description of the model and the thermodynamics will be kept brief, as full details can be found in our previous papers [30, 29]. We will give emphasis on the effect of salt. The effect of salt on the glass transition is still debated in the scientific literature. Hence, we will discuss this aspect more in depth.

After the exposition of the model and theory, we will present the simulation results. These will be analysed with help of the supplemented state diagram, with the transition lines adjusted for the amount of salt. The simulation results will be summarized with the graph indicating how the moisture content for optimal expansion depends on the salt level.

MULTISCALE MODEL

The multiscale model describes the expansion process of snacks, having dried preforms, that are fried in oil, at temperatures between 160-200°C. The snacks are thought to consist of a mixture of starch and water, with possible addition of salts. These ingredients are mixed via extrusion, which are formed to pellets via the die at the end of the extruder. The pellets are dried back to a moisture content of about 10-20%. They dried pellets are shelf-stable, because they are in the glassy state. At a later stage they are expanded via immersion in frying oil.

During frying, the snack is heated and the starch matrix enters the rubbery phase. If the temperature is above the boiling point of water, superheated steam is formed which makes bubbles to be formed and expand. Due to partial rupture of the thin walls surrounding the steam bubbles, moisture escapes from the system - which brings the matrix again in the glassy state. The expanded snacks are removed from the oil after about one minute of frying, and are cooled back to room temperature. Being again in the glassy

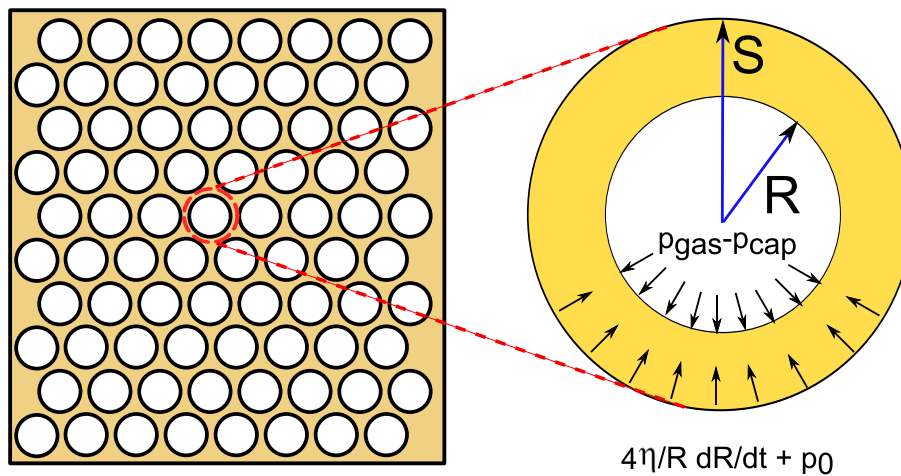


Figure 1: Schematic of the multiscale model: at the macroscale the snack is viewed as porous medium, with heat and mass transfer. At the pore scale the bubble expansion is modelled via a balance between the gas pressure and the viscous stress. A cell consists of a bubble of size R , surrounded by a shell of hydrated starch. Total size of cell is S .

state the expanded snacks are shelf stable. The resultant food texture is that of a solid foam with bubbles of sizes 50-500 microns. The complete expansion process is conveniently depicted in a state diagram [19, 31, 28, 29].

The multiscale model describes the physics of snack expansion at two levels: 1) at the product level, and 2) the pore scale level of the expanding bubble [29]. At the pore scale we make use of the cell model of Amon and Denson [1]. In cell models one assumes that the system can be approximated as a regular periodic array of identical cells, with each cell containing a single dispersed phase at its center. In our case the dispersed phase is the expanding steam bubble. The dispersed phase is embedded in the continuous phase, which is the dried amorphous starch/water matrix. At the outer boundary of the cell one assumes no flux boundary conditions for mass transport, and zero stress boundary conditions for momentum transport. A homogeneous temperature is assumed, which is obtained from the macroscale model. A schematic representation of the multiscale model is shown in figure 1.

This cell model has been applied earlier to snack expansion by Schwartzberg [21]. However, we have used in the context of a multiscale simulation framework, similar to Alavi for the case of expansion via extrusion. At the product level of a snack pellet, we describe the heat and mass transfer during frying - taking into account the effect of the changing porosity of the transport properties, like thermal conductivity and water diffusivity.

The cell model describes the time evolution of the bubble radius R as

follows:

$$\frac{1}{R} \frac{dR}{dt} = \frac{(p_{gas} - p_{cap} - p_0)}{4\eta} \quad (1)$$

p_{gas} is the gas pressure, $p_{cap} = 2\sigma/R$ is the capillary pressure and p_0 is the ambient pressure. σ is the interfacial tension between matrix and air bubble, and η is the viscosity. The above expression is a reformulation of the momentum balance, stating that the (effective) gas pressure in the bubble, $p_{gas} - p_{cap}$, is balance by the pressure in the liquid, which is the sum of the ambient pressure p_0 and the viscous stress $4\eta dR/dt/R$.

The gas of the bubble is mainly water vapour, which is in equilibrium with the surrounding shell of starch dough, having a certain water activity a_w , depending on moisture content y_w and temperature T , which is modelled by FHFV [30]. Hence,

$$p_{gas} = a_w(y_w, T)p_{sat}(T) \quad (2)$$

with p_{sat} the saturated vapour pressure, as given by the Clausius-Clapeyron relation:

$$p_{sat} = p_{boil} \exp\left(\frac{\Delta H}{M_w R_{gas}} \left(\frac{1}{T_{boil}} - \frac{1}{T}\right)\right) \quad (3)$$

with p_{boil} the vapour pressure at boiling point T_{boil} under atmospheric pressure ($p_{boil} = p_0$). ΔH is the latent heat of vaporization (in J/mol), and R_{gas} is the gas constant. The viscosity of the matrix η follows the WLF model [21]. The WLF theory takes the glass transition temperature T_g as an input parameter. T_g is a function of moisture content, y_w , which we have modelled earlier with the Couchman-Karasz theory [30]. The number of cells in the matrix is assumed to be linear with the number of native starch granules present in the original food formulation. During mixing the starch is thought to be gelatinized, but fragments of the granule remain, and act as nucleation site for the bubble expansion [21, 7].

At the product scale we describe the overall energy and mass balance for moisture in the snack. These equations are obtained after integration of Fouriers and Ficks law [29]. The energy balance is formulated in terms of enthalpy, because of the phase transition of boiling.

$$\frac{dE}{dt} = \Phi - \Delta H/M_w J_{surf} \quad (4)$$

$$\frac{dm_w}{dt} = -J_{surf} - \frac{dN_{vap}}{dt} \quad (5)$$

$$E = (m_s c_{p,s} + m_w c_{p,w})(T - T_{boil}) + N_{vap}[\Delta H + c_{p,v}/M_w(T - T_{boil})] \quad (6)$$

$$N_{vap} = n_b \frac{4}{3} \pi R^3 \frac{p_{gas}}{R_{gas} T} \quad (7)$$

E is the total energy contained in the snack, and takes the enthalpy of the water vapour present in the bubbles. m_s and m_w are the masses of starch and water in the dough, each having a specific heat denoted by $c_{p,s}$ and $c_{p,w}$. $c_{p,v}$ is the specific heat of vapour. The number of bubbles is n_b , which is thought to be related to the number of native starch granules in the original formulation [29]. The number of moles of vapour N_{vap} is computed from the gas pressure p_{gas} via the ideal gas law. The mass fraction of water present in the dough is computed as $y_w = m_w/(m_w + m_s)$. The change in water vapour dN_{vap}/dt is computed via the change of volume of the gas bubble, which is assumed to be in thermodynamic equilibrium with the starch dough.

The fluxes Φ and J_{surf} follow from the boundary conditions at the surface of the product, which are formulated in terms of the surface temperature, T_{surf} :

$$p_{surf} = a_w(y_w, T_{surf})p_{sat}(T_{surf}) \quad (8)$$

$$J_{surf} = \frac{\beta AM_w}{RT_{surf}}(p_{surf} - p_0) \quad (9)$$

$$\begin{aligned} \Phi &= h_{ext}A(T_0 - T_{surf}) \\ &= h_{int}A(T_{surf} - T) + \Delta H/M_w J_{surf} \end{aligned} \quad (10)$$

Here A is the external surface area, which changes if the snack expands. h_{ext} is the external heat transfer coefficient, which is determined by the frying process. h_{int} is the internal heat transfer coefficient, and accounts for moderate temperature gradients inside the product, cf. [25]. The internal heat transfer coefficient is related to the effective thermal conductivity of the starch dough λ_{eff} , via $h = 6\lambda_{eff}/H$. $H/6$ is a characteristic distance which is dependent on the geometry of the snack, which is linear with the thickness of the snack - which of course changes in time due to the expansion. The effective thermal conductivity depends on 1) the thermal conductivity of the dough (and is computed based on the composition cf. rules in [26]), and 2) the conduction of heat in the bubbles - which is enhanced by the evaporation-condensation (heat-pipe) effect [11]. The effective thermal conductivity is computed via Maxwell-Eucken [29].

The formulation of the boundary conditions in terms of surface temperature, accounts for the evaporative cooling of water vapour escaping (via boiling) from the surface [25]. Consequently, the boundary conditions are to be solved implicitly for the surface temperature T_{surf} . We assume that snack is fried in oil having a temperature of $T_0 = 220$ Celsius, and a heat transfer coefficient. If $p_{surf} < p_0$ $h_{ext} = 200$ W/m².K, otherwise $h_{ext} = 1000$ W/m².K - which is due to the vapour bubbles rising in the frying oil. The boundary condition for the mass flux represents the escape of moisture via boiling, which is linear with the pressure difference between gas bubbles at the surface p_{surf} and the liquid pressure p_0 . The mass transfer coefficient is taken equal to $\beta = 9 \times 10^{-4}$ m/s, which renders a frying time in the range

of 1 minute, as is observed experimentally.

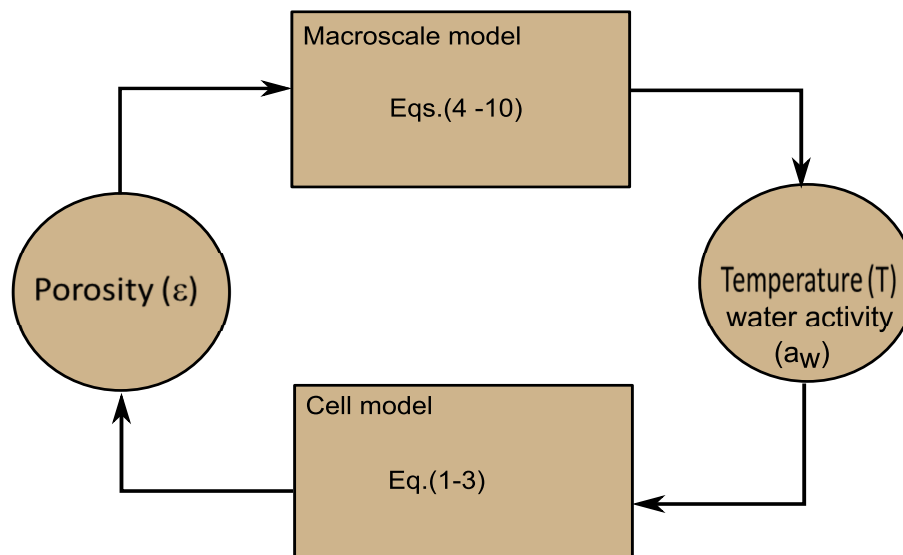


Figure 2: The computational scheme of the multiscale model, where the macroscale and cell model operate in parallel coupling, via exchange of temperature T and water activity a_w , and porosity ϵ .

EFFECTS OF SALT ON BOILING AND GLASS TRANSITION

The boiling line of starch/water mixtures is described by the FHFV theory [30]. This theory also applies to many other food materials, and has been applied to mixtures of meat proteins, water and salt [27]. Here, we have made use of the Flory-Rehner hypothesis, that the ionic contribution to the chemical potential is independent of that of the interaction of the biopolymer with water. This means that we can apply the Ross equation for the water activity $a_{w,tot}$:

$$a_{w,tot} = a_{w,FV FH} \times a_{w,ion} \quad (11)$$

$a_{w,FV FH}$ is as follows from our previous paper. For $NaCl$ we can compute $a_{w,ion}$ via an approximation of the Pitzer equation [27]. The computed water activity can be inserted into Eq.(2), which will give rise to boiling point elevation. The boiling point elevation of salts is well known, and undisputed.

The scientific literature is often contradictory on the effect of salts on the glass transition of food materials. Solutions of monovalent cations (except for lithium) are not glass formers [2]. Hence, it is not likely that sodium

chloride acts as a plasticizer. This is indeed reported in fa[12, 18, 16], for the system of NaCl and sucrose or trehalose solution. However, others state that addition of NaCl to trehalose solution increases the T_g [17]. Furthermore, it is reported that addition of NaCl decreases the mobility of concentrated sugar solutions - while there is no apparent change in T_g [34]. It has been proposed that this effect can be explained by the formation of NaCl micro-crystallites [22].

Similar contradictory results are found for other carbohydrate systems. For mixtures of maltodextrin and NaCl it is reported that the freezing point depression by salt can fully explain the slight lowering of T_g' (the intersection of glass transition and freezing lines). The similar effect is reported for dough and NaCl mixtures[15]. Farahnaky et al. [10] have investigated glass transition of extruded starch/salt mixtures. It is found that NaCl lowers the glass transition of the starch/water mixture. However, X-ray diffraction has shown no evidence of NaCl crystals.

We view it out of scope of this paper to resolve the contradictions concerning the effect of NaCl on T_g of food matrices. As it is the single source of data on starch, we take the findings of Farahnaky et al. [10] as the basis of the effect of salt of T_g of starch/water mixtures.

The data of Farahnaky is reproduced in figure 2. We assume that the starch/salt/water system still follows the Couchman-Karasz relation, with $\Delta C_{p,s}$ the same universal value as found for other food material. We have modelled the effect of salt via lowering $T_{g,s}$, linear with the mass fraction of salt (y_{NaCl}):

$$T_{g,s} = T_{g,s0} - \alpha y_{NaCl} \quad (12)$$

From linear regression follows $T_{g,s0} = 523 \pm 5$ K, and $\alpha = 833 \pm 80$ K. The glass transition as function of mass fraction of water y_w is following Couchman-Karasz:

$$T_g = \frac{y_w T_{g,w} \Delta C_{p,w} + y_s T_{g,s} \Delta C_{p,s}}{T_{g,w} \Delta C_{p,w} + T_{g,s} \Delta C_{p,s}} \quad (13)$$

$T_{g,w}=134$ K is the glass transition of pure water, and $T_{g,s}$ is the glass transition of starch, as influenced by salt - via Eq.(12). y_w is the mass fraction of water, and $y_s = 1 - y_w$ is the mass fraction of solids. The change of specific heat at the glass transition is $\Delta C_{p,w}=1.94$ kJ/kg.mol and $\Delta C_{p,s}=0.42$ kJ/kg.mol for water and starch respectively. The above correlation holds for $y_{NaCl} \leq 0.06$. In figure 2 the correlations for $y_{NaCl} = 0$ and $y_{NaCl} = 0.06$ are shown, which compare favourably with the experimental data.

RESULTS AND DISCUSSION

With the above presented multiscale model we have performed calculations on the expansion of starchy snacks pellets with different initial moisture

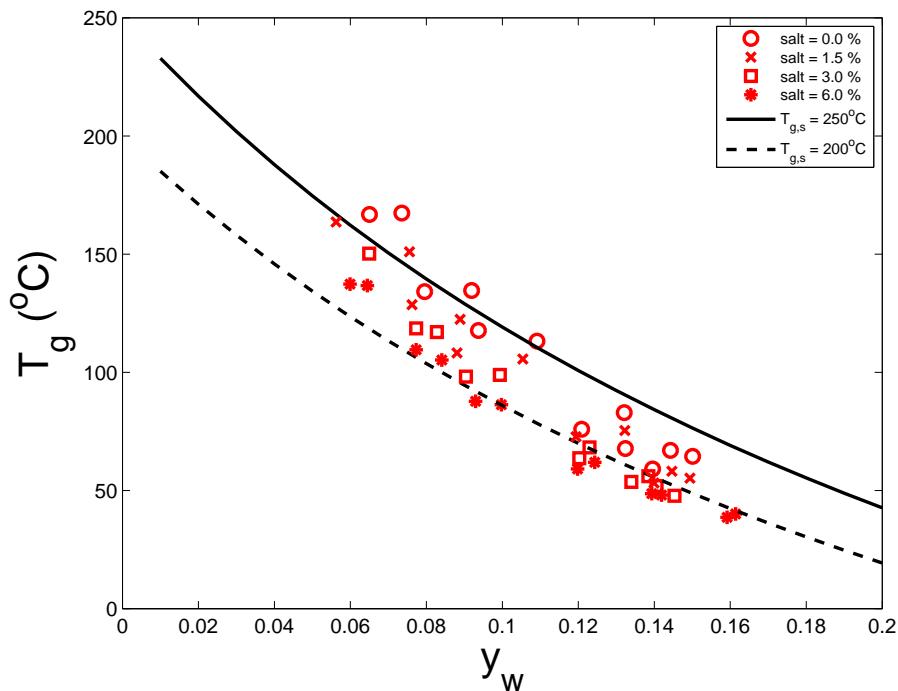


Figure 3: Glass transition temperature T_g as function of mass fraction of water y_w for various amounts of salt (dry weight basis), based on the experimental data of Farahnaky et al. [10]. The lines indicate the prediction of T_g using Couchman-Karasz with $T_{g,s} = 200^\circ\text{C}$ and $T_{g,s} = 250^\circ\text{C}$, corresponding with salt content of $y_{NaCl} = 0.06$ and $y_{NaCl} = 0.0$ respectively.

and salt contents. First we have performed simulations for salt content of $y_{NaCl} \leq .04$, and the initial moisture content in the range of $0.05 < y_{w,0} < 0.20$. Geometrical parameters are taken equal to those of our previous study [29].

The simulation are performed with time running in the range $0 \leq t \leq t_p$, with $t_p=90$ s the typical processing time of snack pellet frying. The frying oil temperature is assumed to be 200°C . If the strain rate exceed the critical value of 10 s^{-1} , we assume the bubble ruptures, and the simulation is stopped. The simulation results for $y_{NaCl} = 0.04$ are shown in figure 3.

In the left pane of the figure we show the radius of the expanding bubble as a function of time, i.e. the time series $R(t)$. We have plotted the results of all investigated moisture contents in the same figure, and are indicated with different colors. The corresponding initial moisture content is easily read from the figure in the right pane. There, we have indicated the path followed by each pellet through the state diagram. At each time, we have recorded the state of the solid phase, i.e. its temperature and moisture

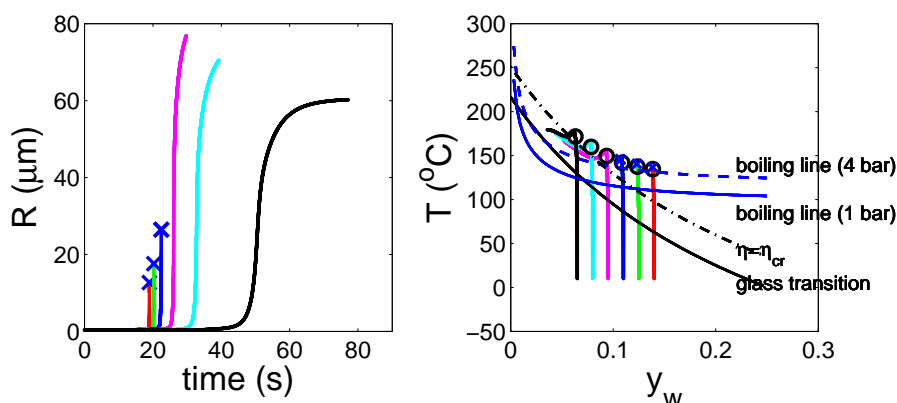


Figure 4: The evolution of bubble radius in time for various moisture contents, and salt level of $y_{NaCl} = 0.04$. The evolution of the state of the expanding pellet is plotted in the supplemented state diagram.

content. These state points are plotted in the state diagram, and give a unique path for each pellet. All paths start at the point $(y_{w,0}, T_0)$, with T_0 the initial (room) temperature.

In the state diagram we have plotted the boiling lines at 1 and 4 bars, the glass transition line, and the isoviscosity line at $\eta = 10^6$ Pa.s. We note again, that the glass transition line is also an isoviscosity line with $\eta = \eta_g = 10^{13}$ Pa.s. The other isoviscosity line is computed with the WLF theory.

During frying, first the temperature rises without significant loss of moisture from the solid phase. Under certain conditions, the bubble expansion starts. This moment is indicated with the open circle projected on the path of each sample. The expansion starts quite abruptly, as is shown by the time series $R(t)$ in the left pane. During expansion moisture is lost from the solid phase and forms the steam in the expanding bubble. In the expansion stage the gas pressure can reach pressures over 4 bar. The expansion enlarges the external surface area, and the moisture is lost from the product via steam bubble formation at the surface. Therefore, we observe that after the moment of expansion the path in the state diagrams move towards lower moisture content - while the temperature increase is quite slowed down. This slow down is due to the evaporative cooling effect of the steam generated for the expanding bubbles, i.e. most of the heat from the frying oil is transferred to latent heat of the steam in the bubbles, and is not available for the rise of temperature (sensible heat).

We investigate whether for pellets containing salt, the optimal expansion occurs also the point where the boiling line (of 4 bar) intersects the critical viscosity of $\eta_{cr} = 10^6$ Pa.s. Mind, that salt induces displacement of both the boiling line and the critical isoviscosity line in the state diagram. The boiling

line is displaced due to the boiling point elevation, and the isoviscosity line is displaced due to the change of T_g by salt, which determines the viscosity via the WLF theory.

As in our previous paper, we have determined for a multitude of samples, with an initial moisture content in the range of $0.05 \leq y_{w,0} \leq 0.22$, the moment of the start of the expansion. Results are shown in figure 4. In the right pane of figure 4 we have plotted the final bubble radius as a function of moisture content, for both $y_{NaCl} = 0.04$ and $y_{NaCl} = 0.0$.

From figure 4 we observe that also for snack pellets containing salt the optimal expansion also occurs at the moisture content where the (4 bar) boiling line intersects the isoviscosity line of $\eta_{cr} = 10^6$ Pa.s. Due to the displacement of both these lines in the supplemented state diagram, the moisture content for optimal expansion for salty snacks is lower compared to pellets without salt, as shown in the right panel of figure 4. Furthermore, the width of the range of moisture content with stable bubble formation (without collapse) is more limited for salty snacks compared to snacks without salt. Namely, salty snacks expand if the initial moisture content is in range $0.05 < y_{w,0} < 0.1$, while snacks with zero salt expand if the initial moisture content is in the range of $0.08 < y_{w,0} < 0.15$, which is definitely wider. This means that by reducing the amount of salt, the expansion process becomes less sensitive to variation and non-uniformity in the amount of initial moisture in the dry pellets. Pellets are extruded at moisture contents of 20%, and need to be conditioned (dried) to the optimal moisture content for expansion, which is lower. At such low moisture contents the drying process takes quite a long time, which can not be available for logistical reasons.

For salt contents in the range of $0 \leq y_{NaCl} \leq 0.06$ we determine the moisture content for optimal expansion. The results are plotted in figure 5. We observe that if the amount of salt is reduced in the snack formation the moisture content for optimal expansion has increased. Currently, snacks have a salt content of about $y_{NaCl} = 0.03$. Hence, a reduction of salt towards a level of $y_{NaCl} = 0.02$ implies that the initial moisture content of the dry pellets has to be increased from $y_{w,0} = 0.12$ to $y_{w,0} = 0.13$. The simulation model predicts that the bubble radius at optimal expansion is hardly dependent on the amount of salt. This is important for snack producers, because similar texture can be obtained for snacks with reduced salt content, if one adjusts the initial content of the pellet to the value of optimal expansion, as can be read from figure 5.

Sjoqvist found similar moisture content for optimal expansion of starch foams without salt using microwave [23]. Norton and coworkers show that increase of salt level (at same moisture content) shows increase of expansion during air heating [20]. Such an increase of expansion with increase of salt content has also been found for keropok products, expanded via frying [13, 5] and for starchy product expanded via extrusion cooking [8].

Our estimation for pore diameter might well be an underestimate of the

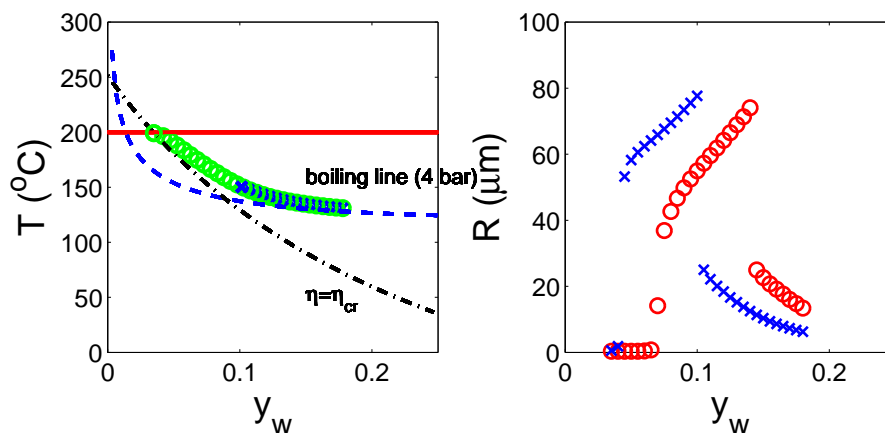


Figure 5: In the left pane we have indicated with green circles the values of the state variables (y_w and T) of the solid phase at the moment of the start of the expansion. This is done for a range of initial moisture content $0.05 \leq y_{w,0} \leq 0.22$, a salt content of $y_{NaCl}=0.04$ and a frying oil temperature of 200 degrees Celsius. Also, we have indicated with crosses whether bubble collapse occurred. In the right pane we show the maximal bubble radius at steady state, or the moment of rupture, for the case of zero salt content (red circles) and $y_{NaCl} = 0.04$ (blue crosses).

actual pore diameter. In our model we have assumed no (partial) coalescence of bubbles - which gives a significant increase of pore diameter in expanded snacks. Furthermore, trial simulations has shown that our pore diameter is dependent on the estimated amount of initial nucleii. Kraus et al. have assumed that microwaved snacks the amount of nucleated bubbles is much less than the number of native starch granules in the original pellet formulation (prior to extrusion or mixing) [14]. The resulting pore diameter will not have any influence on the moisture content required for optimal expansion. The physical explanation of the latter factor has been the objective of this paper, rather than the actual size of the pore diameter.

CONCLUSIONS

In this paper we have applied the multiscale simulation model for the expansion of starchy snacks with salt during frying. The multiscale model has previously been applied to the expansion of starchy snacks without salt. Similar to our previous paper, we have found that the optimal expansion for salty snacks occurs at the same conditions as for snacks without salt, namely at the moisture content where the 4 bar boiling line intersects the isoviscosity line of $\eta_{cr}=1$ MPa.s. Because salts is influencing both the boiling

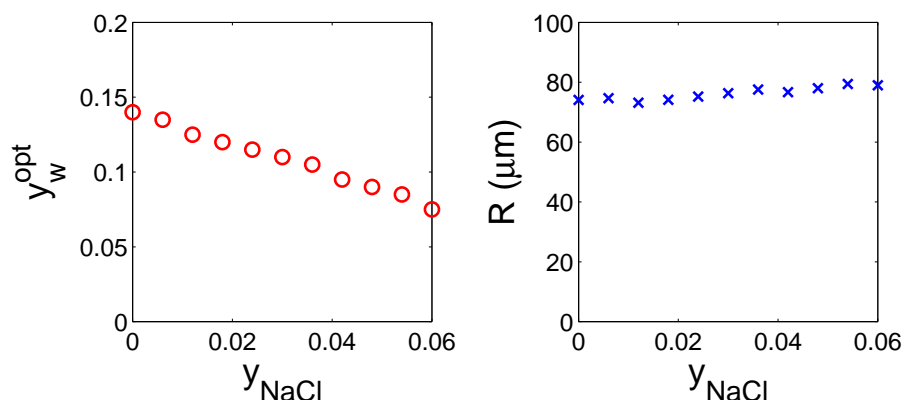


Figure 6: In the left pane we have indicated the moisture content for optimal expansion, $y_{w,opt}$, as a function of salt content y_{NaCl} . In the right pane we show the bubble radius at optimal expansion as a function of salt content.

line and the isoviscosity line (via change of T_g , which is a parameters of the WLF model for viscosity), the optimal moisture content for salty snacks is lower compared to that of snacks without salt. This prediction of our model is shown to be consistent with experimental findings on the effect of salt on expansion.

If pellets with reduced salt content are conditioned at an initial moisture content, corresponding with that for optimal expansion, the amount of expansion will be comparable to the snack with increased salt level. This is an important finding for food formulators, who want to reduce salt content. We expect that product properties will not be compromised, if the pellets are preconditioned at the proper initial moisture content, which will be higher compared to that of salty snacks. Hence, there are good opportunities for producing snacks with reduced salt, and thus less health risks.

The presented tools, the multiscale simulation model and the supplemented state diagram, have potential use beyond this case study of expanding starchy snacks. It can be used for a wide variety of reformulation problems in structured foods, like in baked cake [33], cookies [24, 6] and bread [9, 3].

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