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Review

Clumping of frozen par-fried foods: Lessons from frosting on structured surfaces

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ABSTRACT

In this paper, we review the problem of clumping due to frost formation on frozen vegetables, like par-fried potato products. This problem has been very scarcely investigated in the scientific literature. Yet in the industry it is a significant problem, as evident by the various patents on this topic. Thanks to the enormous, recent growth of scientific literature on frost formation on engineered, structured surfaces, we have drawn a multitude of hypotheses of factors governing the clumping and frost formation of frozen foods, which can also be viewed as a structured surface.

1. Introduction

One of the quality problems with frozen foods, like frozen vegetables and par-fried potato products, is that they can clump to each other. Consumers may have experienced the clumping with prepackaged frozen peas or pieces of spinach, which are sold with the promise of easy dosing. However, due to temperature variations during transport from the supermarket to their freezer or temperature fluctuations of their own freezer, it will occur that ice (or frost) has grown on the surface of the peas. If the frost of different pieces has grown into each other, all the pieces have become one big clump, which is poorly dosable. Even powerfull consumers will not be able to break this clump.

Also in food industry clumping of frozen food is a problem. In the business-to-business market selling ingredients for multicomponent meals like pizzas, one often makes use of frozen foods. Here the easy dosing of frozen vegetable pieces is also highly desired. Next, to the dosing problem, clumped frozen par-fried potato products have the enhanced risk of splashing of oil during finish frying (Hamann & Henderson, 2009; Leguizamon & Leonardo, 2009). To solve this problem one has designed special de-clumping machinery, which detaches the clumps mechanically. But, this is always accompanied by mechanical damage to the foods. Clearly, this is not the ideal solution.

Clumping of frozen foods has received very little attention in scientific literature, except for a select number of patents on this topic. Yet, frost formation on structured surfaces, like superhydrophobic surfaces based on the Lotus-effect, is currently a very popular and active research field, even attracting researchers from the field of physics. This is because, frost formation is a more eminent problem in sectors like aviation, and refrigeration. Nowadays, frost on airplane wings is removed by chemical means, but this is not desired with current concerns about the environment. The recent research on frost formation is centered on passive means to prevent frost. Here the solution is sought in the engineering of surface properties (Rykaczewski, Anand, Subramanyam, & Varanasi, 2013). Hence, in this paper we review the insights from this research field, and how it can apply to frost formation on frozen foods, and in particular on parfried frozen foods.

In the patent literature of foods, it is stated that the type of oil applied during par-frying has a substantial influence on frosting (Benson D.B. & H., 2006; Hamann & Henderson, 2009). For nutritional reasons industry has recently switched over to vegetable oils, that are rich in unsaturated fatty acids. This switch has increased the occurrence of clumping. Traditionally these foods are par-fried in oil rich in saturated fats or transfats. These frying oils are characterized by a higher melting temperature compared to vegetable oil rich in unsaturated fatty acids. The latter will have a liquid-like consistency at room temperature, while the former will have a more solid-like consistency at room temperature. The melting point of the oil with respect to the frozen storage temperature is thought to be a determining factor for clumping. Furthermore, it is thought that also the crystal structure is of importance (Hamann & Henderson, 2009).

The clumping of frozen foods is mediated by the formation of frost on the surfaces of individual pieces of food. Clumping occurs if the frost layers grow into each other, and form a single dense network of dendrites. For clumping, it requires that the two dendrite networks will sinter (van Herwijnen & Miller, 2013). Sintering is accelerated by water vapor transport, which can occur in presence of gradients in temperature or water activity.

Frost formation is also a problem for other frozen foods, as stored in

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domestic freezers (Laguerre & Flick, 2007). In a domestic freezer, the air temperature fluctuates due to the action of the refrigeration equipment. The water used to build up the frost layer is supplied by the frozen food, which dehydrates (Reid & Perez-Albela Saettone, 2006). Dehydration increases with storage temperature and fluctuations. However, the effect of fluctuations is smaller at lower storage temperatures. In this regime, there might even be some potential for reduction of energy consumption (Moleeratanond, Kramer, Ashby, Bailey, & Bennett, 1979).

We have organized this review paper as follows. First, we start with a description of the several steps in the frost formation, as envisioned in the fields of frost formation on refrigeration equipment and structured surfaces. Subsequently, we describe the different solutions investigated in the field of structured surfaces to prevent frost formation. The structured surfaces make use of different physical mechanisms to prevent frost formation, which are briefly discussed in the theoretical section. Finally, we discuss the potential causes to frost formation on frozen, fried foods using the knowledge from the field of structured surfaces, and patent literature from the food area.

2. Stages of frost formation

A better insight into frost formation is obtained if one divides the process into several stages. For the division of frost formation in stages, we will follow the well-developed academic research line investigating frosting on heat exchangers of refrigeration equipment (Hoke, Georgiadis, & Jacobi, 2000). The different stages one distinguishes in this field are depicted in Fig. 1. However, we have extended this with a final step of sintering – which is required for clumping individually frozen food particulates. Some refinements of these stages one finds in the literature on frost formation on structured surfaces (Oberli et al., 2014). We will include that too in the detailed description below.

The initial step in frost formation is the nucleation of water droplets on the surface (Hoke et al., 2000), see Fig. 1a. The condensation only occurs if the surface temperature is below the freezing point of water, and the dewpoint of the air in the head space is below the surface temperature. This initial stage is called condensation frosting. Due to the difference in the amount of released latent heat, it is more likely that water vapor from the air condenses as liquid instead of directly as ice. Classical nucleation theory is thought to apply to condensation frosting (Oberli et al., 2014).

Before the freezing of the droplets occurs, the nucleated liquid droplets often coalesce, as shown in Fig. 1b. This is expected to happen quite extensively on structured surfaces because of their delay of the freezing step (Oberli et al., 2014). One has to recall that for coalescence the droplet needs to remain in the liquid state. If droplets are frozen, coalescence cannot happen. The driving force for coalescence is the minimization of the free energy via reduction of the air–water interface. A precondition for significant coalescence between condensed droplets it that the droplet size is larger than the length scale of the surface roughness.

Subsequently, individual droplets start to freeze (see Fig. 1c). The nucleation of ice starts at the rim of the droplet, i.e. at the contact line between surface, water, and air (Georgiadis & Hoke, 2012; Oberli et al., 2014). The ice front will invade the droplet, which will freeze completely.

At the end of the droplet freezing one has often observed a cusp column of ice on top of the droplet (Georgiadis & Hoke, 2012), as depicted in Fig. 1d. This is the start of the early growth stage of frost formation. The column at the top of the droplet is especially observed under conditions of forced convection. This phenomenon is attributed to the difference in density of ice and liquid water. It is not clear whether that also happens with natural convection. The frost will form first via columnar growth.

Later in the transition to mature growth stage, the existing columns will thicken via direct solidification from the vapor phase

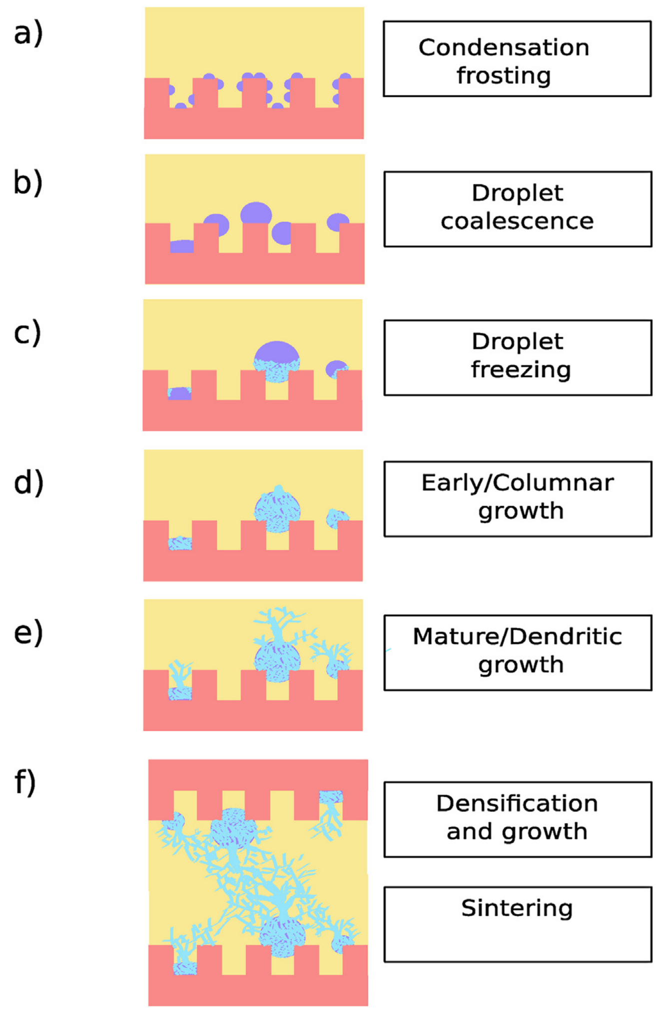

Fig. 1. Different stages in the frosting process leading to clumping of food particulates.

(desublimation), and dendrites will form due to the branching of the columns, see Fig. 1e. Later, there is mainly dendritic growth, which will thicken and coalesce later to form a network (a frost layer) (Laguerre & Flick, 2007). The thickness of the frost layer will increase with time, as long as the surface temperature is below the freezing point of water. The frost layer will remain porous.

Via microscopy one has observed that there is a significant interaction between frozen droplets and unfrozen neighboring droplets: (1) neighboring small droplets undergo strong evaporation, and (2) there is ice-bridge formation between frozen and unfrozen droplets, which will contact the unfrozen droplets and will let them freeze. Both phenomena are consequences of the fact that the frozen drop has a lower saturated vapor pressure than the small surrounding liquid drops. Particularly, on structured surfaces one observes freezing via ice-bridge formation, which spreads like a wave over the surface. Ice bridge formation can even occur above air gaps in between droplets (Zhao & Yang, 2016). Here, the ice bridge has quite a similar form as the ice cusp, growing on top of freezing droplets. But, in other cases with ice bridges forming on the surface, they have a dendritic shape (Oberli et al., 2014). Because of the ice-bridge formation, the heat transfer properties of the surface is of little importance for the initiation of freezing step.

The frost structure depends on the wetting properties of the surface (Georgiadis & Hoke, 2012). In the early stage one observes a larger frost thickness on hydrophobic substrates, but with a lower density (more porous), and for hydrophilic substrates, it is the opposite. The thickness and density of the frost layer will determine the thermal conductivity,