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Modelling water evaporation during frying with an evaporation dependent heat transfer coefficient

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ABSTRACT

In this study a cylindrical crust-core frying model was developed including an evaporation rate dependent heat transfer coefficient. For this, we applied a Nusselt relation for cylindrical bodies and view the release of vapour bubbles during the frying process as a reversed fluidised bed. The characteristic length and velocity for the Reynolds number are taken as the average diameter of the vapour bubbles and vapour bubble release frequency multiplied with the bubble diameter, respectively. The model assumes limited conductive heat transfer and convective water vapour flow through the crust following Darcy's law. The predictions of temperature profiles and water loss in potato cylinders of different size and at varying frying temperature were found in good agreement with experimental data. Extensions to the crust-core model are suggested to improve prediction of the heat transfer coefficient and water vapour flux; however this should be balanced to keep the model simple for engineering purposes.

1. Introduction

Deep-fat frying is a method to prepare food through rapid dehydration by completely submerging it in hot oil. Heat is initially transferred from the oil to the product surface through free convection, and from the surface to the interior via conduction. As water starts to evaporate from the product, the external heat transfer changes from free to forced convection by the emergence and escape of water vapour bubbles. A dry crust forms, which hinders conductive heat transfer and provides a resistance for moisture loss. The latter results in a pressure gradient between the moist interior of the product and the surface (Sandhu et al., 2013; Vitrac et al., 2000). As the evaporation rate decreases due to increasing crust thickness, the pressure gradient over the crust also decreases and oil may enter the product (Van Koerten et al., 2015a). When the product is removed from the frying medium, the pressure gradient is lost with the heat transfer driving it, resulting in significant oil uptake (Bouchon et al., 2003; Ziaiifar et al., 2008). Since the moisture evaporation forms the basis for frying and is connected to oil uptake, an accurate description of the kinetics of water loss during frying is important for optimal control of the frying process.

Various models have been developed to describe moisture loss during frying, ranging in complexity from simplified empirical equations to complex numerical models, which incorporate mechanistic equations for both heat and mass transfer. All models have their own advantages in describing the moisture loss during frying. The simplest empirical models fit very well with the data set that is used, but they have to be fitted for every new data set and are therefore not well suited for extrapolation and prediction (Costa and Oliveira, 1999; Gamble et al., 1987; Krokida et al., 2000).

On the other side of the spectrum, numerical models have been developed based on heat and mass transfer in porous media (Halder et al., 2006). These models incorporate phenomena such as diffusion, Darcy flow, heat transfer, and volume reduction. The main problem is that these models are highly computational intensive and contain many input parameters. Meanwhile, also relatively more simple models have been developed on the basis of additional assumptions that still provide accurate predictions. For example, Farid (2001) developed an analytical model based on the assumption that frying is limited by heat transfer.

A recurring problem in modelling moisture evaporation during frying is the lack of a thorough description of the external heat transfer coefficient during forced convection. Models either use

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constant values for the heat transfer coefficient (Lioumbas et al., 2012a; Ni and Datta, 1999; Warning et al., 2012) or variable values based on literature (Bansal et al., 2014). However, studies show that the heat transfer coefficient varies greatly during frying due to water evaporation (Farinu and Baik, 2007; Mir-Bel et al., 2012). It would be logical to assume that the heat transfer coefficient is a function of the evaporation rate, as bubble formation at the product surface enhances forced convection.

In this work we present a relatively simple, though mechanistic model assuming a sharp moving boundary between the dry crust and moist interior of potatoes, in which the external heat transfer coefficient is connected to the water evaporation rate via a Nusselt correlation. While the water evaporation is mainly considered to be heat transfer dependent, the convective flow resistance of the water vapour in the crust was modelled following Darcy's law. Both the moisture loss during frying and the temperature profile at the surface and the center of the potatoes were compared to experimental values for model validation.

2. Materials & methods

2.1. Preparation of raw potato samples

Alexia potatoes purchased at a local supermarket were used. The potatoes were cut into uniform cylinders with a cork borer and a stainless steel knife into three different diameters: 8.5, 10.5, and 14 mm. The cylinders were cut to a length of 50 mm with a calliper. Samples were then soaked for 10 min in tap water to equilibrate the moisture content of the batch; tissue paper was used to remove excess surface water.

2.2. Frying experiments

Potato samples were fried in a professional fryer (Caterchef EF 4L), with a build-in thermostat controlled at ± 2 °C, containing 3L of 100% sunflower oil as frying medium (Horeca Select, Makro, the Netherlands). Three different temperatures were used to fry the samples: 140, 160, and 180 °C. The sample frying times were 20, 40, 60, 120, and 180 s. One sample was fried at a time, and three duplicates were performed for each sample. Combined with the varying potato diameters (Section 2.1), this resulted in 9 data sets with different potato diameter – frying temperature combinations.

2.3. Moisture content

Prior to frying, the raw potato cylinders were weighed to determine their initial mass. After frying, the moisture content of the potato cylinders was determined by oven drying at 105 °C to constant weight (approximately 24 h). Afterwards, all oil was extracted from the cylinders using soxhlet extraction (Büchi extraction system B-811), leaving only the dry matter of the potato cylinders. To determine the amount of moisture evaporated from the cylinders during frying, the mass balance was solved assuming oil, water, and dry matter as the only components.

2.4. Temperature measurements

A thermocouple (type X4/P4 chromel-alumel, Tempcontrol, The Netherlands) was inserted in the potato, either at the surface or at the centre. The potato with the thermocouple was lowered in the frying oil for four centimetres. Therefore, the thermocouple could not conduct heat directly from the oil to the measuring tip (Fig. 1). After frying, the potato was cut to exactly determine the position of the thermocouple using a calliper. A data logger (EL-USB-TC, Lascar, UK) was used to obtain a time-temperature profile from the thermocouples at a frequency of 1 Hz.

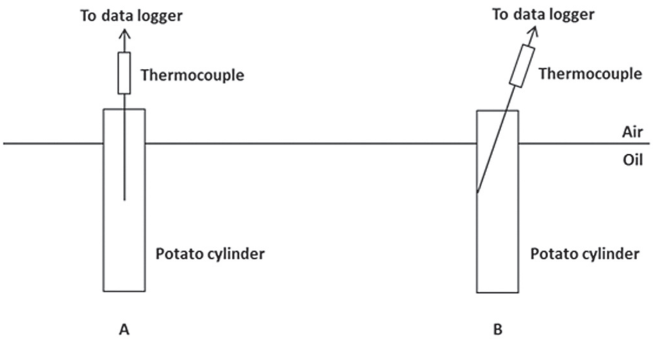

Fig. 1. Schematic representation of the frying of a potato cylinder. A: Measuring the temperature at the center. B: Measuring the temperature profile at the surface.

3. Model development

3.1. Model assumptions

To minimise computational effort, several assumptions were made for development of the model.

1) The evaporation front is modelled as a sharp boundary with a completely dehydrated crust on one side and a moist interior with the initial moisture content on the other side.
2) Shrinkage is neglected. Besides the fact that this reduces the computational effort, potatoes only experience around 10% shrinkage for the time intervals used in this work (Costa et al., 2001). The creation of pores is taken into account.
3) The model assumes a cylindrical potato with infinite length, which allows for a one-dimensional formulation of the model.

Since the experiments were also performed using cylindrical fries, representative results are expected. The frying process itself is divided into 3 phases:

- Phase 1 (Initial heating): In this first phase no water evaporation takes place as the fry surface is heated to the boiling temperature of water. Heat is transported from the oil to the fry surface through free convection, while conduction takes place from the fry surface to the interior.
- Phase 2 (Surface water evaporation): This phase starts as soon as the surface of the fry reaches the boiling temperature of the water (T_{boil}). Water starts evaporating while the surface temperature of the fry remains at T_{boil}.
- Phase 3 (Crust formation): As all the surface water is evaporated, crust formation begins and forms an additional barrier for heat transfer and vapour expulsion. The external heat transfer coefficient increases due to forced convection as a function of the evaporation rate. The sharp evaporation boundary migrates inwards, increasing the crust thickness.

3.2. Governing equations

During phase 1 of the process, only heat transfer takes place without water evaporation. Thus, the temperature profile inside the potato can be described using the general heat equation using