



# Studying fluid-to-particle heat transfer coefficients in vessel cooking processes using potatoes as measuring devices



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## ABSTRACT

This paper presents and demonstrates a novel idea of using spherical potatoes as a dispensable, cheap device for determining the fluid-to-particle heat transfer coefficient,  $h_{fp}$  in vessel cooking processes. The transmission of heat through the potato can be traced by measuring the distance from the surface to the gelatinization front, which is easy to identify visually. Knowing this distance, the gelatinization temperature, the period of immersion, and the average radius of the potato, the heat transfer coefficient can be calculated. Either a numerical model based on the Finite Element Method (FEM) or an analytical solution of the Fourier equation can be applied for the calculation. The gelatinization temperature of the potatoes used was determined to be 67 °C by a direct temperature measurement and by visual inspection of the progression of the gelatinization front. A sensitivity analysis demonstrates that the method is rather precise at relevant values of  $h_{fp}$  in vessel cooking (100–300 [W/m<sup>2</sup> K]), allowing a prediction of the centre temperature within  $\pm 0.6$  °C.

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## 1. Introduction

Heating of suspended particles in a liquid is a very common operation in the food industry, for example in many canning processes (Meng and Ramaswamy, 2005), in continuous aseptic processing (Ramaswamy et al., 1997), or in vessel cooking of soups and sauces with suspended pieces of meat and/or vegetables (Bouvier et al., 2011). It is the vessel cooking process that is the focus of this paper. The common practice in industry is first to make the base soup or sauce and then add the solid food pieces at prescribed intervals. At the time of addition, the solid food pieces are colder than the fluid, or even frozen; this can cause a significant drop in the temperature of the fluid. After processing the product needs to be cooled, and this also induces considerable temperature gradients between the fluid and the particles.

To evaluate if the suspended food particles have received an adequate heat treatment in the course of the process it is necessary to know the geometry and thermo-physical properties of the food particles and also to have a rough assessment of the fluid-to-particle heat transfer coefficient,  $h_{fp}$ , under the prevailing process conditions. Calculation of the thermo-physical properties from knowledge of the composition of the food can be done with

reasonable accuracy (Nesvadba, 2014; Singh and Heldman, 2014: 275–282). In contrast, the most realistic option in the vessel cooking process is to determine  $h_{fp}$  experimentally, because a theoretical calculation by numerical simulation of the fluid-to-particle heat transfer in vessel cooking would be very difficult. The suspended particles generally, but not fully, follow the movement of the liquid, the slip velocities are low, and both forced and natural convection contribute to the heat transfer. Natural convection will evidently dominate if stirring is not applied or only used intermittently to minimise mechanical damage (Bouvier et al., 2011).

In the literature several different techniques have been reported for measuring fluid-to-particle heat transfer coefficients in food processes, primarily in continuous heat treatment processes or in canned foods processed in rotating autoclaves. A complete listing of references is out of scope here, as the literature (the majority of references are from the 1980s and 1990s) is well covered by three extensive reviews (Maesmans et al., 1992; Ramaswamy et al., 1997; Barigou et al., 1998). The most common approach is to measure the temperature–time profile inside a real food particle or replicas of either materials having thermal properties close to food products or of a highly conductive material, usually aluminium. By fitting the temperature–time curve to a mathematical solution of the Fourier equation for non-stationary convective heat transfer into a body of the relevant geometry, usually a sphere, it is possible to estimate  $h_{fp}$  (Maesmans et al., 1992; Barigou et al.,

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## Nomenclature

$\alpha$	thermal diffusivity; $\alpha = k/(\rho \cdot c_p)$ ( $\text{m}^2/\text{s}$ )	$\rho_g$	density of glass ( $\text{kg}/\text{m}^3$ )
$Bi$	Biot number; $Bi = h_{fp} \cdot k/R$ (-)	$\rho_p$	density of potato ( $\text{kg}/\text{m}^3$ )
$c_{p,p}$	specific heat capacity of potato ( $\text{J}/\text{kg K}$ )	$R$	radius of potato (m)
$c_{p,g}$	specific heat capacity of glass ( $\text{J}/\text{kg K}$ )	$t$	time (s)
$dfs$	distance from surface (m)	$T$	temperature ( $^{\circ}\text{C}$ )
$D$	diameter of potato (m)	$T_{air}$	temperature, air ( $^{\circ}\text{C}$ )
$Fo$	Fourier number; $Fo = t \cdot \alpha/R^2$ (-)	$T_{fluid}$	temperature, fluid ( $^{\circ}\text{C}$ )
$h$	heat transfer coefficient ( $\text{W}/\text{m}^2 \text{K}$ )	$T_g$	gelatinization temperature ( $^{\circ}\text{C}$ )
$h_{air}$	heat transfer coefficient, air ( $\text{W}/\text{m}^2 \text{K}$ )	$T_s$	temperature, surface ( $^{\circ}\text{C}$ )
$h_{fg}$	heat transfer coefficient fluid–glass ( $\text{W}/\text{m}^2 \text{K}$ )	$T_0$	temperature, initial ( $^{\circ}\text{C}$ )
$h_{fp}$	heat transfer coefficient fluid–particle ( $\text{W}/\text{m}^2 \text{K}$ )	$x/R$	relative distance from center (-)
$k_g$	thermal conductivity of glass ( $\text{W}/\text{m K}$ )		
$k_p$	thermal conductivity of potato ( $\text{W}/\text{m K}$ )		

1998). Three examples of studies using this approach are: one represents particles in tube flow (Ramaswamy and Zareifard, 2000), another is dealing with the determination of  $h_{fp}$  for surface pasteurisation of eggs (Denys et al., 2003), and a third is a study of the autoclaving of a canned, viscous model food with particles (Meng and Ramaswamy, 2005).

The advantage of using particle replicas of metal, for which the Biot number is very low ( $Bi < 0.1$ ), is that the solution to the heat transfer equation is simple and allows a high precision in the determination of  $h_{fp}$  (Barigou et al., 1998). It is also an advantage that the position of the temperature sensor inside the body is not critical (Ramaswamy et al., 1997). The use of particles with food-like thermo-physical properties ( $Bi > 0.1$ ) generally results in a less precise determination of  $h_{fp}$ , and the heat transfer equation must be solved by a series expansion of the Fourier equation (Maesmans et al., 1992; Barigou et al., 1998) or by numerical methods (Finite Element Method = FEM). However, an advantage of using model particles with food-like thermo-physical properties is that the heat transfer conditions are more realistic than for metal replicas; this holds in particular for cases where natural convection is significant (Åström and Bark, 1994). The different solutions to the heat transfer equation at  $Bi > 0.1$  are presented in standard textbooks (Mills, 1995: 167–176; Singh and Heldman, 2014: 355–383) and need not be expounded here.

The recording of the temperature inside the particle represents a major experimental obstacle in nearly all processes since the food pieces are normally free flowing in the liquid, and a connecting wire will restrict the particle flow. Alternative, wireless methods are therefore much sought for (Maesmans et al., 1992). Time-temperature-integrators based on the kinetics of microbial inactivation have been proposed and tested, but the method requires calibration and does not seem to be precise for determination of  $h_{fp}$  (Maesmans et al., 1994). The method is, however, useful for studying the temperature distribution in agitated vessels (Mehauden et al., 2008). Particles with embedded liquid crystals, which are heat sensitive and change colour with temperature have been tested (Balasubramaniam and Sastry, 1994). Calibration is difficult and the use of the technique is restricted to transparent liquids in transparent equipment (Ramaswamy et al., 1997; Barigou et al., 1998). A promising technique is magnetic resonance imaging (MRI) which has been tested in continuous aseptic processing of potato cubes (Kantt et al., 1998). The method relies on the temperature dependence of the proton resonance frequency, and it does seem to produce a reliable image of the temperature distribution inside the potato cubes, from which  $h_{fp}$  may be calculated by numerical modelling and fitting. The method requires a metal-free imaging region (Kantt et al., 1998) which may be difficult to achieve experimentally in vessel cooking. Tessneer et al.

(2001) have demonstrated that the mechanism of ablation heat transfer could be used for determining  $h_{fp}$  in tube flow. Spheres of ice were introduced into the tube flow and recovered after leaving the tube. From the weight difference an energy balance can be set up, allowing the calculation of  $h_{fp}$ . The method could best be applied at low fluid temperatures, around  $10^{\circ}\text{C}$  and below; this speaks against the feasibility of this method because the viscosity and hence  $h_{fp}$  at those temperatures would be much different from the viscosity in vessel cooking in the typical temperature range of  $75$ – $100^{\circ}\text{C}$ .

As appears from the above discussion of the literature, there are only few studies concerned directly with the study of fluid-to-particle heat transfer in vessel cooking. In this paper we propose to use spherical potatoes as dispensable, cheap devices for studying fluid-to-particle heat transfer in such processes.

## 2. Theoretical background for using potatoes for measuring the fluid-to-particle heat transfer coefficient

The gelatinization of the starch in intact potatoes occurs in a narrow temperature interval around  $T_g = 67.5^{\circ}\text{C}$  (Pravisan et al., 1985; Verlinden et al., 1995). Below this transition temperature the activation energy for the gelatinization reaction is very high, around  $800 \text{ kJ}/\text{mole}$ , while it is lowered by a factor of 3 when the temperature,  $T > T_g$  (Verlinden et al., 1995). Conversely, the reaction rate increases by a factor of  $10^7$  when  $T > T_g$  (Verlinden et al., 1995). These kinetic characteristics means that the gelatinization reaction is very slow for  $T < T_g$ , but as soon  $T$  reaches  $T_g$ , the reaction will accelerate drastically, as shown by simulations (Verlinden et al., 1995). This explains why the gelatinization front during cooking of potatoes is easily identified visually and is rather sharp (Derbyshire and Owen, 1986; Lamberg and Olsson, 1989).

The gelatinization interval for intact potatoes is not statistically significant for different typical varieties of potatoes available in the late season (autumn) (Karlsson and Eliasson, 2003a). This means that the potato samples can be selected according to availability and shape. It should be adduced that for isolated potato starch, the gelatinization temperature interval is considerably lower, with a peak temperature at  $62$ – $63^{\circ}\text{C}$ , as measured by differential scanning calorimetry (Karlsson and Eliasson, 2003b).

The back-calculation by iteration of the Fourier equation to obtain  $h_{fp}$  from measurements of the progression of the gelatinization front is in principle not more complex than doing it from measurements of the measured temperature in a known position inside a spherical probe for which  $Bi > 0.1$ . The only difference is that in the present method, the temperature is constant =  $T_g$ , while the spatial position of  $T_g$  changes with time.

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