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Evaluation of convective heat transfer coefficient between fluids and particles in suspension as food model systems for natural convection using two methodologies

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A B S T R A C T

This study was conducted to evaluate the convective heat transfer coefficient between Newtonian and non-Newtonian fluids and food particles inside of a glass vessel and to assess the effect of controlled variables: convection phenomena, heating temperature, immersion fluid, and different food particles. The coefficient was evaluated from the sample temperature as a function of the heating time by two approaches: a lumped parameter method and an analytical methodology. High values corresponded to heating in Newtonian fluids (70–181, 57–248 W/m^2 K), and lower corresponded in non Newtonian fluids (31–169, 28–167 W/m^2 K). Similarly, major heat transfer coefficient corresponded to the heating of mushrooms (32–110, 28–132 W/m^2 K), followed by tomatoes (30–181, 35–183 W/m^2 K) and potatoes (31–148, 34–248 W/m^2 K), respectively. Fluid properties were more important than the thermal properties of the particles. This coefficient was higher at 85 °C in both types of fluids. Both methods generated satisfactory values, but the analytical approach showed more accuracy.

1. Introduction

Food process operations frequently involve heating or cooling stages between fluids and solid particles, being the heat transfer by conduction and convection the dominant mechanisms. The increasing interest for manufacturing high quality, nutritious and safe food products, as well as thermal processes modeling and food equipment design have resulted in an imperious need for evaluation of the convective heat transfer coefficient. It is necessary to understand the contribution of this convective heat transfer coefficient by self and to the overall heat transfer coefficient for processes, involving solid foods within Newtonian and non-Newtonian fluids (Vélez-Ruiz, 2009). The convective coefficient is commonly quantified from the temperature evolution obtained from test materials of known shape, size and thermal properties.

Over the past fifteen years, research efforts around the world have been conducted to study and characterize a diversity of heating/cooling treatments in which the convective heat transfer coefficient between fluids and particles has been evaluated, among other aspects. Including, heat exchange for non-Newtonian fluids and irregular particles (Alhamdan and Sastry, 1990), non-Newtonian fluids and regular items (Awuah et al., 1993, 1995; Baptista et al., 1997; Palazoglu, 2006); heating/cooling of food particles in Newtonian fluids (Dincer, 1997; Hulbert et al., 1997; Carson et al., 2006; Laurindo et al., 2010); frying processes of food items (Costa et al., 1999; Sahin et al., 1999; Budzaki and Seruga, 2005; Seruga and Budzaki, 2005), aseptic processing in continuous flow (Ramaswamy and Zareifard, 2000; Chakrabandhu and Singh, 2002; Palazoglu and Sandeep, 2002), industrial freezing (Amarante and Lanoisellé, 2005), and during end-over-end agitation of canned food items (Anantheswaran and Rao, 1985; Sablani and Ramaswamy, 1998; Varga and Oliveira, 2000; Meng and Ramaswamy, 2007; Dwevedy and Ramaswamy, 2009), among others. Additional information on heat transfer between fluid and particulate foods is required, in which its quantification has remained as a challenging issue of the transport phenomena in food engineering.

Works on natural and forced convection in food particles include those of Alhamdan and Sastry (1990) in which irregular shapes were investigated, finding h_{fp} values between 22 and 153 W/m^2 K for cooling, and 75 and 310 W/m^2 K for heating. Chandarana et al. (1990) studied the effect of the fluid behavior at UHT conditions, they reported values of 56–90 for particles in a non-Newtonian fluid, and 65–107 W/m^2 K for particles heated in a Newtonian fluid. Awuah et al. (1993), evaluated the h_{fp} in CMC solution finding values of 76–556 W/m^2 K for cylinders of carrots and potatoes. Gadonna et al. (1996) developed predicting correlations for h_{fp} in forced convection, where higher values (290–1587 W/m^2 K) were obtained as consequence of the turbulence.

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Nomenclature

a	sphere radius (m)
α	thermal diffusivity (m^2/s)
A	shape dependent function of Biot number (Eq. (13))
A_p	surface area of the particle (m^2)
β	thermal expansion coefficient (T^{-1}, $°C^{-1}$)
B	shape dependent function of Biot number (Eq. (13)) = ${\delta_n}^2$
Bi	Biot number $\left(Bi = \frac{h_{fp}L_c}{k_p}\right)$(dimensionless)
C	Empirical coefficient for Eqs. (17) and (18)
Cp	specific heat capacity of the fluid (Cp_f) or particle (Cp_p) (J/kgK)
D	diameter (m)
δ_n	nth positive root of characteristic Eq. (13)
E	Empirical coefficient for Eqs. (17) and (18)
f_H	negative reciprocal slope of the straight line portion of the heating curve on semi-log coordinates (s)
Fo	Fourier number $\left(Fo = \frac{\alpha t}{L_c^2}\right)$ (dimensionless)
Gr	Grashof number $\left(\mathrm{Gr} = \frac{\beta g \rho_f^2 L_c^3 \Delta T}{\eta^2}\right)$ (dimensionless)
g	gravitational acceleration (m/s^2)
γ	shear rate (s^{-1})
h_{fp}	surface or convective heat transfer coefficient (W/m^2 K), also h in Eq. (13)
J	Empirical coefficient for Eq. (18)
k	thermal conductivity of the fluid (k_f) or particle (k_p) (W/mK)
K	consistency coefficient (Pas^n)
Lc	particle characteristic length (m): radius for sphere, half of side for cube and ratio of volume/area for mushroom
m_p	particle mass (kg)
η_{ap}	apparent viscosity for non-Newtonian fluids (Pa s)
η	viscosity for Newtonian fluids (Pa s)
n	flow behavior index (dimensionless)
Nu	Nusselt number ($\mathrm{Nu} = \frac{h_{fp}D}{k_p}$) (dimensionless)
Pr	Prandtl number ($\mathrm{Pr} = \frac{Cp_f \eta}{k_f} = \frac{Cp_f \eta_{ap}}{k_f}$) (dimensionless)
σ	shear stress (Pa)
r	radial position for a sphere ($0 < r < a$, m) equation 13
ρ	density (kg/m^3), at temperature T_0 (ρ_0) and T_1 (ρ_1), of the fluid (ρ_f) or particle (ρ_p)
Re	Reynolds number $\left(\mathrm{Re} = \frac{D\rho v}{\mu} = \frac{D\rho v}{\mu_{ap}}\right)$ (dimensionless)
t	time (s)
T	temperature (°C)
ΔT	temperature difference between the heated fluid and the bulk value (°C)
T	dimensionless temperature relationship $\left(\frac{T_p - T_f}{T_i - T_f}\right)$
T_f	fluid temperature (°C)
T_i	initial temperature (°C)
T_p	particle temperature (°C)
X_w	mass fraction of water (dimensionless)
v	velocity (m/s)
V	volume (m^3) for suspended particles (V_p) and fluid (V_f)
z	dimension of change (m)

Related to thermal processes, several of the studies on h_{fp} have been related to pasteurization and sterilization treatments. Palazoglu and Sandeep (2002) developed a computer program to determine the effect of h_{fp} on microbial and nutritional responses during aseptic processing. Using the most conservative value of h_{fp}, a high quality food product was obtained by Pannu et al. (2003), who carried out a study to asses the effect of flow direction and rate, food particle interaction, shape and size, as well as steam temperature on product temperature during packed bed heating of carrot and potato cubes and slices. Food center and surface temperatures were measured by these researchers under diverse process conditions reporting h_{fp} values of 1500 and 2000 W/m^2 K for cubes with low Biot numbers of 14.2, and 17.8, respectively.

To quantify the convective or surface heat transfer coefficient there are different approaches, the sample temperature as a function of time is indispensable for all of them. Some methods are very sophisticated, employing numerical solution (Gadonna et al., 1996) or finite difference technique (Palazoglu and Sandeep, 2002; Palazoglu, 2006), other method includes the use of a time–temperature integrator combined with mathematical modeling (Maesmans et al., 1994). An alternative instrumental approach was utilized by Amarante and Lanoisellé (2005) to measure the heat transfer coefficients in freezing equipment, in which heat sensors were coupled to temperature recording devices with satisfactory results. Other approaches are practical and simple, two of these are the rate method and the ratio approach, both methods require accurate thermophysical properties in order to get conservative h_{fp}, and other one, is the quasi-steady method.

Additionally most of the revised works, have established empirical correlations between the Nusselt number as a function of Reynolds, Grashof, Prandtl, and other dimensional relationships (Welty et al., 2002; Vélez-Ruiz, 2009, 2010), depending of the experimental conditions; three of them that are utilized in this study are next.

$$\text{for water}: \quad h_{fp} = 3.69\mathrm{Re}^{0.434} \tag{1}$$

$$\text{for starch solutions}: \quad h_{fp} = 2.33\mathrm{Re}^{0.438}\ \mathrm{Pr}^{0.349} \tag{2}$$

$$\text{and, for non Newtonian fluids} \quad \mathrm{Nu} = 1.41\mathrm{Re}^{0.482}\ \mathrm{Pr}^{0.355} \tag{3}$$

Also, the Froude number, density rate, particle concentration and diameters relationship have been incorporated in more specific correlations, such those developed by Dwevedy and Ramaswamy (2009) for foods canning.

Reviews developed by Maesmans et al. (1992) and Barigou et al. (1998), on the determination of fluid to particle heat transfer coefficient for food processes, mention the influence of important factors in the heat transfer phenomena. These factors are: natural or forced convection, fluid rheology, particle size and concentration, particle properties and particle displacement (translational and rotational). In the included studies of both reviews, a wide range of h_{fp} values, 8–7870 W/m^2 K, has been reported as a function of a diversity of variables, corresponding to Reynolds number from 0.006 to 50000, as the important factor; several particle shapes; different solid items; immersed in Newtonian and non Newtonian fluids.

Even though there are several studies on h_{fp} evaluation and modeling; still there is a lack of information on it. Very little is known about the h_{fp} in food process operations in which the heat transfer is involved, particularly the effect of particle load on the h_{fp}, and there exist variations from one work to other; consequently more studies are needed. Thus, the objective of this research was to evaluate the convective heat transfer coefficient as a function of the heating temperature (70 and 85 °C), fluid nature