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Sensitivity analysis using a model based on computational fluid dynamics, discrete element method and discrete phase model to study a food hydrofluidization system

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ABSTRACT

A sensitivity analysis was performed to study a hydrofluidization system, using a previous partially validated model that considers multiple fluid immersed jets and moving food spheres. The inputs were the average velocity of jets at the orifices (*V*), the refrigerating medium temperature (*T*), the distance between orifices (*S*), and the number of spheres (*E*). The outputs were the fluid and spheres velocities, the turbulence level, the dispersion level of the spheres, and the mass and heat transfer in the food. In general, the transfer phenomena in the fluid were mainly affected by *E*, *S* and *V*. In the food, the energy transfer was influenced by all variables, while its mass counterpart mainly depended on *T*. This study showed that a combination of computational fluid dynamics, a discrete element method and a discrete phase model is a simple but powerful tool to simulate food processing systems with relatively low computational requirements.

1. Introduction

As mentioned in a recent review by James et al. (2015), hydrofluidization (HF) is one of the novel freezing technologies designed to improve the economics and production quality of frozen foods, originally developed by Fikiin (1992) and Fikiin and Fikiin (1998). This technology uses an unfreezable liquid which is pumped through orifices or nozzles in a vessel to create agitating immersed liquid jets (Fikiin and Fikiin, 1998). The highly turbulent liquid and moving products ensure therefore extremely high surface heat transfer coefficients and high freezing rates (Fikiin, 2003, 2008; Fikiin and Fikiin, 1998).

The modeling approach of HF has evolved through different configurations (Belis et al., 2015; Peralta et al., 2007, 2009, 2010, 2012; Verboven et al., 2003). Although, the main heat and mass transfer parameters were thoroughly studied and related to the operative variables, the movement of the particles and its effect on the transport phenomena needed to be modeled. On one hand, computational fluid dynamics (CFD) represents a powerful tool that helps to describe fluid systems and their main heat and mass transfer variables. Its versatility allows researchers to use it to design, operate and optimize fluid systems (Norton and Sun, 2010; Thévenin and Janiga, 2008). On the other hand, the discrete phase model (DPM) and the discrete element method (DEM) are novel techniques used to estimate the particle movement in fluid systems (Fryer et al., 2011; Norton and Sun, 2007; Tsotsas and Mujumdar, 2014).

Recently, Orona et al. (2017) developed a model that additionally takes into account mobile foods. The strategy consists in combining CFD with DPM and DEM. DPM allows tracking the food spheres through the flow field calculated by CFD while DEM allows obtaining information related to sphere-sphere and sphere-wall interactions. The model was completed with the necessary parameters, the restitution coefficients being experimentally obtained. The combination of CFD-DPM-DEM applied to a study case of 13 potato spheres in a domain with 69 immersed jets within a representative operative scenario allowed studying the main features of the system.

Although, the proof of concept presented by Orona et al. (2017) laid the groundwork for the use of DEM as a tool to study HF systems, a detailed investigation of the individual and combined effect of the main operative variables on the heat and mass transfer (i.e. sensitivity analysis) is needed. The objective of this work was to study a HF system through a sensitivity analysis of the main variables involved using the model described by Orona et al. (2017). This methodology will improve the understanding of HF systems by analyzing the effect of the main operative variables ranged within the values commonly found in the literature on the main phenomena involved.

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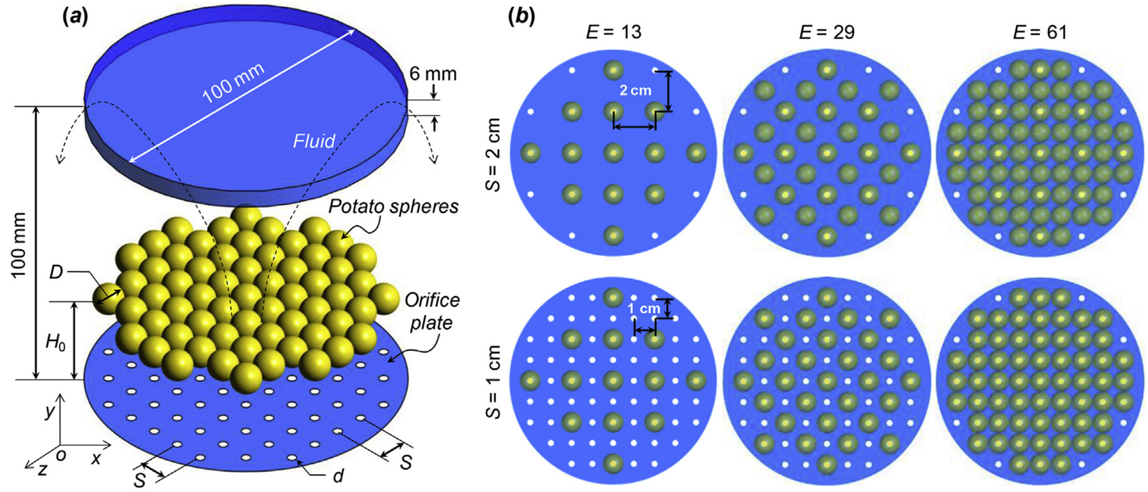

Fig. 1. (*a*) Schematic diagram of the hydrofluidization system studied and (*b*) geometric arrays of orifices and spheres used in this study.

2. Materials and methods

2.1. System studied

The studied hydrofluidization system was described by Orona et al. (2017). Briefly, it consisted of a cylindrical vessel of 100-mm diameter and 100-mm in height and a plate with 3-mm diameter (d) round orifices to produce jets at its base (Fig. 1*a*). A regularly spaced squared array of 10-mm diameter (D) spheres initially placed at a distance H_0 of 50 mm from the orifice plate was used. The liquid-air interface was considered as an adiabatic wall to simplify computations (Orona et al., 2017). As food samples, spheres were considered made by potato (*Solanum tuberosum* L.). As refrigerating medium, an aqueous solution of NaCl 0.231 kg kg^{-1} (w/w) was considered.

2.2. Geometric arrays and operative conditions studied (inputs)

The orifices to produce jets were squared arrays of 21 orifices (minimum distance among the geometric orifice centers, $S = 2$ cm) and 69 orifices ($S = 1$ cm), while the spheres were regularly spaced in squared arrays of 13, 29, and 61 spheres ($E = 13$, $E = 29$, $E = 61$, respectively) (Fig. 1*b*).

The operative conditions studied were the refrigerating medium temperature ($T = -5\,^{\circ}\text{C}$, $T = -10\,^{\circ}\text{C}$) and average velocity of the refrigerating medium at the orifices ($V = 0.30\,\text{m s}^{-1}$, $V = 0.59\,\text{m s}^{-1}$, $V = 1.18\,\text{m s}^{-1}$). The conditions studied are codified as T*xx*V*xxx*S*x*E*xx*, where the *x*'s are replaced by the absolute values of the operative conditions used. For example T5V030S1E13 refers to the condition where $T = -5\,^{\circ}\text{C}$, $V = 0.30\,\text{m s}^{-1}$, $S = 1$ cm and $E = 13$.

2.3. Mathematical modeling of the transport phenomena

The mathematical modeling of the transport phenomena of the system studied was thoroughly described by Orona et al. (2017). Briefly, each simulation consisted in first solving the fluid phase using the Continuity and Navier-Stokes equations through CFD until steady state conditions were obtained (3 s of simulated time). Turbulence was modeled using the $\kappa - \omega$ SST model. Then, spheres were injected at positions described in Fig. 1 and particle interactions (particle-fluid, particle-particle and particle-wall) were solved using a combination of CFD, DPM and DEM (additional 5 s of simulated time). When spheres appear in the domain, heat and mass transfer in the solid and fluid domain were solved. Each time step consisted in: (*a*) the heat, mass and momentum transfer in the liquid refrigerating medium by combining CFD with DPM and DEM, and then, (*b*) the heat and mass transfer inside the food sample. In the first step, the velocity and position of the particles are estimated through DPM and DEM. An average surface heat transfer coefficient for each sphere is obtained and used to transfer information from the liquid to the solid phase. In the second step, a heat and mass transfer model proposed in previous studies (Peralta et al., 2010, 2012; Zorrilla and Rubiolo, 2005a, 2005b) is used.

It is worth recalling that DPM allows estimating the velocity vector of each sphere accounting different forces: the drag force per unit sphere mass F_D (Gidaspow, 1994) and the force per unit sphere mass due to interactions between spheres or between spheres and the domain wall $\underline{F}_{DEM}$, composed by the normal component $\underline{F}_N$ and the tangential component $\underline{F}_T$. Particularly, DEM accounts for forces $\underline{F}_{DEM}$ (Crowe et al., 2012). In Table 1, the main data used for simulation in DEM are shown. Additional details related to the computational domain, the partial validation process and conditions of the simulations are thoroughly discussed by Orona et al. (2017).

2.4. Variables analyzed (outputs)

In Table 2, a summary of the variables analyzed is shown. The main features related to those expressions can be found in Orona et al. (2017).

3. Results and discussion

3.1. Mesh independence test

The mesh independence was checked by Orona et al. (2017) using the local values of $\langle v_p \rangle$, $\langle v_f \rangle$ at 3 s, $\langle Tu \rangle$ at 3 s, and $\langle h_c \rangle$ at 3 s, as reference variables. A mesh composed of 170770 elements was considered appropriate for simulations.

Table 1
Data used for simulations in DEM.

Force	Data	Source
$\underline{F}_N$	$K = 10{,}000\ \text{s}^{-2}$	(a)
	$\eta_w = 0.52$	(b)
	$\eta_p = 0.77$	(b)
$\underline{F}_T$	$\mu_{stick} = 0.5$	(a)
	$\mu_{glide} = 0.2$	(a)
	$\mu_{limit} = 0.1$	(a)
	$v_{glide} = 1\ \text{m s}^{-1}$	(a)
	$v_{limit} = 10\ \text{m s}^{-1}$	(a)
	$s_{limit} = 100\ \text{s m}^{-1}$	(a)

(a) Assumed; (b) Measured, Orona et al. (2017).