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Effect of the number of orifices and operative variables on the heat and mass transfer in a hydrofluidization system with static spheres

Eliana E. Belis, Susana E. Zorrilla, Juan M. Peralta *

Instituto de Desarrollo Tecnológico para la Industria Química (INTEC), Universidad Nacional del Litoral – CONICET, Güemes 3450, S3000GLN Santa Fe, Argentina

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ABSTRACT

Hydrofluidization is a method of chilling and/or freezing that uses submerged jets of a refrigerating liquid. The objective of this work was to study the effect of refrigerant temperature (−5 °C, −10 °C), fluid velocity at the jet exit (1.18 m s^{-1}, 2.36 m s^{-1}), distance between adjacent jets (1 cm, 2 cm), and distance between spheres and jet exit (1 cm, 5 cm) on the heat and mass transfer in a hydrofluidization system (*e.g.* heat transfer coefficient, turbulence intensity, solute concentration in the food) with several static spheres using a previously developed and validated mathematical model *via* CFD simulations. The variables that most affected the transport phenomena in the fluid domain were the distance between spheres and jet exit, the distance between adjacent jets, the fluid velocity at the jet exit, and the distance between spheres. The refrigerant temperature only had significant effect on the transport phenomena inside the food samples.

1. Introduction

Hydrofluidization (HF) can be defined as a method of chilling and/or freezing that uses a circulating system for pumping a refrigerating liquid upwards through orifices or nozzles into a vessel full with the refrigerating media. Thus, submerged agitating jets are created ensuring extremely high surface heat transfer coefficients (Fikiin, 1992, 2008). As a technique derived from the immersion chilling and freezing (ICF) method, HF shares some of its advantages such as: fast freezing method, energy-saving and environmentally-friendly technology, capacity to formulate desired final products by controlling the mass transfer during processing (addition of micronutrients, flavoring, antioxidants, etc.) (Fikiin, 2008; Peralta et al., 2009).

The effect of some of the operative variables of a HF system on the transport phenomena between the refrigerant and the food samples has been subject of study by several research groups over the recent decades (Fikiin, 1992; Verboven et al., 2003; Peralta et al., 2007, 2009, 2010, 2012). Those studies were carried out experimentally and/or theoretically and helped to identify some of the main variables that influence the heat and mass transfer during processing such as the refrigerant velocity at the orifices (or flow rate), the temperature and the food size. In general, the complexity of combining the study of the transport phenomena in the fluid and food system with the phase change phenomenon makes the mathematical modeling a very difficult problem to tackle. Some of the main contributions using the simplest and idealized HF configuration (*i.e.* single sphere and single jet) were developed using computational fluid dynamic (CFD) simulations (Peralta et al., 2010, 2012). These studies presented a validated mathematical model to estimate the heat and mass transfer inside a food sample with a regular geometry during its freezing and using a simplified configuration of a hydrofluidization system.

Nevertheless, the effects on the transport phenomena of some important parameters that are related to the geometry of the system were not studied, such as the number of the orifices that produce the jets and the number of the food samples (Peralta et al., 2012). The objective of this work was to study the effect of the operative variables (refrigerant temperature, average velocity of the refrigerant fluid at the orifices, distance between the plane of the orifice plate and the stagnation point of the spheres, distance between the geometrical centers of the round orifices and the distance between the geometrical centers of the spheres) on the heat and mass transfer in a hydrofluidization system with several static spheres and round jets using a previously developed and validated mathematical model *via* CFD simulations.

2. Materials and methods

2.1. System studied

The studied hydrofluidization system consisted in a cylindrical vessel of 100 mm diameter and 100 mm height and a plate with

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* Corresponding author. Tel.: +54 342 451 1595; fax: +54 342 451 1079.
E-mail address: jmperalta@intec.unl.edu.ar (J.M. Peralta).

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Nomenclature

A_y	cross sectional area to the domain axis at the height y (m^2)
$a_{i,j}$	fitting coefficients of Eq. (5) (–)
C_{NaCl}	average NaCl concentration in the potato spheres ($g\ kg^{-1}$)
C_p	heat capacity of the fluid ($J\ kg^{-1}\ K^{-1}$)
Cp	pressure coefficient calculated using Eq. (2) (–)
Cp_{CFD}	pressure coefficient obtained from simulations ($p/(1/2\rho V^2)$) (–)
D	diameter of the spheres (cm)
d	diameter of the orifices (cm)
H	distance between the orifice plate and the plane of the stagnation points of the spheres (cm)
h_c	surface heat transfer coefficient obtained from Eq. (1) ($W\ m^{-2}\ K^{-1}$)
$h_{c,CFD}$	surface heat transfer coefficient obtained from simulations ($W\ m^{-2}\ K^{-1}$)
$h_{c,stg}$	averaged values of h_c evaluated on $\varphi = 0$ for all spheres ($W\ m^{-2}\ K^{-1}$)
h_c^*	averaged surface heat transfer coefficient (Peralta et al., 2009) ($W\ m^{-2}\ K^{-1}$)
k	thermal conductivity of the fluid ($W\ m^{-1}\ K^{-1}$)
L	distance between the geometric centers of the spheres (cm)
L_y	curve on the surfaces of the spheres at height y (m)
Nu_{ave}	average Nusselt number based on h_c^* ($h_c^* D/k$) (–)
Nu_{stg}	stagnation-point Nusselt number based on $h_{c,stg}$ ($h_{c,stg}D/k$) (–)
Pr	Prandtl number ($\mu C_p/k$) (–)
p	pressure (Pa)
R	radius of the spheres (m)
Re	Reynolds number ($\rho DV/\mu$) (–)
r	radial position (m)
S	distance between the geometric center of the orifices (cm)
T	temperature of the refrigerant fluid (°C)
T_c	temperature of the geometric center of the spheres (°C)
t	time (s)
t_R	relative freezing time (–)
Tu	turbulence level calculated from Eq. (3) (–)
Tu_{CFD}	turbulence level obtained from the simulations ($\sqrt{2/3\kappa}/v$) (–)
V	area averaged fluid velocity at the orifices ($m\ s^{-1}$)
V_T	volume of the fluid domain (m^3)
v	fluid velocity ($m\ s^{-1}$)
y	axial position in the fluid domain (m)
y^+	dimensionless distance on the sphere walls (–)

Greek symbols

θ	polar position (grad)
κ	turbulence kinetic energy ($m^2\ s^{-2}$)
μ	viscosity of the fluid (Pa s)
ρ	density of the fluid ($kg\ m^{-3}$)
φ	azimuth position (grad)

different number of 3 mm diameter round orifices (to produce the jets) in its base (Fig. 1). This system is a smaller version of the one studied by Peralta et al. (2009, 2010, 2012). A regularly spaced squared array of 20 mm diameter static spheres placed at different distances from the orifice plate was used. Fig. 2 shows the orifice and sphere arrays studied. The spheres were considered made by copper for the determination of the surface heat transfer coefficient and made by potato (*Solanum tuberosum* L.) to model the heat and mass transfer in a food sample. An aqueous solution of NaCl was considered to model the refrigerant solution (with a concentration of 0.231 kg kg^{-1} (w/w)) and the occluded solution in the food sample.

2.2. Operative conditions and geometric arrays studied

A combination of thermal, flow and geometric variables were tested. Those variables were: the refrigerant temperature ($T = -5$ °C and $T = -10$ °C), the average velocity of the refrigerant fluid at the orifices ($V = 1.18\ m\ s^{-1}$ and $V = 2.36\ m\ s^{-1}$), the distance between the plane of the orifice plate and the stagnation point of the spheres ($H = 1$ cm and $H = 5$ cm), the distance between the geometrical centers of the round orifices ($S = 1$ cm and $S = 2$ cm) and the distance between the geometrical centers of the spheres ($L = 2$ cm and $L = 6$ cm). It is worth mentioning that $L = 6$ cm allows representing a single sphere placed at the domain axis (Fig. 2). The 32 conditions studied are shown in Table 1, including their codification.

2.3. Mathematical modeling of the transport phenomena

The transport phenomena that take place in the studied system were estimated using a mathematical model for the conditions proposed in Table 1. Heat, mass and momentum transfer balances were solved for the refrigerant liquid domain, and heat and mass transfer balances were solved for the food sample. In all cases, numerical methods were used to solve the proposed balances, due to the high nonlinear nature of the mathematical expressions.

2.3.1. Heat and momentum transfer in the liquid refrigerant

2.3.1.1. Mathematical model. The momentum (Navier–Stokes), mass (continuity) and energy transfer in the refrigerant liquid domain was simulated using the mathematical model proposed by Peralta et al. (2010) for a hydrofluidization system. The model

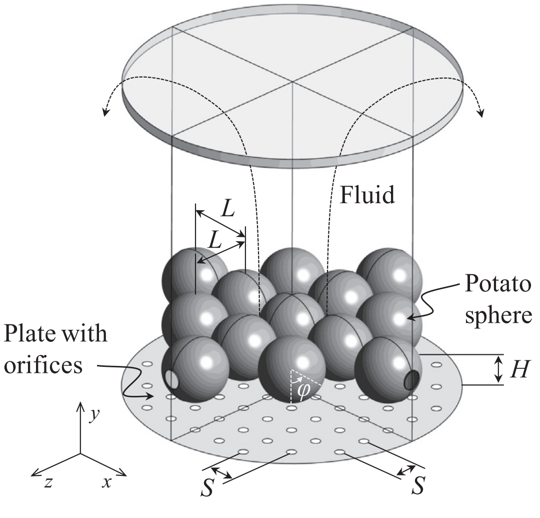

Fig. 1. Schematic diagram of the hydrofluidization system studied.