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Influence of operating conditions on residence time distributions in a scraped surface heat exchanger during aerated sorbet production

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ABSTRACT

The residence time distribution (RTD) inside a scraped surface heat exchanger (SSHE) during simultaneous crystallization-foaming process for continuous production of an aerated sorbet was studied. The effect of mix flowrate, air flowrate and refrigerant temperature on the unfrozen liquid/ice crystals phase RTD was investigated using a dye tracer method. The experimental results revealed that both mix and air flowrates increase leads to a lessening of the minimum and of the mean residence time inside the SSHE. Flow diagnosis showed the presence of a nearly stagnant air pocket which volume increase with the air flowrate increase, resulting in an augmentation of the liquid phase velocity. More axial dispersion was observed at higher air flowrates and at lower refrigerant temperature due to greater radial temperature and axial velocity gradients. These conclusions were confirmed by the parameters of the fitted flow models (axial dispersion, tank-in-series and gamma distribution models) even if only the gamma distribution model succeeded to well describe the flow patterns observed. The findings of this pioneering work in the field of gas-liquid flow in SSHEs might be useful for several applications involving multiphasic flow in SSHEs.

1. Introduction

Scraped surface heat exchanger (SSHE) is a tubular heat exchanger composed of two concentric cylinders acting like a rotor-stator device: a stationary external cylinder in contact with the heating or cooling fluid (the thermal transfer surface) and a rotating internal cylinder (opened or closed dasher) that is equipped with scraping blades. Since they allow efficient heat transfer, SSHEs are extensively used in processing of complex fluid undergoing structural transformations that induce high viscosities or non-Newtonian behaviour during heating or cooling. In food industries, SSHE are used for heating and freezing applications. Sorbet production is one of the main freezing applications.

Sorbet is a complex multiphasic system composed of a dispersion of ice crystal and air bubbles inside a concentrated liquid matrix. The manufacturing process of sorbet is carried out in several unit operations ranging from the ingredients homogenization (liquid mix production) to the hardening of the crystallized product, via the crystallization step which occurs in a SSHE. In addition to the mix, air is also incorporated into the sorbet mix flow inside the SSHE, leading to a combined crystallization-foaming operation. The microstructure of the sorbet product is defined inside the SSHE where ice crystals nucleate and grow, and air bubbles are formed. The functional properties and quality attributes of the finished product are essentially related to both ice crystal and bubble size distributions. These latter are strongly dependent on operating conditions, especially on the coupled effect of heat transfer, phase change and flow phenomena. Phase change occurring during crystallization induces an increase of ice crystal volume fraction and of apparent viscosity. It has also been demonstrated that the air incorporation increases the apparent viscosity (Arellano et al., 2012). An increase in apparent viscosity leads to a modification of the fluid flow pattern and of the velocity profile. Consequently, the time-temperature-shear rate history inside the SSHE is changed and that considerably affects the size distributions of both ice crystals and bubbles (Fayolle et al., 2005, 2013; Yataghene et al., 2008; Fayolle et al., 2013). Therefore, knowledge of the fluid flow behaviour within the SSHE is crucial for

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Nomenclature

$C(t)$	concentration of tracer (kg m^{-3})
CoV	coefficient of variation
$E(t)$; E	residence time distribution function, E-curve (s^{-1})
$E^{*}(\theta)$	dimensionless E-curve
K	consistency index for power law fluids (Pa s^{n})
L	SSHE cylinder length (m)
m_i	mass of cup sample i (kg)
M	number of experimental data
MSE	mean squared error of the dimensionless E-curve
n	flow behaviour index for power law fluids
N	rotor's rotational speed (tr s^{-1})
N_T	number of tank for the TSM
p	GDM parameter
Pe	Peclet number
Q_m	mass flowrate (kg h^{-1})
Q_v	volumetric flowrate (m^3 s^{-1})
R	radius (m)
Re	Reynolds number
t	time (s)
$\bar{t}$	mean residence time (s)
t_{min}	minimum residence time (s)
t_{inj}	injection time (s)
Δt_i	sampling time for cup i (s)
$\Delta t_{sampling}$	total sampling time (s)
T	temperature (K)
Ta	Taylor number
v	mean velocity (m/s)
V	internal volume (m^3)

Greek letters

Γ	gamma function
μ	viscosity (Pa s)
θ	dimensionless time
θ_0	breakthrough time
π	constant pi ($\pi = 3.1416$)
ρ	density (kg/m^3)
σ	standard deviation
σ^2	variance
τ	geometrical residence time (s)
Ω	rotor's rotational speed (rad s^{-1})

Subscripts

ax	axial
d	dead
exp	experimental
G	gas
L	liquid
r	rotor
rot	rotational
s	stator
th	theoretical
tot	total

Abbreviations

ADM	axial dispersion model
GDM	gamma distribution model
MB	methylene blue
RTD	residence time distribution
SSHE	scraped surface heat exchanger
TC	Taylor - Couette
TSM	tank in series model

the optimization of the crystallization-foaming process and the induced finished product functionalities.

The flow behaviour in SSHE for a single-phase fluid is described as a superposition of an axial and a rotational flow, with possibly Taylor vortices, above a critical value of the rotating cylinder angular velocity (Trommelen and Beek, 1971; Wang et al., 1999). The axial component corresponds to the classical Poiseuille flow (characterized by the axial Reynolds number – Reax) through the annular space between the dasher and the external wall. The rotational flow results from the combined actions of the rotating dasher and the scraping blades. This component has been assimilated to a Taylor-Couette (TC) flow characterized by the Taylor number. The combination of these two flows yields to helicoidal flows with a variety of observable patterns depending on both axial Reynolds and Taylor (Härröd, 1986; Fayolle et al., 2005; Yataghene et al., 2011). These flow regimes may be modified in case of two-phase systems, especially for gas/liquid flow. There has been no investigation about the hydrodynamics of gas/liquid or gas/liquid/solid in SSHE. Only few studies dealing with gas/liquid TC flows (without scraping blades) were found in the literature. Shiomi et al. (1993) described the air bubble/water flow in a vertical upward TC flow with internal cylinder rotation, in turbulent regime. They identified different flow patterns according to the mean velocity values of the two phases and the inner cylinder rotation speed: dispersed bubbly, ring-form, spiral and transitional flows. Later, Djéridi et al. (1999) also studied the two-phase air/water upward flow in concentric cylinders with internal cylinder rotation, but for low Taylor numbers corresponding to the first instabilities. The authors showed that air bubbles are captured in flow structures generated in single phase flows (helicoidal flow) and migrate from the bottom to the top following the organized flow pattern. Recently, Hubacz and Wroński (2004) investigated flow regimes in a horizontal TC using nitrogen/water and nitrogen/glycerin fluids, as a function of rotational speed, both liquid and gas volumetric flowrates and rotor diameters. They described 6 different flow patterns and constructed flow regimes maps according to the different parameters studied. In particular, the authors identified ring flow of the bubbles for high rotational speed and showed that increasing the liquid viscosity improved the stability of the gas rings. Afterwards, this flow regimes map was extended in a more generalized form taking into account more geometries and larger liquid phase physical properties such as density, viscosity and surface tension (Hubacz, 2015). These authors (Hubacz and Wroński, 2004; Hubacz, 2015) showed that gas/liquid flow behavior in horizontal TC systems are different to that observed in vertical ones, except in the case of high rotational speed.

In such complex flow dynamic systems, the residence time distribution (RTD) can be used as a simple and effective method to describe the fluid flow behaviour within the heat exchanger. By definition, RTD represents the fluid age dispersion, describing the different path and length of time a fluid element can spend between the inlet and the outlet of the exchanger. RTD is related to the global motion of the flow, but provides additional information about mixing, dispersion, recycling and flow anomalies such as dead zone and bypass. RTD studies on SSHEs have been already presented by several authors and have been reviewed extensively