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Simultaneous optimization of heat transfer and reciprocation intensity for thermal processing of liquid particulate mixtures undergoing reciprocating agitation

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ABSTRACT

Simultaneous optimization of heat transfer and reciprocation intensity (RI) was carried out for reciprocating agitation thermal processing (RA-TP) of liquid-particulate foods. Heat transfer data under various processing conditions (temperature, frequency, and headspace) and product properties (liquid viscosity, particle concentration, and particle density) during RA-TP were utilized to develop a composite model using quadratic stepwise regression analysis. Heat transfer coefficients were maximized individually and simultaneously with minimal RI using multiple-variable optimization. High RI (37–45 ms^{-2}) was recommended to maximize heat transfer alone, whereas lower RI (16–19 ms^{-2}) was found optimal for simultaneous optimization of heat transfer & RI. Product formulations containing low viscosity liquids filled with 23–27% volume of particles with density of 1130–1350 kg/m^3 were found most desirable for maintaining good quality under RA-TP. Optimal conditions were also reported for applying RA-TP under different operating temperatures, liquid viscosities, particle concentrations and particle densities.

Industrial significance: Reciprocating agitation of containers is receiving interest from thermal processing industry for enhancing product quality. The aim of this study was to optimize the use of reciprocating agitation thermal processing for processing particulate liquid foods. This study attempts to predict optimal conditions of processing conditions and product compositions for reciprocating agitation thermal processing. Multi-variable optimization based on data from multiple experimental designs is conducted in this study, which will be directly relevant to be used by industry seeking to employ reciprocating agitation thermal processing.

1. Introduction

Recent innovations in the field of thermal processing have inspired the food industry to migrate from conventional sterilization in still retorts to the application of more novel technologies for quality optimization (Awuah, Ramaswamy, & Economides, 2007). Innovative processes like agitating cookers, processing in thin profile containers, high temperature short time processes and aseptic processing technologies have largely used still retort processing meet consumer demands for high quality safe food (Pratap Singh & Ramaswamy, in press-a). Every new technology requires a thorough evaluation to achieve balance between its conducive and harmful effects (Balsa-Canto, Banga, & Alonso, 2002). Reciprocating agitation thermal processing (RA-TP), as used in the commercial Shaka retorts, is one of the emerging technologies for in-container sterilization of food products involving rapid reciprocating agitation (back and forth motion) of containers & promises to give high quality canned products (Walden & Emanuel, 2010). Pratap Singh, Singh, and Ramaswamy (2015b) found that reciprocating agitation can reduce process times by 46–62% and quality deterioration index (cook-value/lethality) by 26–36% as compared to conventional still retort processing. With developments of new modes of agitation like RA-TP, optimization studies in thermal processing have become a necessity, and these studies need to cover various situations and constraints (Singh, Pratap Singh, & Ramaswamy, 2015a).

General principles for optimization of a food process have been reviewed by Holdsworth (1985). Singh et al. (2015a) discussed the recent literature on application of optimization techniques in thermal processing. Maximization of heat transfer rate to reduce process time has been the sole objective of most of the optimization studies on thermal processing (Awuah et al., 2007; Lund, 1982; Rattan & Ramaswamy, 2014). The broad aim of these studies has been to impart the lethality required for ensuring microbiological safety at minimal levels of damage to quality attributes (Awuah et al., 2007). However, as each process can have a different effect on quality attributes, optimization is bound by several constraints and criteria specific to the particular process (Silva, Hendrickx, Oliveira & Tobback, 1992). During RA-TP of liquid-particulate foods, researchers have found reciprocation intensity (RI) to be the main factor affecting process times and product quality (Batmaz & Sandeep, 2015; Pratap Singh et al., 2015b; Singh & Ramaswamy, 2016; Singh & Ramaswamy, 2015; Singh, Pratap Singh, & Ramaswamy, 2015b, in press-c). Pratap Singh and Ramaswamy

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(2015) reported that, although RI was the most predominant variable for optimizing reciprocating agitation processing, no noticeable increase in heat transfer was observed beyond 30 ms^{-2} RI for horizontal cans and 60 ms^{-2} RI for vertical cans. However, the objective in this study was only to maximize heat transfer, and did not consider the effect of high RI on product quality & process efficiency. Singh et al. (in press-c), while working with canned green beans, found that too high RI may lead to extensive product damage and may not be desirable. High RI damages soft products and causes excessive nutrient leaching, texture degradation, mechanico-chemical reactions etc., and thus will adversely affect the quality of food product. Minimization of RI is also desirable for optimizing energy requirements; however it has to be above a threshold level so the heat transfer is not compromised. Singh and Ramaswamy (2016) suggested using RI of 18 ms^{-2} for processing liquid particulate mixtures based on such an approach and provided the first attempt to moderate the process; however the study was not very exhaustive and included only limited variables. Hence, an exhaustive optimization study is warranted to identify optimum reciprocation intensity for RA-TP under different conditions & constraints.

A combined effect of maximization of heat transfer and minimization of reciprocation intensity was considered in this work, for predicting optimal processing conditions for RA-TP. In this work, data on effect of various process variables (temperature, RI, headspace, liquid viscosity, particle concentration, and particle density) on heat transfer coefficients (U and h_{fp}) during RA-TP of liquid-particulate mixtures was used to develop a composite model through regression analysis. This composite model was subsequently used for generating optimal processing conditions & product properties for RA-TP. Optimization was conducted for three objective functions (max U, max h_{fp} & min RI) under various constraints. The results of optimization are presented and implications on optimal processing conditions & product compositions are discussed.

2. Materials and methods

2.1. Materials

A vertical retort, modified to including reciprocating mechanism (Pratap Singh et al., 2015b), was used for imparting RA-TP. Sterilization studies were conducted on 307 × 409 cans (Home Canning Co., Montreal, QC) placed in the reciprocating cage with horizontal axis along the axis of reciprocation (Pratap Singh & Ramaswamy, 2015). Various concentrations of glycerin (Fisher Scientific, Montreal, PQ) were used to simulate different levels of liquid viscosity encountered in liquid foods. Teflon, nylon and polypropylene spheres (19 mm diameter) (Small Parts Inc., Miami, FL) were used as model particles simulating the diverse density of food particles. The thermo-physical properties of these model materials, listed in Table 1, represent the various ranges of liquid viscosity and particle density found for canned particulate liquid foods (Dwivedi & Ramaswamy, 2010; Singh & Ramaswamy, 2015). Flexible thin-wire thermocouples were used to measure particle-center temperatures, while needle-type thermocouples placed at can's geometric center were used to measure liquid temperatures. The thermocouple outputs were recorded at 1 s intervals using a data acquisition system (HP34970A, Hewlett-Packard, Loveland, CO). The particle assembly, can preparation and data gathering are detailed elsewhere in literature (Hassan, Ramaswamy, & Dwivedi, 2012; Ramaswamy & Dwivedi, 2011; Rattan & Ramaswamy, 2014;Pratap Singh & Ramaswamy, 2015).

2.2. Data gathering and analysis

For gathering data on RA-TP, 128 experiments were carried out by varying the 6 process variables using two experimental designs obtained from Design Expert software (Stat-Ease Inc., Minneapolis, Minnesota, USA) — a central composite rotatable design (CCRD) and a full-factorial design. In the CCRD design, different levels of operating temperature (110–130 °C), RI (0.3–45.5 ms^{-2} by using reciprocations of 0.3–3.6 Hz at 15 cm amplitude) and can headspace (5–15 mm) were used. In the full-factorial design, liquid viscosity (0.001, 0.011 & 0.942 Pa s obtained from 0, 50 & 100% glycerin concentration), particle concentration (single, 15, 30 & 45% *v*/*v*), RI (3.5, 14.1 & 31.6 ms^{-2} by using reciprocations of 1, 2 & 3 Hz at 15 cm amplitude) and particle density (830, 1130 & 2210 kg/m^3 obtained from Teflon, nylon and polypropylene particles) were varied. CCRD design experiments were conducted with 50% glycerin concentration and 19 mm nylon spheres at 30% (*v*/*v*) particle concentration, while full-factorial design experiments were performed at 121 °C operating temperature and 10 mm can headspace. All experimental runs were duplicated cans placed equidistant from the axis of reciprocation, and were replicated twice.

Time-temperature data of each experimental can until steam off were analyzed to evaluate the heating rate index of liquid ($f_{h\text{-}l}$) and particle-center ($f_{h\text{-}p}$) from negative reciprocal of slope of the straight-line portion of the semi-logarithmic time temperature curve (Pratap Singh et al., 2015b). These values ($f_{h\text{-}l}$ and $f_{h\text{-}p}$) were used to evaluate the overall heat transfer coefficient at the can wall (U) and fluid-to-particle heat transfer coefficient (h_{fp}) using the methodology developed by Singh et al. (2015b). Mean values of U & h_{fp} from four readings (two replicates of each experiment containing two duplicate cans each) of each experimental run are reported in Table 2. Regression analysis and analysis of variance (ANOVA) were carried out using Design Expert (Stat-Ease Inc., Minneapolis, Minnesota, USA) software.

2.3. Optimization

Data from all 128 experiments and their replicates were used for optimization study. A composite model was first developed for predicting modeling of U & h_{fp} using a single equation containing effects of all variables, viz. operating temperature (T), reciprocation intensity (RI), container headspace (H), liquid viscosity (LV), particle concentration (PC) and particle density (PD). For this, a quadratic model was evaluated using stepwise regression, which involved removal of non-significant ($p > 0.05$) model terms, and hence the composite model equation contained only significant effects. RI used in composite model was obtained from corresponding reciprocation frequency by calculating maximum acceleration from position analysis of can during its motion (Pratap Singh & Ramaswamy, 2015; Walden & Emanuel, 2010), and can be represented by Eq. (1).

$$\text{Reciprocation Intensity (RI)} = \omega^2 a(1 + (a/2l))/2 \tag{1}$$

Table 1
Thermo-physical properties of materials used.

Material	Density (kg/m^3)	Heat capacity (J/kg K)	Thermal conductivity (W/m K)	Thermal diffusivity (m^2/s)	Viscosity (Pa s)
Nylon	1130	2070	0.370	1.52×10^{-7}	–
Polypropylene	830	1840	0.360	2.35×10^{-7}	–
Teflon	2210	980	0.290	1.35×10^{-7}	–
Glycerin (100%)	1260	2430	–	–	0.940
Glycerin (50%)	1130	3340	–	–	0.011
Water	1000	4180	–	–	0.001