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Model-based energy performance analysis of high pressure processing systems

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ABSTRACT

Mathematical models are developed to simulate the behaviour of high pressure processing systems (single- and multi-cycle processes of different pulse-shapes) and predict the effects of processing parameters on their energy consumption. The validity of the models is established by comparing simulation results with experimental measurements from published works and the present study. Specific energy consumption is shown to depend mainly on holding pressure, pressure medium compressibility, equipment scale and vessel filling efficiency. Inlet temperature, compression and decompression times show negligible effects as do cycle pressure shapes. Longer compression times, however, reduce power capacity requirements, if all other conditions remain constant. The holding time has negligible effects on energy consumption, save for leakages and standby power, hence, extending it does not incur significant energy penalties. On the other hand, a drop in holding pressure leads to a more than proportionate drop in energy consumption. Hence, lower-pressure, longer-time processes are more advantageous from an energy standpoint, provided they satisfy product quality, safety and throughput requirements. Lower-compressibility fluids enable higher pressures to be established with lower energy losses. Higher equipment scales and vessel filling efficiencies reduce the proportion of wasted energy. These conditions are therefore beneficial for energy-efficient operation.

Industrial relevance: The production of clean-label, minimally-processed and microbial-safe food products with excellent nutritional, organoleptic properties and extended shelf life is becoming increasingly important. High-pressure processing HPP is a promising technology in this regard, increasingly being deployed at commercial scale. To reduce per-unit HPP product costs, which are currently higher than those of traditional thermal systems, it is important to reduce energy usage, which constitutes a significant proportion of operating costs. The modelling scheme developed in this work would help process designers and operators determine optimal processing conditions with respect to energy consumption, while satisfying product quality and safety constraints; providing a basis for improved process automation.

1. Introduction

In today's world, the production of clean-label, minimally-processed food products with extended shelf life is becoming increasingly important. Traditional thermal processing systems are limited by hot wall with cold centre effects, leading to temperature-induced degradation of product quality attributes like flavour, texture and nutrients. There are also occurrences of cold spots in the food, which compromise microbial safety. Hence, alternative processes are required that not only address these shortcomings of conventional processing technologies but also lead to lower energy consumption (Atuonwu & Tassou, 2018a, 2018b; Misra et al., 2017). Since the discovery by Hite (1899) of the capacity of high pressures to inactivate vegetative microorganisms and enzymes at near-room temperatures, significant research effort has been devoted towards the use of high pressure processing (HPP) systems to address the limitations of traditional thermal pasteurisation and sterilisation systems. Depending on operating conditions, HPP has been proven to have stronger effects on pathogenic microorganism destruction than traditional heating (Barba, Koubaa, do Prado-Silva, Orlien, & Sant'Ana, 2017; Chakraborty, Kaushik, Rao, & Mishra, 2014; Considine, Kelly, Fitzgerald, Hill, & Sleator, 2008; Reineke, Mathys, & Knorr, 2011; Yaldagard, Mortazavi, & Tabatabaie, 2008; Rosello-Soto et al., 2018; Sevenich et al., 2015). Improved colour, flavour, texture, yield and nutritional properties have been reported for various food products (Oey, Lille, Loey, & Hendrickx, 2008; Kaushik, Kaur, Rao, & Mishra, 2014; Gong et al., 2015; Chauhan, Kumar, Nagraj, Narasimhamurthy, & Raju, 2015). HPP has also been shown to improve the extractability and bioavailability of bioactive compounds in foods (Barba et al., 2017;

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Barba, Terefe, Buckow, Knorr, & Orlien, 2015). Most importantly, product shelf life extensions, in some cases up to 10 times, with fresh-like properties retention have been observed in many applications, opening up opportunities to reduce wastage and develop new long-distance markets for products (UHDE, 2017). These advantages however come at the expense of significant amounts of energy. A comparative analysis of the energy consumption of HPP and conventional thermal systems conducted by Sampedro, McAloon, Yee, Fan, and Geveke (2014) for an orange juice case study showed the HPP system to consume > 26 times the energy consumed by equivalent traditional thermal systems. A comparison by Rodriguez-Gonzalez, Buckow, Koutchama, and Balasubramamian (2015) for apple juice processing at a different operating condition and scale of operation showed a two-fold increase in specific energy consumption using HPP. A similar trend was shown by Aganovic et al. (2017), reporting a five-fold increase in specific energy consumption for HPP processing of tomato and watermelon juice, relative to conventional thermal processing. Overall costs per unit of HPP products are significantly higher than that of equivalent thermal products, with energy consumption a contributing factor (Sampedro et al., 2014). Reducing energy consumption in HPP systems is thus an important research challenge in the food industry. It is therefore not surprising that energy studies on HPP systems have recently been gaining increased attention in the literature (Aganovic et al., 2017; Milani, Ramsey, & Silva, 2016; Rodriguez-Gonzalez et al., 2015). Previous HPP energy studies have been based on either experimental measurements under specific conditions, or simplified modelling that lack the necessary level of detail for sensitivity analysis and process optimisation. Results have been largely influenced by the scale of operation and processing conditions. The studies also did not include input-output relationships or the extrapolation of developed models beyond experimental conditions, as is necessary for process optimisation studies.

Rodriguez-Gonzalez et al. (2015), categorised HPP energy consumption calculations into three levels: level 1 (based on internal energy changes-compression work); level 2 (based on pressure energy differentials at the pump head with time); and level 3 (based on empirical power-pressure relationships). Milani et al. (2016) in their computations, neglected the effects of pressure on the compressibility and specific volume of the pressure-transmitting medium, in spite of their high significance. Also, only the compression energy (in addition to product heating energy), was calculated, neglecting the other aspects of HPP energy consumption. The analysis of Aganovic et al. (2017) focussed primarily on the use of electrical energy measurements via clamp-on power meters. In all these studies, there has been no detailed sensitivity analysis of the effects of processing and equipment conditions on energy consumption. Where models were employed, the adiabatic heat of compression and pressure-volume-temperature characteristics of pressure-transmitting media have not been explicitly considered. Hence, fundamental understanding of the mechanisms of energy consumption is lacking. Moreover, studies have been restricted to conventional commercially-available single-cycle trapezoidal systems. Multi-cycle and non-conventional patterned (e.g. sinusoidal and triangular) systems have been proposed as potentially viable alternatives to the conventional trapezoidal HPP systems (Buzrul, 2014). For equivalent conditions, multi-cycle systems have in many cases, proven to be more effective in microbial and enzyme inactivation than conventional systems, depending on values of other multi-cycle system parameters (Aleman et al., 1996; Basak & Ramaswamy, 2001; Buzrul, 2014; Donsì, Ferrari, & Maresca, 2010; Hayakawa, Kanno, Yoshiyama, & Fujio, 1994; Palou, Lopez-Malo, Barbosa-Canovas, Welti-Chanes, & Swanson, 1998). In addition, they offer the possibility of product conveyance during low-pressure periods (especially when there are time intervals between pressure cycles), thus, enabling quasi-continuous operation and improving overall process flexibility (Izydor, Hainthaler, Gaipl, Frey, & Schlucker, 2017). There is however a general lack in the literature of models describing the unique behaviours of these cyclic processes, and specifically, their energy performance. Such models, when developed and integrated with appropriate inactivation kinetics, would provide a good platform for determining overall optimal operating conditions (with respect to energy and product quality) using multi-objective optimisation techniques. In this work, a modelling framework is developed to estimate the cumulative energy consumption of high pressure processing systems (single & multi-cycle), of different cycle pressure shapes. The model, which takes into account, the adiabatic heat of compression and pressure-transmitting media pressure-volume characteristics, provides valuable insights into how the different processing variables affect energy consumption.

2. Process description and mathematical model

Most industrial HPP systems operate in batch mode and consist essentially of a high-pressure vessel, sealing closures (plugs, wedges and frames or yokes), pressure-generating system, pressure-transmitting medium reservoir and material handling system. The food sample to be processed is in most cases, packaged in a flexible, air-tight hermetically-sealed container, e.g. plastic pouches, and loaded onto a carrier basket, and inserted into the high-pressure vessel. The vessel and its contents are moved from the loading to the working position, and subsequently filled with the pressure-transmitting medium, usually water, by a low-pressure pump, with all air displaced. The plugs are closed, secured with a wedge and the system thereafter, pressurised. After the desired pressure is attained, and held for a specified time, which depends on the intended purpose, it is depressurised, the pressurising medium drained or recirculated, and the basket and its contents, unloaded. HPP systems can be pressurised either directly, with the aid of a piston in direct contact with the vessel's pressurising medium, or indirectly by pumping extra pressure medium to the sealed vessel, via an intensifier. Fig. 1 shows a process flow diagram of an indirectly-pressurised HPP system as commonly used in the food industry. Existing commercial batch HPP systems could be either horizontal or vertical, with chamber volumes up to 600 L, and working pressures up to 700 MPa (Barba, Ahrné, Xanthakis, Landerslev, & Orlien, 2017).

The process (pressure and temperature evolution behaviour), and subsequent energy consumption models (Section 4) are formulated based on the following assumptions:

i. Pressure is transmitted instantaneously from the transmitting medium to the packaged food product, and distributed evenly (Toepfl, Mathys, Heinz, & Knorr, 2006).
ii. The temperature changes due to adiabatic heat of compression and all heat loss effects are evenly distributed within the pressure-transmitting medium

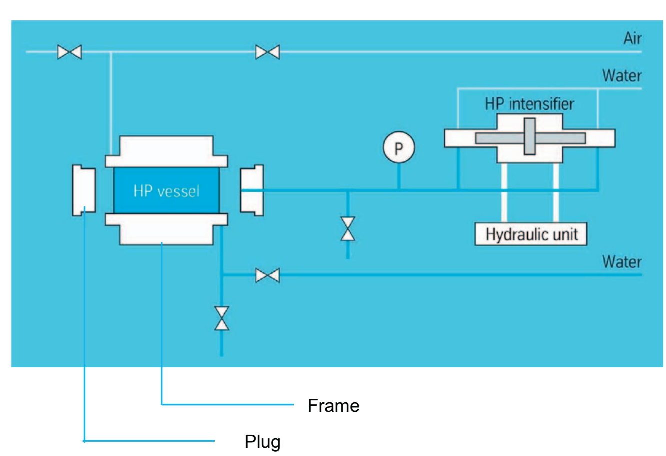

Fig. 1. Process flow diagram of a high pressure processing system.
(Adapted from UHDE, 2017)