Comparative assessment of innovative and conventional food preservation technologies: process energy performance and greenhouse gas emissions

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Abstract

This study aims to establish whether innovative food preservation technologies can offer significant reductions in energy consumption and corresponding greenhouse gas (GHG) emissions while delivering equivalent microbiological lethality, nutritional and organoleptic quality to conventional processes. The energy demand of high pressure processing, microwave, ohmic and conventional heating technologies, for achieving the same pasteurising effect in orange juice under commercially-representative processing conditions are measured and compared. The corresponding GHG emissions are evaluated using UK energy system emissions data, while the effect of equipment scale is explored empirically. The results show that for the same product quality, the innovative technologies are more energy- and non-renewable primary resource-efficient, with ohmic heating performing best, followed by high pressure

processing at high fill-ratios. More significant improvements are expected in future, provided electricity grid decarbonisation is sustained. Energy performance improves with equipment scale for the microwave and high-pressure systems, but remains essentially constant for ohmic heating.

Keywords: food preservation, energy demand, carbon emissions, high pressure processing, microwave volumetric heating, ohmic heating

Industrial relevance: Using orange juice pasteurisation as case study, this work shows that for similar product quality, electrically-driven innovative food pasteurisation technologies like high pressure processing, ohmic and microwave heating are more beneficial than conventional techniques energy- and emission-wise, if a sufficient portion of the electricity is renewable. This is the case given the current decarbonisation level of the UK electricity grid and is expected to be more significant as more electricity is sourced renewably in the future as currently projected. The result should aid future industrial investment decisions.

1. Introduction

The demand for additive-free, extended shelf-life food products, with fresh-like tastes, excellent nutritional quality and guaranteed microbial safety, has led to the development of innovative processing and preservation technologies. A range of these technologies is becoming commercially available to the food industry and there is significant interest in their potentials. Among them are non-thermal processes such as high pressure, pulsed electric field, pulsed light, ultrasonic processing, and volumetric heating schemes such as microwave, radiofrequency and ohmic heating. Currently at relatively low levels of industrial implementation, the potentials of these technologies in contributing significantly to sustainably meeting the food intake needs of the growing population of the world has long been recognised (Langelaan et al., 2013; Probst et al., 2015). The food and beverage market is extremely competitive. Therefore, improving quality alone is not sufficient to assure the success of a new technology. The improvements must be achievable at a commercially viable process cost per production unit. An understanding of the energy demand associated with the use of novel preservation techniques is therefore commercially important, and is the subject of the current contribution.

Although there are many studies and reviews on different aspects of quality and microbial safety of various foods processed by these technologies (e.g. Atuonwu and Tassou, 2018a, Barba et al., 2017 a,b), the same cannot be said for energy and sustainability studies. A recent review on microwave food processing (Atuonwu and Tassou, 2018b) for instance, concludes that little is available in the literature on studies dedicated specifically to energy consumption analysis of microwave food processes. An exception is in the area of microwave and microwave-assisted food drying operations, which were extensively reviewed in that work. Similar conclusions could be reached for most other innovative food preservation technologies, although some energy studies at individual unit operation level, exist (e.g. Kurjak et al., 2012; Cokgezme et al., 2017; Park et al., 2017; Atuonwu and Tassou, 2018c). Fewer comparative studies across technologies are available in the literature. Toepfl et al. (2006) explored the potentials of pulsed electric field PEF and high pressure processing HPP technologies for energy-efficient and environmentally-friendly food processing. Lung et al. (2006) estimated the potential energy savings of PEF orange juice pasteurisation and radiofrequency RF cookie drying, relative to conventional technologies. They reported a 100% savings in natural gas and 18% savings in electricity for the PEF system, and a natural gas savings of 73.8-147.7 TJ per year, but an increased electricity consumption for the RF system. Pereira and Vicente (2010) highlighted the reduced environmental impact potentials of novel thermal and non-thermal technologies in food processing. Sampedro et al. (2014) compared the costs and environmental impacts of PEF, HPP and thermal pasteurisation technologies based on commercial processing conditions validated for a 2-month shelf life of orange juice under refrigeration conditions. The total electricity consumption of the HPP and PEF systems per kg of juice was about 26 and 24 times respectively, that consumed by the thermal system (extra energy from natural gas was also consumed by the thermal system). Overall, there was a 7-8-fold increase in CO_2 emissions by the HPP and PEF systems compared to the thermal process. A simulation-based sensitivity analysis of total production costs with respect to equipment scale, showed that cost per unit reduced with scale. Details of the simulation method were not provided. Rodriguez-Gonzalez et al. (2015) compared the energy requirements of HPP, PEF, membrane filtration MF, ultraviolet UV radiation and conventional HTST thermal pasteurisation using published information for the inactivation of *Escherichia coli* in apple juice. They concluded that MF and UV have the potential to consume less energy per unit mass, than HTST, PEF and HPP. Milani et al. (2016) compared HPP and thermosonication, with conventional thermal pasteurisation in terms of energy requirements and inactivation of *Saccharomyces cerevisiae* ascospores. HPP was found to consume the least specific energy, followed by thermosonication for the same level of inactivation under the experimental conditions. For the same processing time, HPP also showed the highest level of inactivation, followed by thermosonication. Aganovic et al. (2017) conducted comparative energy and life cycle assessments of thermal, HPP and PEF pasteurisation technologies for the preservation of tomato and watermelon juices, at gate-to-gate (processing) and farm-to-gate (preparation, processing and waste treatment) levels. Conventional thermal processing with a plate heat exchanger was found to consume the least specific energy, followed by the PEF and HPP technologies, respectively. There was no significant difference in the specific energy consumption of each technology, for both products.

As most of the studies concerning innovative technologies in food processing have been performed at lab-scale, the results obtained are difficult to scale-up and cannot be generalized. Where scale-up studies have been done, few details have been provided. The broad variety of equipment used, and the large range of different processes, products, and recipes complicate comparison of energy use. Energy consumption data of single production sites are rarely available due to nondisclosure, and the same is true for single unit operations. In most studies, many of the results are based on energy calculations, inferred from product temperature measurements. For instance, in Rodriguez-Gonzalez (2015), Milani et al. (2016) and Aganovic et al. (2017), the energy consumption of conventional thermal processes was calculated based on product temperature measurements, rather than direct energy measurements. Moreover, only a few studies have compared innovative and conventional food preservation technologies on the basis of primary energy resource efficiency and GHG emissions of the pasteurisation step.

The purpose of the current work is to measure and compare the energy performances of HPP, microwave volumetric heating (MVH), ohmic heating (OH) and conventional thermal treatment (UHT), whilst delivering equivalent microbiological lethality in orange juice, under commercially-representative processing conditions. The GHG emissions corresponding to the energy consumed across the technologies are evaluated using the UK electricity grid and other energy system emissions data, collected over many years while the effect of equipment scale is explored empirically.

2. Materials and Methods

A series of trials were conducted using continuous flow microwave processing, conventional heat treatment, high pressure processing and ohmic heating. For the first three processes, trials were conducted using orange juice produced at Campden BRI. Fresh oranges of good and uniform quality (total mass, 300 kg) were purchased from a local supplier (Drinkwater, Chipping Campden), delivered in 15 kg boxes the day before processing, transferred into open crates and chill-stored at 5 °C. The oranges were washed with water and juice, extracted using an FMC citrus reamer (designed to mimic industrial extraction practices). The juice was collected in 10 L stainless steel buckets, immediately wrapped in cling-film and covered in black bags. For the ohmic heating process, fresh oranges were purchased from another supplier, the juices extracted using a compact juicer (Philips HR1832/01) and processed immediately at Brunel University London. In all cases, electrical energy consumption was measured using energy meters (details in Section 2.5). Thermal energy delivery to the food was determined from temperature measurements, mass measurements for batch processes, flowrate measurements for continuous processes and thermophysical data (e.g. density and specific heat capacity) from the literature.

2.1. Continuous microwave heating

Continuous microwave processing was conducted using a Dynowave – AMT 4 system (Advanced Microwave Technologies, Scotland), with a four-magnetron power source. As shown in the basic schematic of the microwave pasteurisation system (Fig. 1a), the orange juice flows through the microwave chamber, then through a holding tube, before being cooled via heat exchange with cold water. The 12-kW capacity unit uses microwave energy to quickly heat up a range of pumpable, non-flammable food products and biotechnical components. Cold juice (20 litres) at approximately 14°C, was added to the equipment feed tank, whilst external heat, using a water bath, was provided to the heat exchanger jacket (tubular heat exchanger), to keep the energy supplied stable and thus, minimise the temperature drop within the holding tube.

A progressive cavity pump (Seepex, UK) was used at 115 ± 5 L/h, for a target process of 75 °C for 26 s. The holding tube dimensions were calculated to be 22 mm diameter and 2.4 m length which yielded a process equivalent to 70 °C for 2 mins (based on the average flow rate with z = 7.5 C°). The come up time (CUT) was between 22 and 25 s. The inlet and outlet temperatures of the holding tube were continuously monitored using calibrated sensors. If the target temperature was not achieved, the product was manually diverted to the drain. Once the set initial temperature was reached, the liquid food was directed to the heat exchanger. The process was repeated three times.

Fig. 1

2.2. Ohmic heating

Here, 250 ml orange juice was fed into a 10-kW batch ohmic heater (CTech Innovation, Capenhurst, Chester, UK) operating at atmospheric pressure. The heater comprises:

- A polypropylene product container into which the juice was filled (with an electrode at each end), located in a bunded tray with an interlocked cover.
- A free-standing control panel (housing the power supply unit with a proportional-integral-derivative PID controller for voltage control), attached to the heater.

The polypropylene product container internally measures 90mm wide x 95mm high, with a variable length between 80mm and 300mm, adjustable between the two end electrode housings via 80mm- and 220mm-long spacer sections, fitted with tie rods. The maximum operating voltage between the electrodes is the mains supply voltage (~240V). This electrode voltage is controllable via the PID controller between 0 and maximum voltage to achieve desired product temperatures. In this work, only the 80mm option, corresponding to a maximum voltage gradient of ~30V/cm, is used. The orange juice was heated from ambient to 76°C, with a holding time of 26s, similar to the microwave system. The come-up time was in the range 50-70s. Electrical energy consumption data was collected at two levels: from the mains (which determines the total energy costs), and between the electrodes, via the control panel, by measuring the electrode terminal voltages with a voltmeter, and the current through it, using a clamp-on ammeter. This approach enables the actual electrode control voltage signal and hence, voltage gradient dynamics to be determined. Fig. 1 b shows a schematic of the ohmic heating system with the electrical energy instrumentation connections.

2.3. HPP

Energy use was monitored on a 700 ml laboratory-scale HPP system (EPSI, Belgium). The pressure medium consisted of water with 3% (v/v) of MKU, an oil based corrosion inhibitor. The pressure was recorded using an MMS3000 data logger (RiL Instruments, Nottingham), logging at 1 second intervals. Fig. 1 c shows the operating principle of the HPP system. The pressure medium is pumped via a pressure generator (intensifier) to the already-filled pressure vessel containing the packaged juice, leading to pressure build-up to a maximum of 600 MPa, which is maintained for a hold time of 3 mins, after which, rapid depressurisation occurs. The juice temperature during the hold step is, 30 ± 2 °C and reduces to 12 ± 1 °C after depressurisation.

2.4. UHT/HTST System

Conventional thermal processing trials were conducted using an FT74XTS miniature-scale UHT/HTST processing system (Armfield, UK). Fig. 1 d illustrates the principle of the UHT system. Process water (PW) is heated by an electrical process heater (EH). The resulting hot water exchanges heat with flowing cold orange juice. When the target temperature is reached, the orange juice flows through the holding tube for the desired residence time before subsequent cooling. The target process is set at 76.8°C for 15 seconds (equivalent of 70.0°C for 2 min based on an average flowrate of about 12 L/h and z = 7.5 C°). The process was repeated 3 times.

2.5. Energy measurements

Electrical energy data for the HPP, MVH and UHT/HTST systems was recorded at 5 second intervals, using a Fluke 1730 energy logger. As each system was three-phase power supply-driven, the logger monitored each phase voltage, while independently monitoring the respective line currents using the induction current measuring principle (clamping the jaws of the meter over each live phase conductor). For the OH process, driven by a single-phase supply, phase voltage, current, power factor, power and cumulative energy were each logged at 10 second intervals, via a Fluke 345 energy logger. The per-phase voltage and current coil connections for all electrical energy measurements are illustrated in Fig. 1 a- d. In each case as shown in the figures, the current coil of the meter is in series with the phase-to-neutral circuit. This is achieved by clamping the jaws of the meter around the live phase conductor L from the mains. The voltage coil is connected in parallel (i.e. one terminal to the live phase conductor L and the other to the neutral N). Note that for the three-phase power supply-driven system, there are three live phase conductors (usually designated L1, L2 and L3) from the mains, hence, three independent voltage and current coils are present in the meter Fluke 1730. In all cases, the data is saved to internal memory, and the relevant Fluke application software used to extract the individual components.

2.6. Comparative analysis methodology

2.6.1. Energy density and efficiency comparison by electrical measurements

To enable all processes under investigation to be logged using the same measuring principle, the conventional technology is represented here by an electrically-powered hot water-to-orange juice heat exchanger (UHT system). Energy comparisons are initially made on the basis of energy density (electrical mains energy consumed per litre of juice), and energy efficiency. Instantaneous energy density SPE_i for continuous processes is calculated as the ratio of the instantaneous power consumption $P(t)$ to the volumetric flowrate $\dot{V}(t)$

$$SPE_i = P(t)/\dot{V}(t) \quad (1)$$

For processes with steady-states, the final value (SPE_f) of SPE_i is the required value. For batch processes, the cumulative energy density SPE_f is the aggregated (or final) mains energy consumed after processing time t_f, divided by the batch volume *vol*.

$$SPE_f = \frac{1}{vol}\int_0^{t_f} P(t)dt \quad (2)$$

The energy efficiency in each case is determined as the ratio of output heat energy Q_{Heat} to the input mains electrical energy Q_{Elect}. For the continuous and batch processes respectively, the instantaneous value of efficiency are calculated as

$$\eta_{Elect}(continuous) = {Q_{Heat}(t)}/{Q_{Elect}(t)} = \dot{m}C(T_{out}(t) - T_{in}(t))/P(t) \quad (3)$$

$$\eta_{Elect}(batch) = {Q_{Heat}(t)}/{Q_{Elect}(t)} = {mC(T(t) - T_{in})}/{\int_0^t P(t)dt} \quad (4)$$

where m is the hold up mass, $\dot{m}$, mass flowrate, C, specific heat capacity, T_{in}, inlet or initial temperature, T_{out}, outlet temperature and T, temperature within the batch vessel. Equations (3 & 4) apply only to the electro-heating technologies (MVH, OH and UHT). As HPP is non-thermal, evaluating the energy efficiency in an equivalent manner is not as straightforward. To facilitate energy efficiency comparison across the technologies, an equivalent HPP pasteurisation energy efficiency is proposed as

$$\eta_{eq(HPP)} = {Q_{Heat(T0=25)}}/{Q_{Elect(HPP)}} = {mC(T(t) - 25)}/{\int_0^t P(t)dt} \quad (5)$$

where, $\eta_{eq\ (HPP)}$ is the efficiency of the HPP system, referred to a thermal system, while $Q_{Heat\ (T0=25)}$ is the heat energy required to heat the orange juice from room temperature (25°C) to the pasteurising temperature of a conventional system (UHT), and $Q_{Elect\ (HPP)}$, the electrical energy consumed by the HPP equipment in achieving the same level of pasteurisation. P and m in (5) are based on HPP process data only.

2.6.2. GHG emissions: innovative vs conventional gas-fired technologies

Although the conventional technology (UHT) is represented by an electrically-powered hot water-to-orange juice heat exchanger, gas-fired hot water or steam heaters are most common in industry (Masanet et al., 2008). Hence, the most effective way of comparing the industrially-relevant gas-fired system with the electrically-driven innovative technologies is to refer all energy consumption to the non-renewable primary energy use. The GHG emissions corresponds to the amount of non-renewable primary energy resource depletion due to processing. For comparison, this can be used as an approximate measure to gauge the non-renewable primary energy efficiency of the gas-fired and electrically-driven innovative process technologies.

First, the efficiency of the studied electrically-powered UHT is defined as

$$\eta_{UHT} = \eta_{Elect,J} = \eta_{Elect,HW}\eta_{HW,J} \qquad (6)$$

where, $\eta_{Elect\ ,J}$ is the efficiency of energy conversion from electricity to heat into the juice, $\eta_{Elect,HW}$, the efficiency of energy conversion from electricity to hot water and $\eta_{HW,J}$, the efficiency of energy conversion from hot water to heat into the juice. Assuming the system is gas-fired, the efficiency $\eta_{G,J}$ (gas-to-juice) would be

$$\eta_{G,J} = \eta_{G,HW}\eta_{HW,J} = \eta_{G,HW}\left(\eta_{UHT}/\eta_{Elect,HW}\right) \qquad (7)$$

where $\eta_{G,\ HW}$ is the efficiency of energy conversion from gas to hot water. By estimating $\eta_{G,HW}$ and $\eta_{Elect,HW}$, $\eta_{G,J}$ can be roughly determined. $\eta_{G,HW}$, which corresponds to the boiler efficiency is in the range $0.5 \leq \eta_{G,HW} \leq 0.8$ (Carbon Trust, 2012a, b), while $\eta_{Elect,HW}$, the indirect resistance heating efficiency of the electrical heating element is estimated as $\eta_{Elect,HW}$ =0.8 (CEATI, 2018). Based on the gas-fired system efficiency $\eta_{G,J}$, the energy density SPG_f with respect to the gas fired technology becomes

$$SPG_f = \frac{1}{\eta_{G,J}}\left(SPE_f/\eta_{Elect}\right) \tag{8}$$

where the term in brackets is the specific thermal energy (kJ/L) delivered to the juice.

The GHG emissions corresponding to using the gas-fired system to supply thermal energy ${}^{1}Q_{Heat}$=1 kWh to the juice is

$$GHG\ Emissions_G\left(kgCO_2e/kWh\right) = {}^{1}Q_G\varsigma_G = {}^{1}Q_{Heat}\varsigma_G/\eta_{G,J} \tag{9}$$

where ς_G=0.18416 kgCO$_2$e/kWh is the 2017 GHG conversion factor (gross calorific value) for natural gas from the UK gas grid (UK GOV, 2018). Changes in the value of ς_G over the years are minor, and hence, ς_G is assumed constant for simplicity. ${}^{1}Q_G$ is the gas energy in kWh that delivers ${}^{1}Q_{Heat}$=1 kWh to the juice.

For the electrically-driven technologies with efficiencies η_{Elect} derived from experimental energy measurements, a similar expression may be written as

$$GHG\ Emissions_{Elect}\left(kgCO_2e/kWh\right) = {}^{1}Q_{Elect}\varsigma_{Elect} = {}^{1}Q_{Heat}\varsigma_{Elect}/\eta_{Elect} \tag{10}$$

where, ς_{Elect} is the GHG conversion factor for the UK electricity grid. Estimates and projections of this, up until 2035 were collected from DBEIS (2018) and ICAX (2018), and presented in Appendix A, Table A1. ${}^{1}Q_{Elect}$ is the electrical energy in kWh that delivers ${}^{1}Q_{Heat}$=1 kWh to the juice. ${}^{1}Q_{Heat}$=1 kWh is used as functional unit because, barring non-thermal effects, 1 kWh of heat delivered to the juice, will for the same initial conditions of the juice, achieve the same pasteurising effect across all technologies.

If 1 L of juice is chosen as functional unit instead of 1 kWh of juice-delivered thermal energy ${}^{1}Q_{Heat}$, the GHG emissions (kgCO_2e/L) can be determined by multiplying the respective kgCO_2e/kWh values (equations 9 & 10) by the corresponding total thermal energy density in kWh/L (i.e. $2.78e^{-4}SPE_f\eta_{Elect}$) as shown in equations (11) and (12).

$$GHG\ Emissions_G(kgCO_2e/L) = 2.78e^{-4}SPG_f\eta_{G,J}GHG\ Emissions_G(kgCO_2e/kWh) \quad (11)$$

$$GHG\ Emissions_{Elect}(kgCO_2e/L) = 2.78e^{-4}SPE_f\eta_{Elect}GHG\ Emissions_{Elect}(kgCO_2e/kWh) \quad (12)$$

2.7. Equipment scale studies

To explore the effect of equipment scale on the specific energy consumption of the innovative technologies, some trials at different scales were performed, where possible (MVH and OH), while for the other case (HPP), experimental results at different scales from published works, and the current study were correlated.

2.7.1. MVH System

For the MVH system, trials were conducted on the same equipment (of cylindrical cavity diameter 34mm, and length 550mm) using water at different flowrates (90-240L/h), below and above that used in the original orange juice experiment (115L/h). The energy input was scaled by different magnetron switching scenarios. Each of the four magnetrons of the microwave heating system is switchable independently to deliver 3kW of power at full-load. Hence, system performance for 3, 6, 9 and 12kW microwave power delivery was evaluated, under the different product flow conditions.

2.7.2. OH System

For the batch OH system, the maximum voltage gradient was maintained at ~30V/cm as the source voltage cannot exceed the mains value (~240V) and the electrode separation was held constant at the minimum possible value (~8cm). Scaling was achieved by changing the volume of orange juice from 250ml, through 375ml to 500ml. For the batch ohmic heater with a rectangular section, at constant electrode separation L, and constant plate length, W, this was achieved by varying the product level, x.

2.7.3. HPP System

For the HPP system, the power consumption-pressure characteristics of two systems at 35L and 55L capacity from previously published studies (Rodriguez-Gonzalez et al.., 2015; Aganovic et al., 2017) are compared with that of the current study (a 700ml system). The 55L system (Wave 6000/55 Hiperbaric, Burgos, Spain) operates at a maximum pressure of 600 MPa, compression time of 3.5 min and holding time of 5 min. The 35L system (AVURE Technologies, Kent, WA, U.S.A.) has a maximum pressure of 600 MPa, a compression time of 2 min and a holding time of 2 min.

3. RESULTS AND DISCUSSION

3.1. Energy consumption analysis

3.1.1. MVH System

The MVH results are shown in Fig. 2. The power consumption characteristics is discontinuous as several subsections of the equipment (magnetron cooling, cabinet cooling, stirrer operation and microwave power delivery) are controlled using on/off control loops. Ordinarily, the MVH power consumption data would have been considered once the product temperature had reached steady state (Fig. 2). However, since the on-and-off switching times of the magnetron cooling system is somewhat random, due to the variable initial state (temperature) of the magnetron within each experimental period, the overall mains power consumption has no steady-state. Further tests were performed to isolate the random magnetron cooling from the overall energy consumption, and show that the magnetron cooling energy is ~1.8kW. Hence, the steady-state MVH power consumption is evaluated as the sum of the minimum value (with no magnetron cooling) and the time-averaged magnetron cooling energy.

Analysing the power consumption characteristics (Fig. 2 b), the maxima occurring in the time region $0 \leq t < 8$, where t is in minutes, is most likely due to a combination of two factors: the low product inlet temperature and high product outlet temperature overshoot (maximum outlet temperature ~85-95°C as against the required 76°C) in that region (Fig. 2 a). This maxima disappears in the region $8 \leq t < 20$ when the product outlet temperature stabilises at the set-point. The minima in the region $11 \leq t < 13$ is most likely due to the random magnetron cooling energy switch-off. When the energy-density and efficiency (Fig. 2 c & d) are evaluated based on the time-averaged steady-state values, the final energy density is 380kJ for 1 litre of orange juice, while the energy efficiency is 45%. When the magnetron cooling energy is recovered, the energy density reduces to 325 kJ/L, while the efficiency becomes 54%. It should be noted that the specific energy consumption (and hence, energy density) depends significantly on the product inlet temperature, which could be subject to environmental variations (Fig. 2 a). A high product inlet temperature means less energy would be spent to achieve the desired outlet temperature. For energy efficiency, these effects tend to cancel out, making it a better index for comparing the performances of different thermal technologies irrespective of inlet temperature variations.

3.1.2. OH System

Fig. 3 shows the various energy performance indicators of the OH system. As a batch system, the comparison with continuous systems is based on the total energy use per cycle of orange juice production. A cycle consists first of a transient stage, where the juice is heated from its initial temperature to the required set-point of 76°C. Thereafter, there is a steady-state stage, where the orange juice is maintained at this set-point for 26 seconds (the residence time in the holding tube of the microwave system). From the experimental results the transient period is about 70s (Fig. 3 a), while the steady-state period is shown (for clarity), extended to make a total time of 5 minutes. The energy consumed in pasteurising a litre of orange juice is 208 kJ, while the cumulative energy efficiency is 80%. At the beginning of the process, the energy efficiency is observed to be 97%, rising to 99% towards the end of the transient stage (at 50s), the onset of voltage control switching. The energy efficiency drops to 80% in the short period of voltage control (50s to 70s), at the end of which, power supply to the electrodes is switched off and the temperature maintained for 26s (during which time, no heat losses are observed). An important implication of the voltage switching as observed in Fig. 3 b is that while the mains voltage V1 remains constant throughout the process (as it should be, being independent of loading conditions I1 and I2), the control voltage V2 delivered to the electrode drops sharply. Since the currents, I1=I2 essentially, the power (V2 x I2 x cos □2), utilised for juice heating falls more sharply than the power (V1 x I1 x cos □1) drawn from the mains. Therefore, the PID controller-based voltage switching control wastes energy in much the same way as a throttling valve does for fluid flow through pipes. This situation can be remedied in continuous-flow ohmic heaters where product outlet temperature can be fixed for a constant voltage gradient, by setting the juice flowrate and electrode length *W*, to achieve the desired product outlet temperature in the resulting residence time. Unsteady environmental conditions can then be compensated for by flow control. This way, overall energy efficiencies above 95% are anticipated for the process. Note that the entire ohmic system including the power supply system elements has a lagging power factor cos □1 (Appendix A, Fig. A1), while within the ohmic cell bounded by electrodes, the power factor cos □2 ≈ 1 (as the food is essentially a pure resistor).

Fig. 3.

3.1.3. HPP System

Fig. 4 (a) shows the pressure-time and power-time characteristics of the HPP system. By dynamically integrating the power curve, with respect to time, and dividing by the hold-up volume of orange juice, the cumulative energy consumption per litre (energy density) was obtained as shown in Fig. 4 (b). It is observed that to achieve the required pasteurisation, 645 kJ of energy is required per L of orange juice. The seal of the HPP equipment was less effective than desired. Short peaks of power were required to maintain the holding pressure in the equipment due to small leaks around the seal as can be observed in Fig. 4a. This leads to energy efficiency reductions.

Fig. 4.

Fig. 5.

3.1.4. UHT/HTST System

The UHT system of section 2.4, whose energy performance indicators are shown in Fig. 5, has an energy density of 470 kJ/L, with an energy efficiency of 46%. As in all continuous processes, whose input and output energies reach steady-states, the steady-state values are considered. The abnormally high energy efficiency (about 200%) recorded in the transient period (Fig. 5d), occurs due the build-up of heat in the indirect resistance heating element used in transferring electrically-generated heat to the hot water. This coincides with the first temperature maxima in Fig. 5a. Hence, although the control system reduces the electrical power input considerably after the first maxima in Fig. 5b, the outlet temperature remains high, ensuring the output thermal energy exceeds the input electrical energy for a short period. It is important to note the very long transient period (~ 2 hours), which occurs due to the low heat transfer rates.

3.2. Energy consumption comparison

As shown in Table 1, the batch OH process has the highest energy efficiency (80%) of all the thermal processes, in spite of the energy lost by control voltage reductions. It also has the least specific energy consumption. A continuous OH process, without voltage switching temperature control would be expected to have the efficiency (η > 95%) before the onset of voltage switching is expected. The MVH and UHT/HTST processes have comparable energy efficiencies (45 & 46%, respectively), when the magnetron cooling is powered electrically from the cabinet. If this cooling energy is discounted, the MVH system energy efficiency could rise to as high as 54%. The specific energy consumption of the MVH system is considerably less than that of the UHT/HTST system, counter-intuitively, due to the much higher temperature of the orange juice fed into the MVH system (compare the inlet temperature values of Figs 2a & 5a). Hence, the MVH system requires much less energy to get one litre of orange juice to a similar temperature set-point, even though the energy efficiencies are approximately equal. The HPP system has the worst energy performance. One reason for this is the low vessel filling ratio (36%) used. Previous studies (Atuonwu and Tassou, 2018c; Rodriguez-Gonzalez et al., 2015) show that specific energy consumption reduces significantly with vessel filling ratio. Using correlations from the power-vessel filling ratio graphical relations of Rodriguez-Gonzalez et al. (2015) for extrapolation, the efficiency of the HPP system is found to improve from its initial value of 31% (at 36% filling ratio) to 51% at 60% filling ratio, and 78% at 85% filling ratio. There also exists opportunities to improve HPP energy performance by recovering the decompression via synchronised twin, semi-continuous systems (Toepfl et al., 2006).

Due to the low heat transfer rates between the hot water and juice in the UHT/HTST system, its start-up performance is very poor, as seen in the long transient time. Over this time (2 hours) of off-spec production, a total of 12.72MJ of energy is consumed. Hence, for processes with frequent shut-downs and start-ups, this would be a major problem. The HPP, MVH and OH processes do not have this problem as electric switching has an almost instantaneous effect on thermal energy generation. When the electrically-powered HTST system (UHT) is converted to an equivalent conventional gas-fired system using equations (2) and (3), the energy efficiency is 29% for a 50% boiler efficiency (UHT1), and 46% for an 80% boiler efficiency (UHT2). As the energy efficiencies of UHT1 and UHT2 are with respect to gas, versus electricity for the other technologies, a simple energy efficiency comparison will not suffice. Hence, in the next section, GHG emissions are used to refer the energy performances of all the technologies to the same basis: non-renewable primary energy resource use.

3.3. Comparison of non-renewable primary energy use via GHG emissions

Fig. 6 shows the GHG emissions (per kWh of thermal energy or equivalent) of all the studied electrically-driven innovative and gas-fired technologies, based on their various energy performances, over a 25-year period (2010-2035). With the rapid decarbonisation of the UK electricity grid over time, the innovative technologies become much more non-renewable primary energy resource-efficient and hence, more environmentally-friendly. The hypothetical continuous OH process at 95% efficiency is seen to have the best GHG performance, followed by the batch OH process, which is then closely-followed by the HPP system at 95% filling ratio, and then, the MVH1 system (MVH with recovered cooling energy). These are all currently (2018 data), more non-renewable resource-efficient than the best gas-fired system. The 60%-filling ratio HPP system, closely follows suit and is currently just as GHG-efficient as the best gas-fired system. Using current projections, the improvements attained by the innovative technologies are expected to be more significant with time. By 2027, even the 36%-filling ratio HPP will become more energy resource-efficient than the most-efficient gas-fired system, provided gas boilers do not become significantly more efficient that 80%. It is important to note that the significant transient energy losses (about 12.72 MJ) of the gas-fired system is ignored in this analysis. If considered, the improvement due the innovative technologies becomes even more significant. Similar conclusions as the foregoing can be reached by examining Table 2 where GHG emissions (in kgCO2e/L of juice product), calculated for the years 2016-2020 are presented. Clearly, the investigated innovative technologies are very promising investments in terms of primary energy resource efficiency. Actual investment decisions would however also consider capital costs, the applicability of the specific technology to the product being processed, in-pack processing vs aseptic filling-only possibilities, water consumption, packaging issues, amongst other factors. The HPP process studied in this work (at 36% fill ratio) is a post-packaging process. Hence, there is virtually no fouling of the processing vessel and consequent waste water from cleaning. Moreover, pressurised water can be reused, thus, increasing overall sustainability. The packaging however, must be capable of maintaining its shape and form after the pressurisation and depressurisation processes. The continuous-flow MVH, UHT and batch OH processes are pre-packaging processes and so lead to fouling of hot surfaces over time, and subsequent cleaning operations which generate wastewater. Moreover, they require aseptic filling with the attendant energy and environmental costs. The same applies to the very high fill ratio (95%) HPP, which is virtually unattainable in a post-packaging process. For the high-power (12 kW) MVH system, the magnetrons require water cooling, which could constitute waste water, or be continuously reused so its energy is recovered to preheat the juice. All these aspects as well as factors such as shelf life, will figure in an overall environmental analysis. The current study however focuses only on the energy required for the actual pasteurisation process step and the associated GHG emissions.

Table 1

Table 2

Fig. 6.

3.4. Results of equipment scale studies

Figs 7 – 9 show the magnitudes of the various energy performance indicators of the MVH, OH and HPP processes, respectively, at different operating scales. For the MVH system, it is observed (Fig. 7a) that irrespective of the flowrate, the electrical power consumption is essentially a linear function of the number of magnetrons, switched on. The heat delivery rate is a linear function of the number of switched-on magnetrons at variable and constant product outlet temperature (Fig. 7b, d). The interplay of the slopes and the vertical axes intercepts of the two functions makes the efficiency (obtained by dividing the functions), a slowly increasing function of scale, represented by the number of magnetrons (Fig. 7c). However, the overall economics of scale would also consider factors other than energy. The experiments on which Fig. 7 were obtained used the same equipment, with a single cavity size. A study (Wang et al., 2015) with different effective cavity sizes (medium volumes), suggests that efficiency increases marginally with cavity size, within limits.

For the batch OH system, the time-averaged electrical power consumption increases with operating volume (Fig. 8a). The area under the power consumption-time graph is observed over a large set of experiments (results not shown), to be approximately a linear function of batch volume, provided the juice initial temperature is constant. The heating power delivered to the juice however depends on the voltage switching regime of the PID controller, which shows no consistent trend with volume over the experiments conducted (Fig. 8b only shows one result from the set of experments). A consistent observation nonetheless, is the fact that prior to voltage switching, the ratio of the heat delivered to the electrical energy consumed from the mains is somewhat constant (~98%, see Fig. 8 b & c). The earlier in time the PID controller switching occurs, the more energy is wasted leading to efficiency reductions (Fig. 8c) as the corresponding area under the control voltage-time graph, which in a sense represents the actual energy delivered to the fluid, drops (Fig. 8b). Over the large experimental set (results not shown), this trend is found to be independent of batch volume. Hence, the efficiency reduction in Fig. 8c is not due to batch volume, but to the voltage switching regimes. For a continuous OH process where the temperature can be controlled without voltage switching, the associated efficiency losses are not expected. Hence, the efficiency is expected to remain essentially constant (~98%), irrespective of scale. The energy density (or specific energy consumption in kJ/L) for the presented case (Fig. 8d) is essentially constant, with volume as the areas under the power consumption-time graphs (Fig. 8a) are essentially, linear functions of volume. This behaviour is however only true if the juice initial temperature is the same across all the experimental volumes. For the HPP system (Fig. 9), the energy consumed per litre of product (assuming a 95% fill ratio) is calculated as 0.242 MJ for the 0.7L case, 0.084 MJ for the 35L case, and 0.095 MJ for the 55L case (without leakage) and 0.45 MJ for the 55L case (with leakages considered). It therefore appears that larger-scale systems have significantly better energy performances than small, lab-scale systems. Many other factors contribute to the energy performance of an actual machine. These include the equipment make (different for each studied case) – this significantly affects start-up and shut-down-related energy indices, and machine conditions (e.g. pressurising medium leakages), which greatly diminishes the performance of the 55L system.

Fig. 7.

Fig. 8.

Fig. 9.

3.5. Critical analysis of results with respect to previously published works

Previously published energy and sustainability studies on innovative mild food preservation techniques (as investigated here), present conflicting results. Milani et al.

(2016) report a HPP energy density of 77 kJ/L, lower than the values (645, 392 and 256 kJ/L) reported here. However, unlike the current study, the results of Milani et al. (2016) were based purely on calculations of compressive work (based on pressure measurements) and initial sensible heating (based on temperature measurements). This underestimates the energy consumption as it does not consider many other factors which also contribute to the energy consumption of typical HPP processes. These include product loading in vessel, overall system movement from loading to working positions and initial vessel filling with water (Atuonwu and Tassou, 2018c). Others are, closing the HPP plug, moving a wedge to secure the plug, maintaining the target pressure for the required time, where there are leakages and product unloading. Furthermore, in Milani et al. (2016), the maximum operating pressure was 300 MPa in 27 s, as against the 600 MPa in 3 mins used here, and Atuonwu and Tassou (2018c) show that energy consumption increases more than proportionately with operating pressure. Using similar methods to Milani et al., Sulaiman (2015) realised an energy density of 240 kJ/kg for strawberry puree processing at 600 MPa, 48 °C for 5 mins, while Rodriguez-Gonzalez et al. (2015) recorded 338.1 kJ/kg, for processing apple juice at 350 MPa, 40 °C and 482.8 kJ/kg at 500 MPa, 42 °C, both for 5 mins. Processing details such as equipment volume and fill ratio were not stated, neither was there any information on contributions of leakages, loading and other energy-contributing factors. Aganovic et al. (2017), perhaps the only previous study in the literature based on energy measurements, reports a much higher value (720 kJ/kg for HPP at 600 MPa, 5 mins), for a 55 L system. This is most likely due to the low fill ratio used (36%) and the significant energy losses during the hold period (see Fig. 9 c & f), which could be attributed to leakages. Overall, the results presented in the current study are within the range of all the reported previous literature values, while providing more energy measurement, equipment parameter and scale details.

For conventional thermal treatment, Rodriguez-Gonzalez et al. (2015), using calculations based on temperature measurement data from other studies, reported specific energies in the range 166.9 - 228.5 kJ/kg, while Aganovic et al. (2017) reported a value of 144 kJ/L. These again are underestimated values as in both cases, the energy consumed was calculated as $mC\Delta T$ (see numerator of equations 3 & 4). This is the energy delivered to the product which is usually much lower than the actual energy consumed. Although Aganovic et al. (2017) adds a cooling energy arbitrarily chosen as 33% of $mC\Delta T$ (which would increase the total energy value), they assume 70% heat recovery (which further reduces the total energy). It is therefore not surprising that such low values of specific energy are calculated. The results of our study (470 kJ/L) are however based on actual energy measurements for an electricity-driven HTST system. When it is driven by a gas-fired boiler at 50% efficiency, the energy density is 746 kJ/L (kJ of gas energy per litre of juice). From the foregoing analysis, the method used in our study is a better representation of reality.

The MVH energy efficiency results presented in this work (45 – 54%) are well within the range of values reported for microwave heating of different liquids at different batch volumes (Wang et al., 2015). Other studies (e.g. Atuonwu and Tassou, 2018a) suggest that possibilities exist, using improved power supplies, to achieve higher efficiencies by microwave power amplitude, frequency and phase optimisation. For OH systems, efficiencies (also termed “system performance coefficients”) in the rage 57–86% were reported for different voltage gradients in the range 20–60 V/cm, with the higher efficiencies corresponding to the lower voltage gradients in orange juice (Icier and Ilicalli, 2005). Similar results were reported for apple juice by Park et al. (2017) as long as the sugar concentration was in the range 18–48 °Brix. Darvishi et al. (2015) reported an efficiency range of 55–100%, but for tomato juice evaporation in the voltage gradient range 6 to 16 V/cm. Our results are within the aforementioned ranges. It should be noted that in all these ohmic heating studies, there was no temperature control. The product temperature increased linearly with time, essentially, until the process end point, where the system was switched off. In the tomato juice evaporation process of Darvishi et al. (2015), the temperature was eventually limited at the boiling point of the juice. In our current work however, temperature control was implemented as it was essential to maintain a non-boiling temperature for a desired pasteurisation time in a batch OH process. Our work demonstrates empirically for the first time, that voltage modulation for temperature control in a batch OH system is an energy-wasting exercise and should be avoided where possible. For this purpose, we recommend the use of continuous-flow processes, where temperature control can simply be achieved by appropriate selection of fixed voltage gradient and product residence times, followed by a properly-insulated holding stage.

4. Conclusions

In this work, we have measured and compared the energy performances of innovative technologies (high pressure processing HPP, continuous-flow microwave volumetric heating MVH, ohmic heating OH) and conventional heat treatment UHT, whilst achieving the same pasteurising effect in orange juice, under commercially-representative processing conditions. We have also evaluated the sustainability of each of these processes with respect to non-renewable energy resource use and explored the effect of equipment scale using model-based and empirical approaches.

For similar product quality attributes, the OH process is observed to have the best energy performance (80% efficiency) among all the processes. However, for the first time, it is shown empirically for the OH process that voltage modulation, as commonly used in batch operations for temperature control, wastes significant energy, in much the same way as valve throttling does for fluid systems in pipes. It should therefore be discouraged. For a continuous OH process which permits temperature control without voltage switching, efficiencies higher than 95% may be obtainable. The MVH and electrically-powered heat exchanger-based UHT processes have comparable energy efficiencies (45 & 46%, respectively), when the MVH magnetron is cooled electrically. If this cooling energy is supplied from available cooling water sources, the MVH energy efficiency could rise to 54%. All the innovative technologies show significantly-better start-up characteristics than the conventional heat exchanger-based process, UHT, thus saving significant amounts of energy.

For a gas-fired system with equivalent heat exchanger behaviour as the UHT process, the efficiency relative to primary energy is 29% (at 50% boiler efficiency), and 46% (at 80% boiler efficiency). Among the innovative technologies, the HPP system (with a filling ratio of 36%) has the least energy efficiency 31%. By increasing the filling ratio to 60% and 95% respectively, efficiencies of 51% and 78% are attained. In terms of non-renewable primary energy usage and hence climate change (evaluated by the greenhouse gas GHG emissions corresponding to equivalent pasteurising effects), the OH, 95%-fill ratio HPP and microwave with magnetron heat recovery processes are currently better than the best gas-fired systems, based on the UK electricity grid conditions. With the current grid decarbonisation trend, all the electricity-driven innovative technologies are anticipated within the next few years to far outperform the best gas-based systems, thus justifying investment in these technologies. Actual investment decisions would however also depend on the applicability of the specific technology to the product being processed, in-pack processing versus aseptic filling-only possibilities, capital costs amongst other factors. Energy performance improves with equipment scale for the microwave and HPP systems, but remains essentially constant for the ohmic heating system. In all these, no significant differences are observed in the critical quality attributes of the raw and pasteurised orange juice across all the technologies. The electricity-driven innovative technologies are thus promising in terms of energy savings, environmental friendliness and product quality.

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Nomenclature

C	Specific heat capacity of juice in OH	J/kg/K
I	Current	A
L	Electrode separation in OH	m
M	Hold-up mass of juice in OH	kg
P	Power	W, kW
Q	Energy	J, kJ
T	Juice temperature	°C
T	Time	s, min
V	Voltage	V
W	Electrode length in OH	m
X	Juice height in OH system	m

Greek letters

η	Efficiency	
ρ	Juice density in OH	kg/m^3
ς	GHG conversion factor	kgCO_2e/kWh

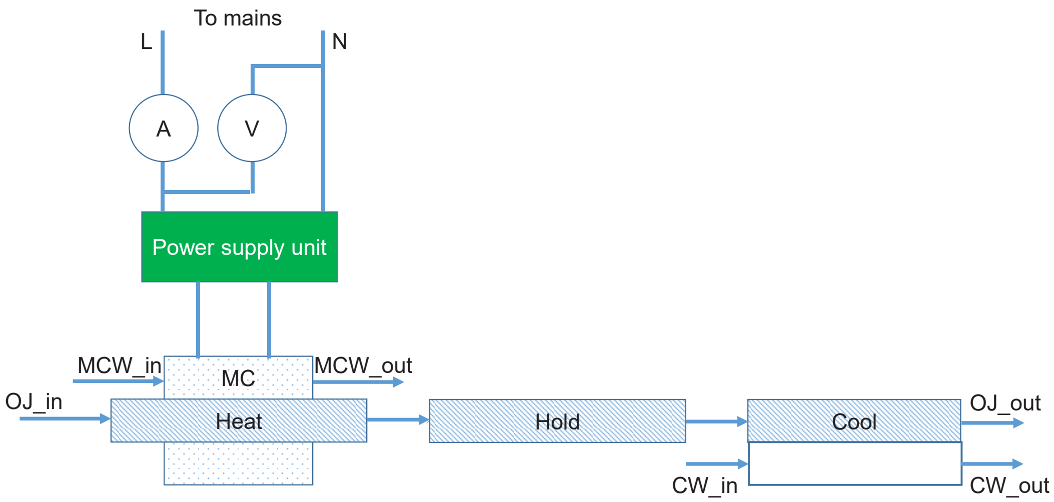
Subscripts

Elect	Electricity
G	Natural gas
Heat	Heat
HW	Hot water
J	Juice

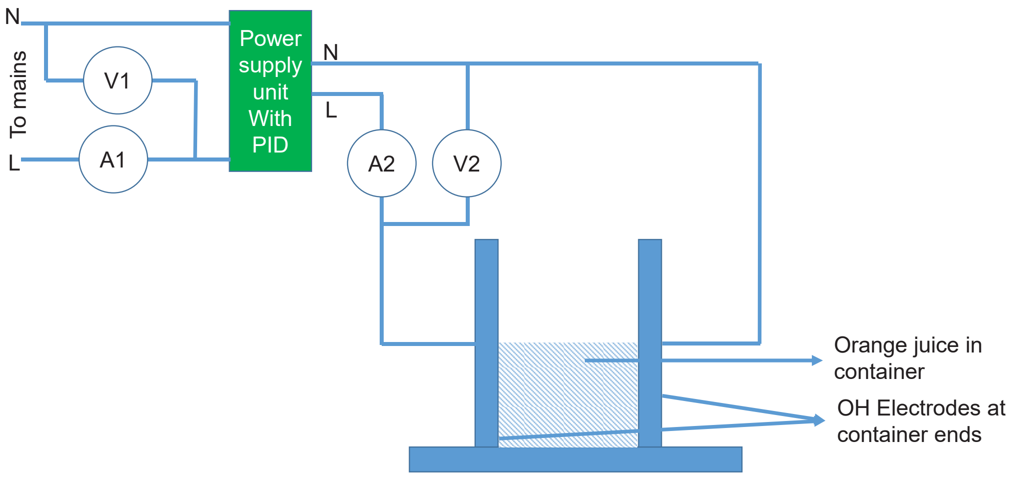
Appendix A

Table A1.

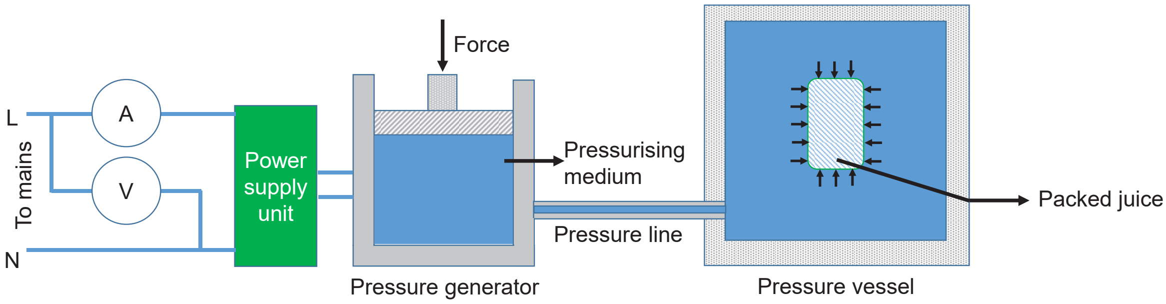
Fig. A1.


To mains
L
N
A
V
Power supply unit
MCW_in
MC
MCW_out
OJ_in
Heat
Hold
Cool
OJ_out
CW_in
CW_out

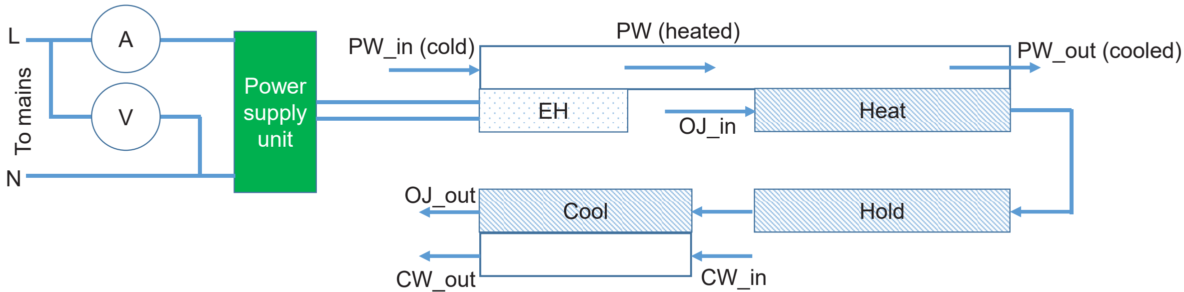
(a)


N
To mains
L
V1
A1
Power supply unit With PID
N
L
A2
V2
Orange juice in container
OH Electrodes at container ends

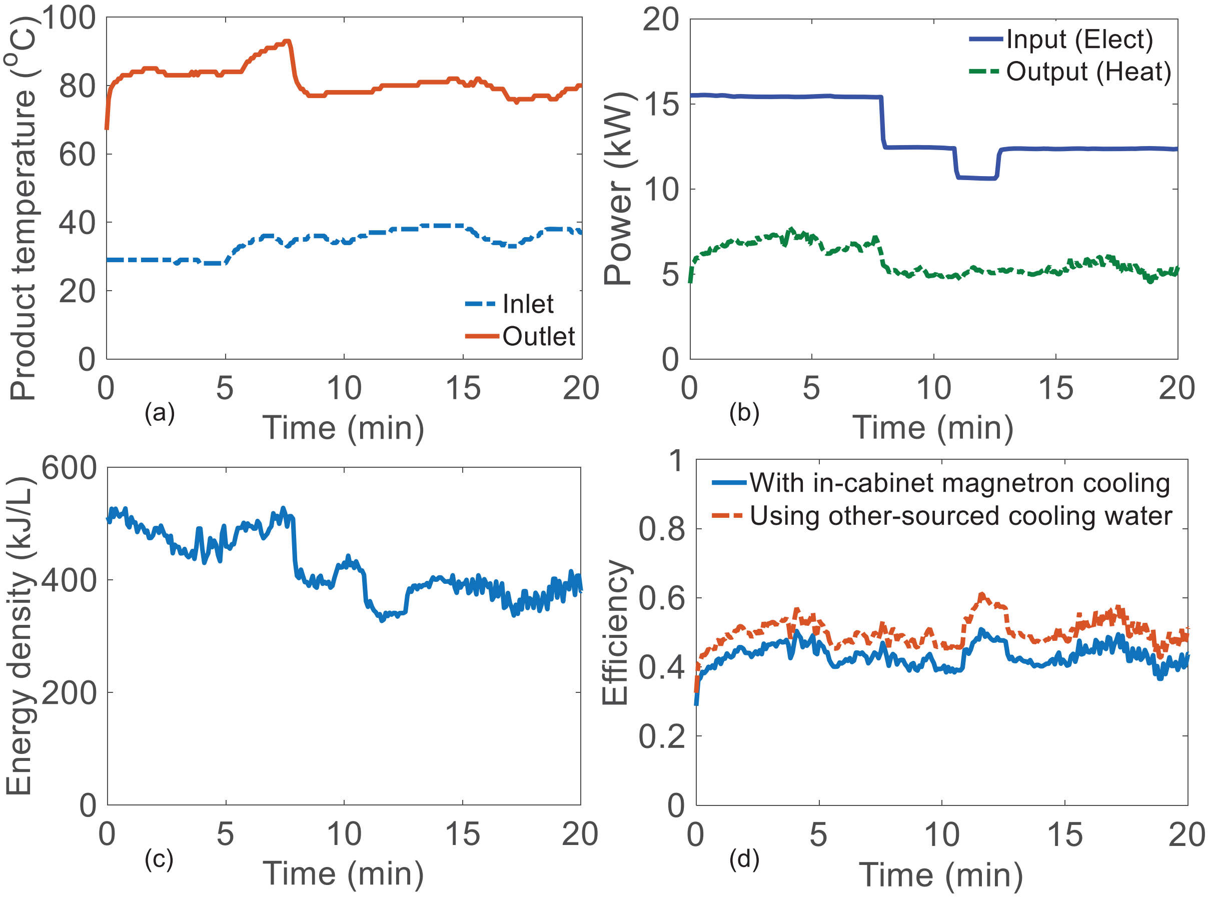
(b)


L
To mains
N
A
V
Power supply unit
Force
Pressurising medium
Pressure line
Pressure generator
Packed juice
Pressure vessel

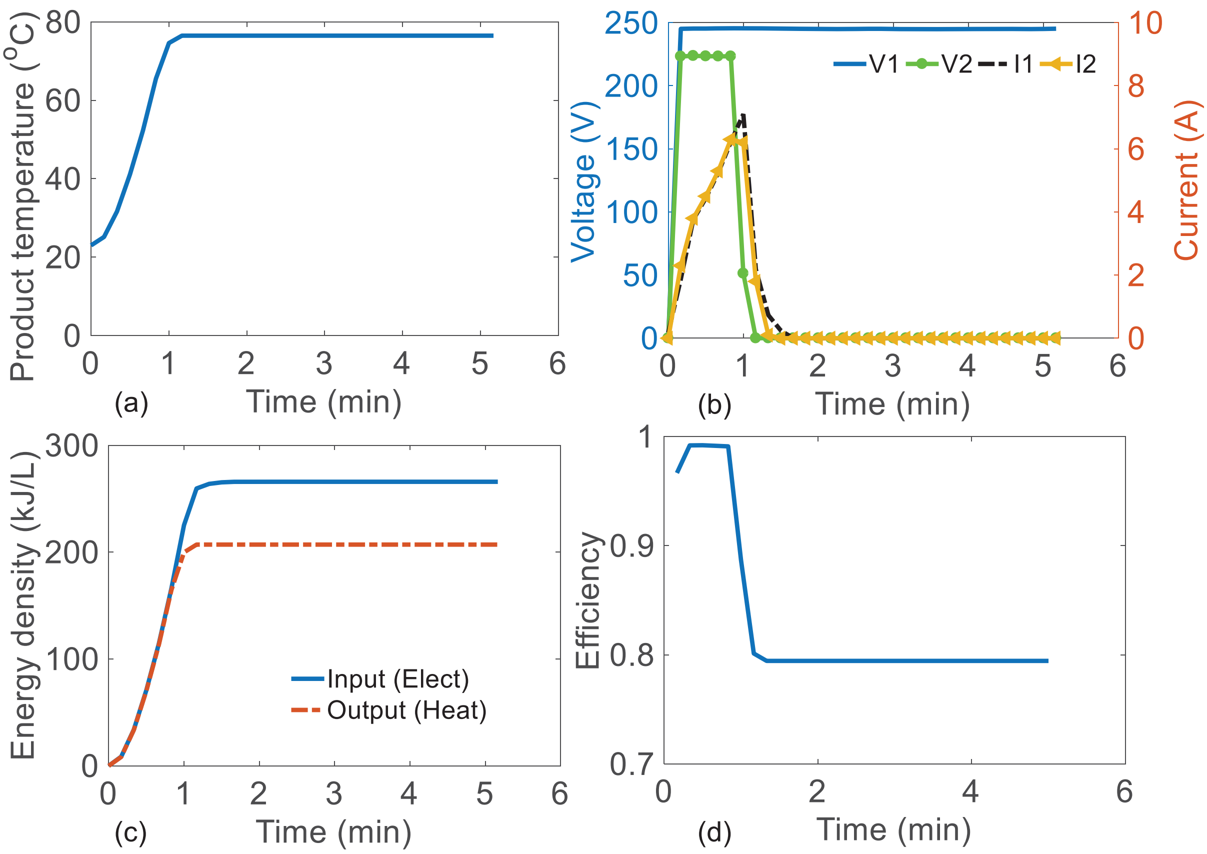
(c)


L
To mains
N
A
V
Power supply unit
PW_in (cold)
PW (heated)
PW_out (cooled)
EH
OJ_in
Heat
OJ_out
Cool
Hold
CW_out
CW_in

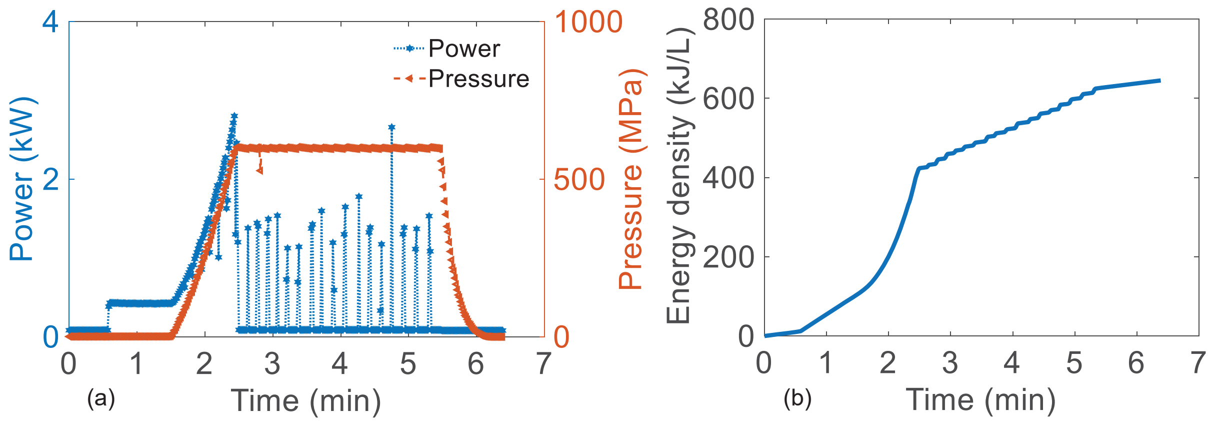
(d)

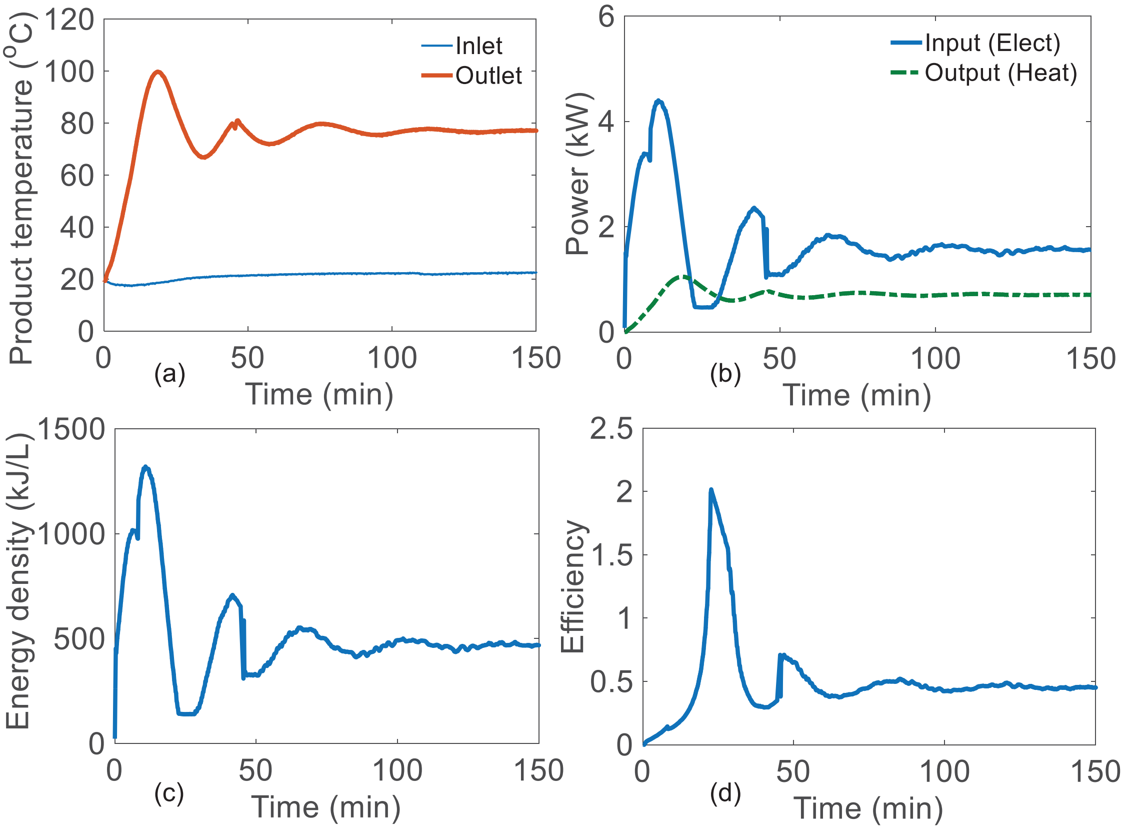


Product temperature (°C)
Inlet
Outlet
Time (min)
(a)
Power (kW)
Input (Elect)
Output (Heat)
Time (min)
(b)
Energy density (kJ/L)
Time (min)
(c)
Efficiency
With in-cabinet magnetron cooling
Using other-sourced cooling water
Time (min)
(d)

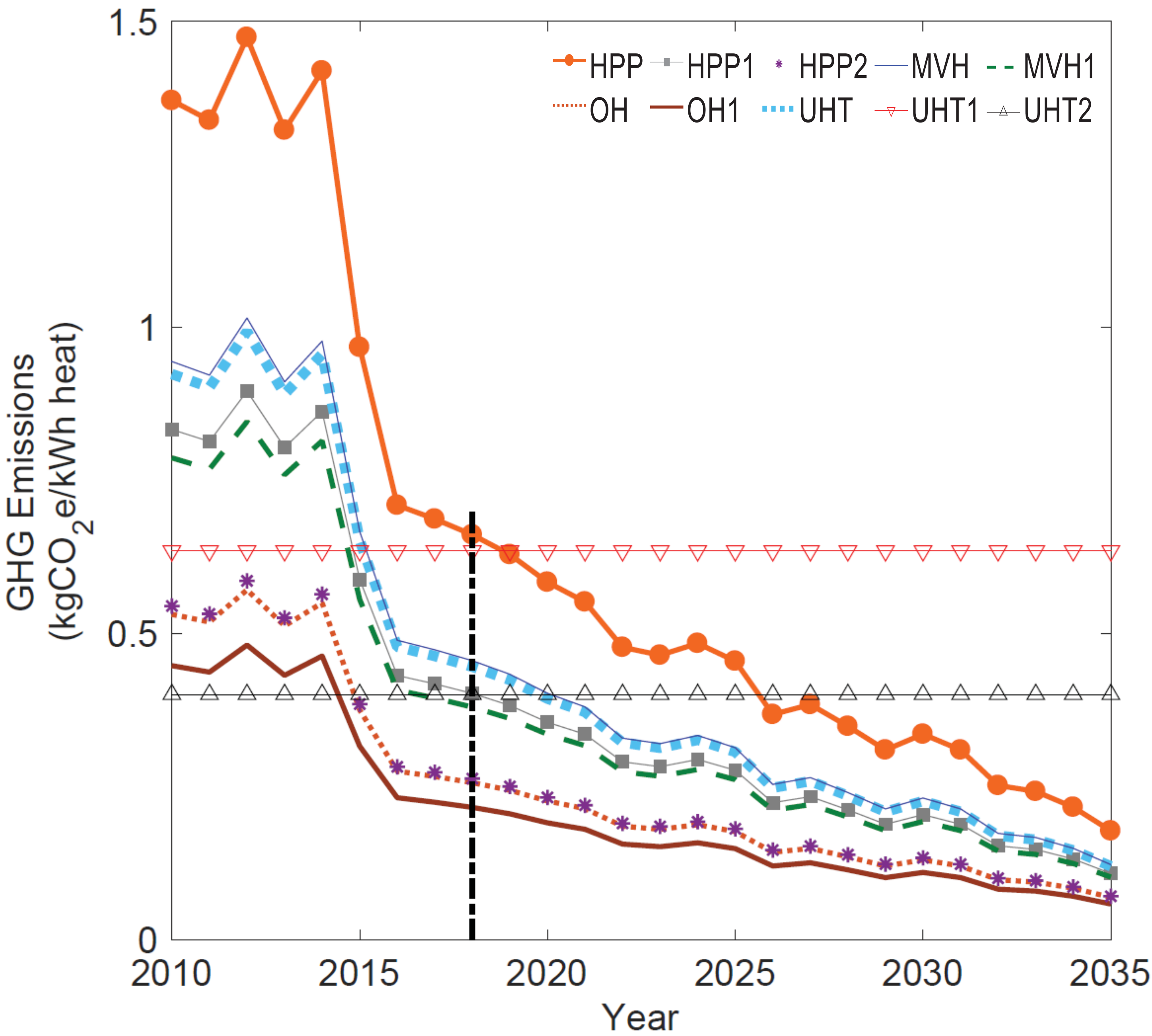


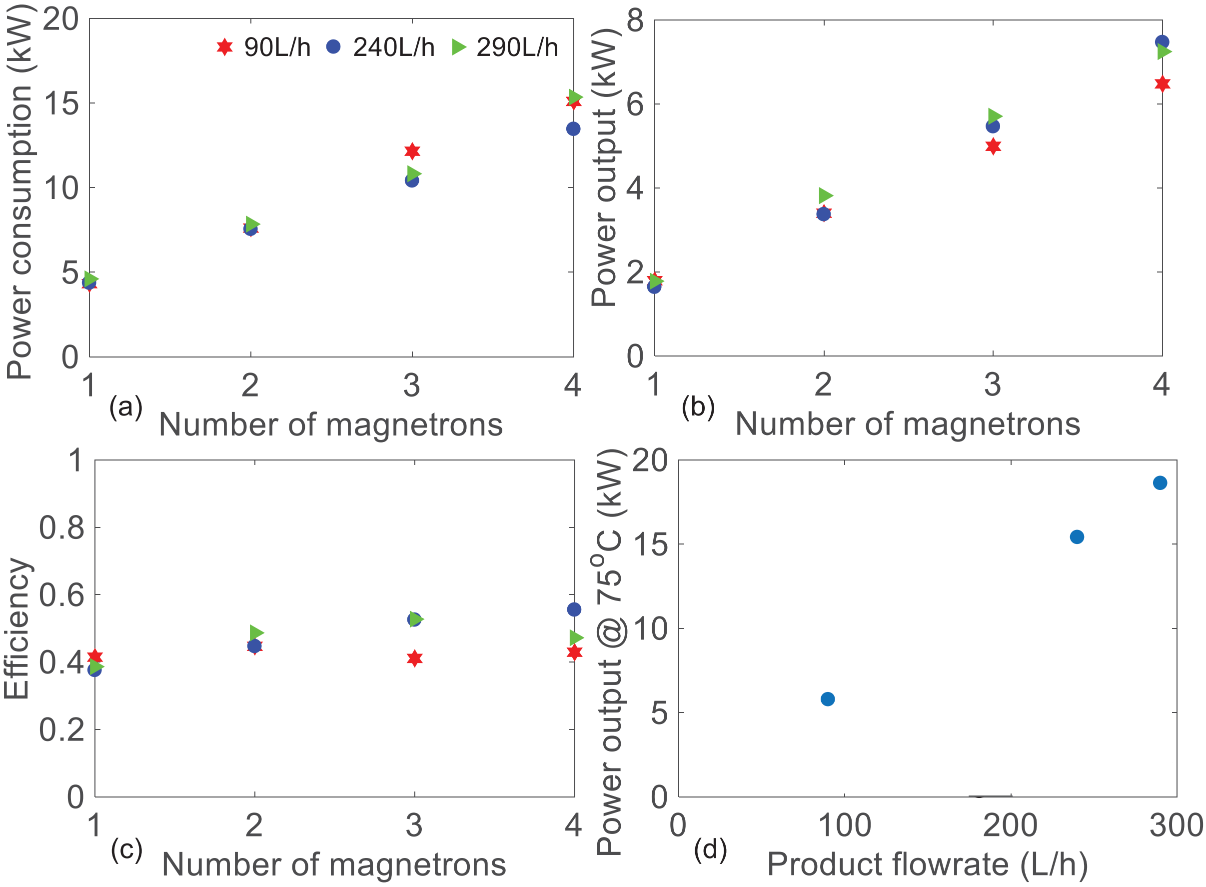
Product temperature (°C)
Time (min)
(a)
Voltage (V)
Current (A)
V1
V2
I1
I2
Time (min)
(b)
Energy density (kJ/L)
Input (Elect)
Output (Heat)
Time (min)
(c)
Efficiency
Time (min)
(d)


Power
Pressure
Power (kW)
Pressure (MPa)
Time (min)
(a)
Energy density (kJ/L)
Time (min)
(b)

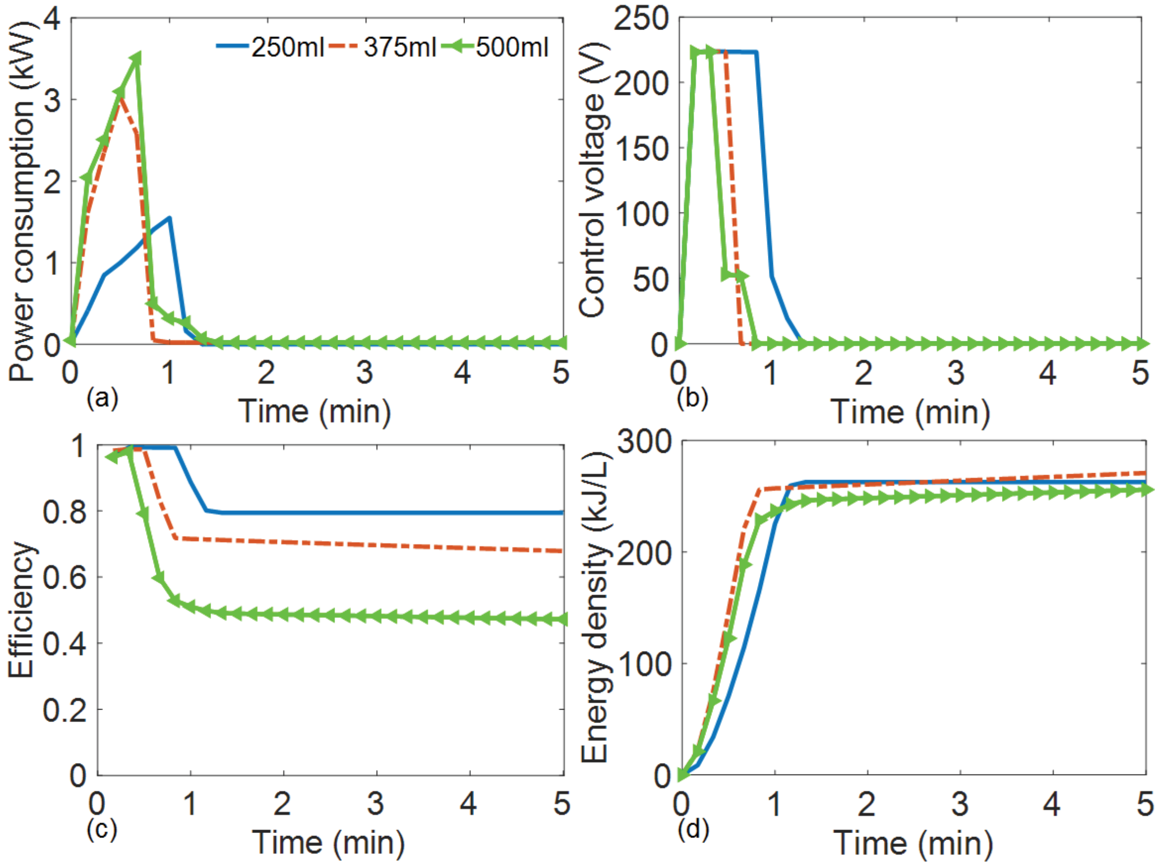


Product temperature (°C)
Inlet
Outlet
Time (min)
(a)
Power (kW)
Input (Elect)
Output (Heat)
Time (min)
(b)
Energy density (kJ/L)
Time (min)
(c)
Efficiency
Time (min)
(d)

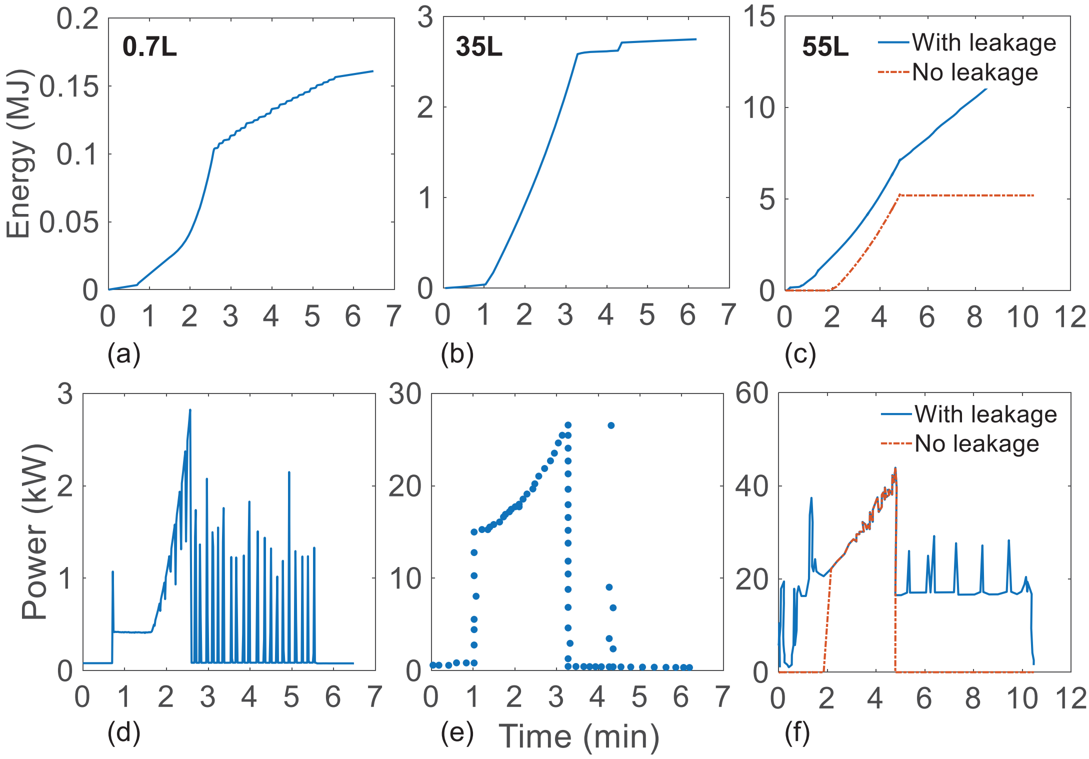

HPP
HPP1
HPP2
MVH
MVH1
OH
OH1
UHT
UHT1
UHT2
GHG Emissions
(kgCO2e/kWh heat)
1.5
1
0.5
0
2010
2015
2020
2025
2030
2035
Year



90L/h
240L/h
290L/h
Power consumption (kW)
Number of magnetrons
(a)
Power output (kW)
Number of magnetrons
(b)
Efficiency
Number of magnetrons
(c)
Power output @ 75°C (kW)
Product flowrate (L/h)
(d)



250ml
375ml
500ml
Power consumption (kW)
Time (min)
(a)
Control voltage (V)
Time (min)
(b)
Efficiency
Time (min)
(c)
Energy density (kJ/L)
Time (min)
(d)


0.7L
35L
55L
With leakage
No leakage
Energy (MJ)
Power (kW)
Time (min)
(a)
(b)
(c)
(d)
(e)
(f)

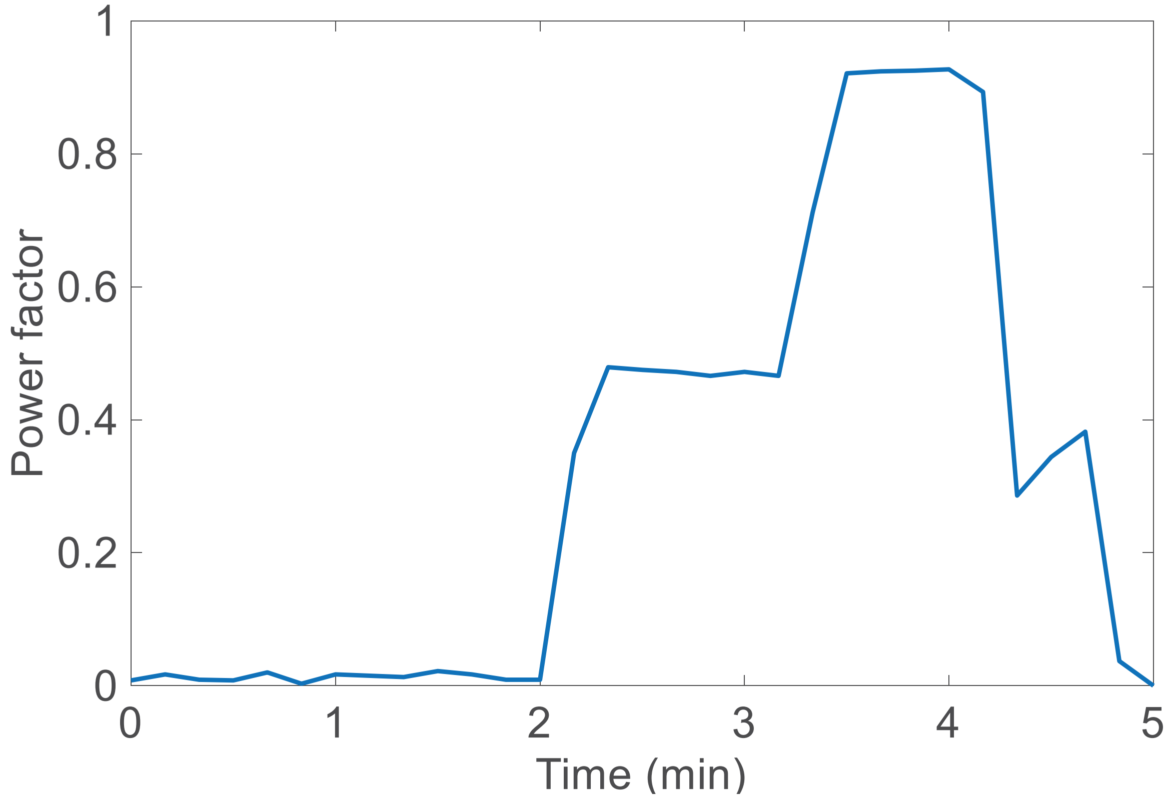

Power factor
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5
Time (min)

Fig. 1. (a) Continuous-flow microwave heating system (b) Batch ohmic heating system (c) High pressure processing system (d) Schematic of UHT/HTST system operating principle. Symbols used are OJ (orange juice), MC (microwave chamber), CW (cooling water), MCW (magnetron cooling water), _in (inlet conditions), _out (outlet conditions), V (voltage coil connections for energy measurement: two terminals connected to live L and neutral N power supply conductors, respectively), A (current coil connections for energy measurement, achieved by clamping the jaws of the meter over the live conductor L from the mains)

Fig. 2. MVH system energy performance-related characteristics

Fig. 3. OH system energy performance-related characteristics

Fig. 4. (a) Pressure-time & power-time characteristics (b) Energy density of HPP system

Fig. 5. UHT/HTST system energy performance-related characteristics

Fig. 6. GHG emission comparisons among processes 2010 – 2035, with 2018 vertical line

Fig. 7. Equipment scale results: continuous-flow microwave volumetric heating (MVH)

Fig. 8. Equipment scale results: batch ohmic heating (OH)

Fig. 9. Equipment scale results: high pressure processing (HPP)

Fig. A1. Power factor dynamics of total OH load (juice between electrodes and power supply system)

	HPP	HPP1	HPP2	**MVH**	MVH1	**OH**	OH1	**UHT**	UHT1	UHT2
Energy efficiency	0.31	0.51	0.78	0.45	0.54	0.8	0.95	0.46	0.29	0.46
Specific energy (kJ/L)	645	392	256	380	325	208	175	470	746	470
Transient time (min)	2.5			8	8	1		120		
KEY										
HPP1	HPP with 60% vessel filling ratio									
HPP2	HPP with 95% vessel filling ratio									
MVH1	MVH with cabinet cooling replaced by available cooling water									
OH1	Continuous OH process (without voltage switching control)									
UHT1	Gas-fired UHT/HTST system with 50% boiler efficiency									
UHT2	Gas-fired UHT/HTST system with 80% boiler efficiency									

Year	**HPP**	HPP1	HPP2	**MVH**	MVH1	**OH**	OH1	**UHT**	UHT1	UHT2
2016	0.0394	0.0240	0.0157	0.0232	0.0199	0.0127	0.0107	0.0287	0.0382	0.0241
2017	0.0382	0.0232	0.0152	0.0225	0.0192	0.0123	0.0104	0.0278	0.0382	0.0241
2018	0.0368	0.0223	0.0146	0.0217	0.0185	0.0119	0.0100	0.0268	0.0382	0.0241
2019	0.0350	0.0213	0.0139	0.0206	0.0176	0.0113	0.0095	0.0255	0.0382	0.0241
2020	0.0325	0.0197	0.0129	0.0191	0.0164	0.0105	0.0088	0.0236	0.0382	0.0241

Year	UK Electricity Grid Emissions factor (kgCO_2e/kWh)
2010	0.425
2011	0.415
2012	0.457
2013	0.41
2014	0.44
2015	0.3
2016	0.22
2017	0.213
2018	0.205
2019	0.195
2020	0.181
2021	0.171
2022	0.148
2023	0.144
2024	0.15
2025	0.141
2026	0.114
2027	0.119
2028	0.108
2029	0.096
2030	0.104
2031	0.096
2032	0.078
2033	0.075
2034	0.067
2035	0.055

Table 1. Energy performance comparison among processes. Note: UHT1 and UHT2 values are based on primary energy (kJ of natural gas) and the others on electrical energy (kJ)

Table 2. Pasteurisation process GHG emissions (kgCO_2e/L of juice) compared across technologies (2016 – 2020)

Table A1. UK electricity grid emissions factor, 2010-2035 (DBEIS, 2018)