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Research Paper

Optimisation of heating uniformity for milk pasteurisation using microwave coaxial slot applicator system

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Microwave heating is a novel solution for milk pasteurisation but the non-uniformity of thermal distribution is still a significant problem that hampers its application especially for milk pasteurisation. This paper reports on the isotherm heating of a coaxial slot antenna applicator with a microwave signal generation using a fabricated mono-mode microwave system designed to improve the temperature uniformity of batch milk pasteurisation. In this paper, applicator simulation, design, characterisation, and fabrication are described in detail. The fabricated microwave pasteurisation system was implemented using a digitally controlled water-cooled magnetron with a waveguide circulator, a three-screw waveguide tuner, a water-based waveguide terminator, and a rectangular to coaxial adapter to channel the output. The impedance matching and power calibration routines of the fabricated microwave pasteurisation system are explained and analysed in detail. Three microwave powers, namely 100 W, 125 W and 150 W were used to test and characterise the pasteurisation performance of the system. For each microwave power the thermal profile and the temperature distribution of the 100 ml milk samples in a glass beaker were simulated and measured. The pasteurisation process was evaluated based on the aerobic plate count (APC) test. Results showed 90% improvement in the temperature uniformity as compared with an existing batch microwave pasteurisation method. The APC test showed

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pasteurisation efficiency was 99.999% and total microbial elimination occurred after 7 min, 6 min, and 5 min of heating using 100 W, 125 W, and 150 W power respectively.

Nomenclature

ε_r'	Dielectric constant
ε_r''	Dielectric loss factor
$\lvert S_{11} \rvert$	Antenna return loss, (dB)
APC	Aerobic plate count
C	Coupling factor for waveguide coupler, (dB)
CFU	Colony-forming units
CUT	Come-up time, (min or s)
C_ρ	Specific heat capacity of milk, (J $kg^{-1}K^{-1}$)
DOL	Direct-on-line protection circuit
D-value	Microbial decimal reduction time, (min or s)
f	Frequency, (Hz)
FDA	US food and drug administration
HPP	High-pressure processing
IR	Infra-red
ISM	Industrial, scientific, and medical
K	Thermal conductivity, (W m^{-2} K^{-1})
L_{slot}	Slot length of coaxial antenna, (mm)
MAPS	Microwave coaxial-based pasteurizer
P_{DC}	Magnetron supplied DC power, (W)
PEF	Pulsed electric field
P_{MICRO}	Magnetron output microwave power, (W)
PMO	Pasteurised milk ordinance
SPLC	Spiral plate count
T	Temperature, (°C)
TE_{10}	Transverse electric mode with the lowest cut-off frequency
TEM	Transverse electromagnetic
Z_{in}	Antenna input impedance, (Ω)
ΔP_{DC}	Uncertainty of magnetron excited DC power, (W)
ΔP_{MICRO}	Rate of change in microwave output power, (W)
ΔP_{SEN}	Uncertainty of microwave power sensor, (W)
ΔT	Maximum temperature difference, (°C)
ρ	Milk density, (kg m^{-3})
σ	Milk conductivity, (S m^{-1})

1. Introduction

Pasteurisation is a micro-biocidal heat treatment that aims to reduce the existing load of microorganisms in raw milk to a safe level such that it does not constitute a significant health hazard (Fellows, 2000). Existing pasteurisation methods use either conventional conduction-based heating or alternative heating technologies. Currently, the predominant industrial pasteurisation process is based on heat exchangers (Lewis & Deeth, 2009). Overheating in heat exchangers (either tube or plate) is the main disadvantage of the current system. When milk cannot be evenly heated up to the required pasteurisation temperature severe deterioration in product quality occurs. It produces chemically complex residues (or fouling) after operation over a period of time. Such deposits must be removed regularly by intensive cleaning in order to meet hygiene and quality regulations (Augustin et al., 2007; Awais & Bhuiyan, 2019; Lewis & Deeth, 2009; Meredith, 1998). From a practical standpoint, milk deposits can be rapidly generated, requiring intense cleaning procedures (Bansal & Chen, 2006) Pipe cleaning procedures involve several factors which increase production losses, such as lowering production rates (Kananeh and Peschel, 2012) and increasing energy losses and labour costs. Fouling mitigation procedures cost about 80% of the total dairy production costs (Bansal & Chen, 2006), which is around 27 billion US dollars annually (Meredith, 1998; Hou et al., 2017; Sosa-Morales and Vélez-Ruiz, 2009). Therefore, there is a continuous demand for more economic and efficient solutions for pasteurisation.

Several emerging technologies have been proposed as alternatives to conventional pasteurisation. The most popular solutions are high-pressure processing (HPP), pulsed electric field (PEF), ohmic heating, infrared (IR) heating, and microwave heating. Microwave heating offers several advantages such as rapid heating, which provides less come-up time (CUT), shorter initial start-up time, easier operation, lower maintenance, and an environmentally friendly free-fouling process (Meshram et al., 2017, pp. 219–251). when compared to other alternatives (Harrison & Whittaker, 2003; Salazar-González et al., 2012). Also, it offers an excellent ability to destroy pathogenic and spoilage micro-organisms thereby preserving the nutritional characteristics of the dairy products (Martins et al., 2019). Microwave pasteurisation has also been shown to be superior to conventional pasteurisation in preserving milk taste by 80% (Goldblith & Wang, 1967).

Microwave heating is also called dielectric heating or volumetric heating (Harrison & Whittaker, 2004), and it involves the processed material being heated through interaction between its polarised molecules and electromagnetic waves. Microwave heating operates at either 915 MHz or 2.45 GHz which are part of the industrial, scientific, and medical (ISM) electromatic bands. However, several limitations exist for microwave heating which hinder its industrial commercialisation. Microwave heating devices are large and bulky, which can make them more expensive than conventional or ohmic heating. But the main hindrance to being adopted on an industrial scale for milk pasteurisation is the uneven temperature distribution of microwave heating (Martins et al., 2019). Vadivambal & Jayas, 2010 have extensively addressed the non-uniformities in microwave heating for several food products. Several factors are involved in the heating mechanism which can affect the uniformity of the temperature distribution either in the cavity or applicator (chamber) or in the material to be processed. Cavity effects are related to the design parameters such as shape, the microwave inlet point location, and hanging parts (i.e. mixer), whilst the workload influence is mainly addressed by dielectric properties, thickness, geometry (size and shape), penetration depth, and the loss factor (Sakai et al., 2004; Vadivambal & Jayas, 2010). Two methods exist in microwave heating, namely single-mode and multi-mode. A single-mode applicator is designed to permit only one resonant mode of propagation. It is mainly applied in heating small volumes. Multimode applicators contribute to 50% of current industrial microwave heating. The electric field distribution formed in the material being processed with multimode applicators is affected by several factors but mainly the dielectric properties, moisture content, and the sample location inside the cavity (Asmussen et al., 1987). A rotating turntable is commonly used in multimode operation to improve the electric field distribution and this in turn improves thermal distribution (Ye et al., 2019). To date, for batch microwave pasteurisation, the use of a multimode applicator with a mode stirrer and a rotating turntable is considered the best technique to mitigate uneven temperature distribution (Hazervazifeh et al., 2019; Martins et al., 2019; Ohnishi, 1989, pp. 833–286). However, for medium and high-loss foods, such as milk, the mode stirrer is not able to overcome the resistance of non-uniformities (Plaza-González et al., 2005; Topcam et al., 2020).

The use of a multimode stirrer or rotating turntable to improve the non-uniformity indicates that the directivity and the radiation pattern are unable to reach some areas, which consequently variates the distribution of electric field within the sample and consequently cause uneven distribution. This paper aims to improve the uniformity of microwave heating for application to milk pasteurisation. It aims to demonstrate the capability of a low-power coaxial slot antenna in generating isotherm heat as a heating source for the pasteurisation of milk. The design, optimisation, and fabrication of a coaxial slot antenna as a heating applicator and the implementation of a microwave signal generator system based on the magnetron source required to feed the applicator are described in detail in section 2. The temperature distribution of the proposed microwave heating system based on simulation and experimental measurements was obtained. Temperature uniformity was compared with previous studies, analysed and discussed in section 3. Pasteurisation quality and microbial reduction of based on the aerobic plate count (APC) tests were explained in section 4.

2. Microwave milk pasteurization system

2.1. Coaxial slot applicator

A coaxial slot antenna was used as the applicator for microwave pasteurisation, and was fabricated using RG405/U 50Ω PTFE-filled semi-rigid coaxial cable as shown in Fig. 1a. A small slot section along the coaxial cable is machined by removing a small segment of the outer conductor to release the microwave energy into milk. The open end of the coaxial cable is terminated with short-circuit by soldering the inner and outer conductor together at the end, as shown in Fig. 1b. The outer conductor of the fabricated antenna is coated by Teflon (PTFE) jacket to avoid microbial contamination, which results in oxidation due to the contact between the milk sample and the antenna as shown in Fig. 1c.

In this study, the slot length, L_{slot} and its position on the applicator were optimised to achieve a minimum return loss, $|S_{11}|$ (better than −20 dB) at 2.45 GHz. Figure 2 shows the parametric study of the slot location based on the simulation results using COMSOL Multiphysics simulator. The input parameters used in the simulation are tabulated in Table 1.

Initially, the slot length, L_{slot} is set to 1.0 mm at 0.7 mm from the end tip of the antenna, followed by sweeping the slot along the antenna axis (z-axis), with 1.0 mm step size toward z-axis. The results show that the best slot position locates at 4.7 mm from the end tip of the antenna, as shown in Fig. 2. The return loss, $|S_{11}|$ of this design equals to − 25 dB with an antenna input impedance, $Z_{in} = 55.15 - j\,0.62\ \Omega$. In fact, the part of the antenna length from the end tip to the slot is corresponding to the half-wavelength (~0.47 λ_{eff}) at 2.45 GHz.

After that, the slot position is set at 4.7 mm from the end (tip) of the antenna, then followed by the change of the slot length L_{slot} from 1.0 mm to 5.0 mm, with an interval of 0.1 mm, to find the best slot length, L_{slot}. The results show the slot length of 2.4 mm gives better return loss, $|S_{11}|$ with ≈ − 31.48 dB, and the corresponding input impedance, $Z_{in} = 51.54 - j\,0.3\ \Omega$ which is more near to ideal impedance matching value of $50 - j\,0\ \Omega$, compared to the case of $L_{slot} = 1.0$ mm as shown in Fig. 3. Consequently, the designed applicator has a slot location of 4.7 mm from the end tip of antenna and a slot length, L_{slot} of 2.4 mm as shown in Fig. 1a and Fig. 1b. The maximum coupling between electromagnetic waves and milk is essential to ensure the optimum energy transfer from the applicator to milk, which increases the heating rate.

2.2. Microwave heating source system

In order to feed the applicator with microwave energy, a magnetron-based microwave source system was customized. The fabricated microwave pasteurisation system was composed of a water-cooling magnetron and a Wepex 1000B-TX digital controlled inverter (Shenzhen Megmeet Drive Technology, Shenzhen, China). The Wepex digital inverter was connected to a potentiometer to control the magnetron output power. The digital inverter was connected to a HB404 Power/Wattage meter (Annex Depot Inc., Sacramento, CA, USA) to monitor and display the supplied DC power (P_{DC}) that controlled the magnetron excitation power (P_{MICRO}). The applied AC power of the Wepex 1000B-TX inverter was controlled and protected using a 10 A direct-on-line (DOL) circuit. A WR430 rectangular waveguide circulator was used to isolate reflected waves to improve system stability and to provide magnetron damage protection from the reflected wave (Hudson, 1975). The water cooling circulation for both magnetron and the water load

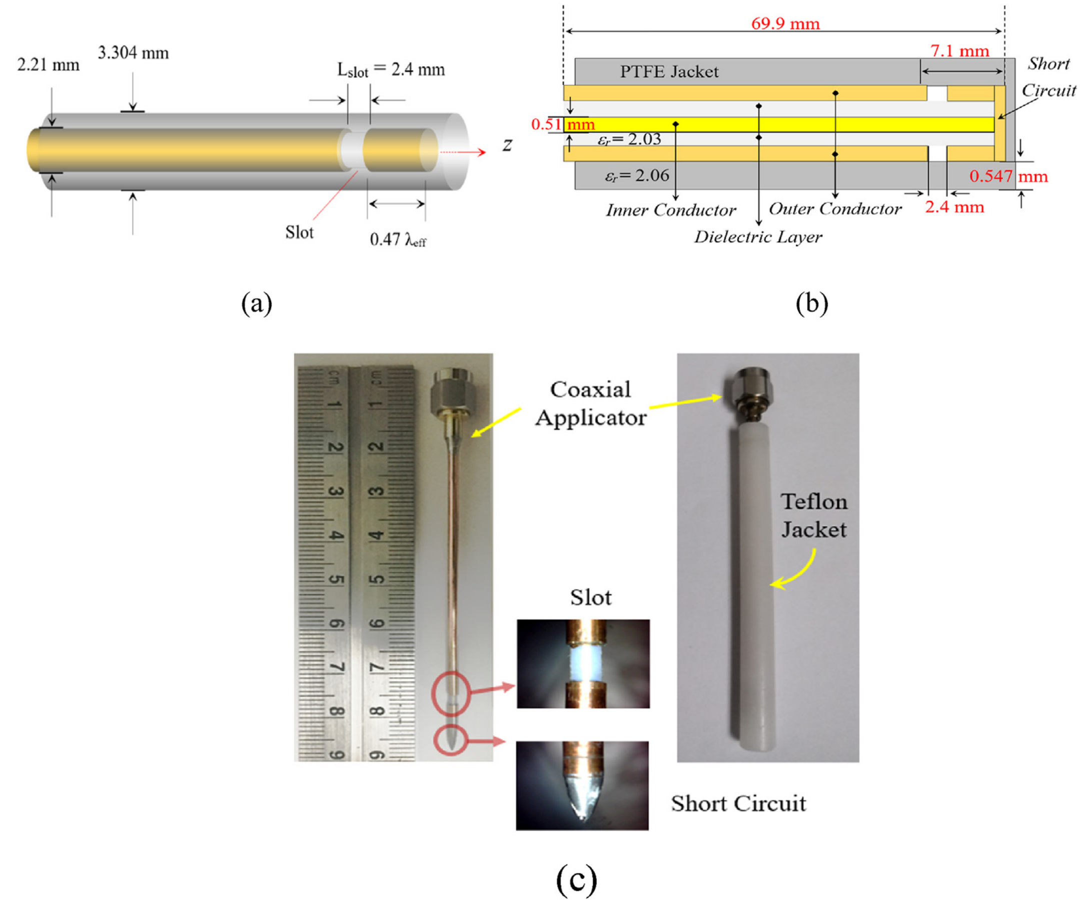

Fig. 1 – (a) 3D structure and (b) dimensions and properties of the antenna applicator; (c) The coaxial slot antenna applicator and the coating Teflon jacket, with two magnified photos show the fabrication of the slot and short-circuit at the end tip.

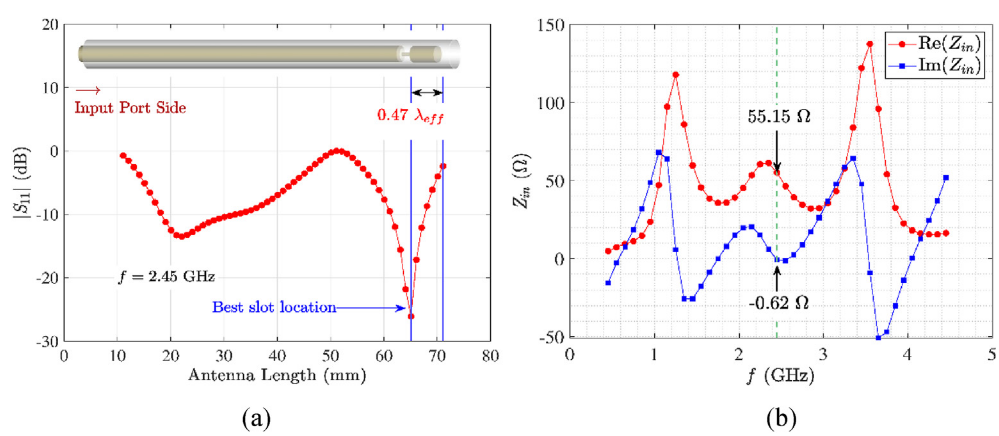

Fig. 2 – (a) Return loss, $|S_{11}|$ response at different slot positions (with L_{slot} = 1 mm at 2.45 GHz); (b) Input impedance, Z_{in} of best slot position.

terminator was realised using an aquarium water pump piping system. A three-screw waveguide tuner was used to resonate the system at the operating frequency, $f = 2.45$ GHz and to ensure maximum energy delivery in the waveguide. The three-screw wave tuner was connected to a WR430 waveguide via a coaxial adapter to feed the antenna applicator with microwave energy as shown in Fig. 4.

2.3. *Impedance matching tuning of the heating system*

When the antenna applicator was connected to the microwave source system, the entire system had to be re-tuned to achieve impedance matching at 2.45 GHz, since the source was excited and transmitted from the WR430 rectangular waveguide in TE_{10} mode to the coaxial antenna applicator,

Table 1 – The temperature-dependent dielectric properties (at 2.45 GHz) (Abdullah et al., 2019; 2020), density, ρ (Short, 1956), and thermal conductivity, K (Fernández-Martan, 1972) of the cow's milk.

T (°C)	ε_r'	ε_r''	Conductivity, σ (S m^{-1})	Density, ρ (kg m^{-3})	Thermal conductivity, K (W m^{-2} K^{-1})
25	64.7083	13.0802	1.8212	1030.5	0.5637
30	63.8003	13.1412	1.8298	1026.4	0.5704
35	63.3613	12.4885	1.7344	1027.5	0.5771
40	62.406	12.7017	1.7541	1022.3	0.5838
45	61.856	12.6033	1.7323	1023.6	0.5906
50	61.2887	12.3083	1.6849	1017.9	0.5973
55	60.7587	12.2715	1.6783	1018.6	0.6040
60	60.2187	12.2346	1.6716	1013.0	0.6107
65	59.7797	12.1842	1.6611	1012.7	0.6174
70	58.8244	11.2329	1.5438	1006.2	0.6241
75	57.9164	11.1345	1.5221	1005.8	0.6.30851

The specific heat capacity of the milk, (C_ρ = 3935.6 J kg^{-1} K^{-1}).

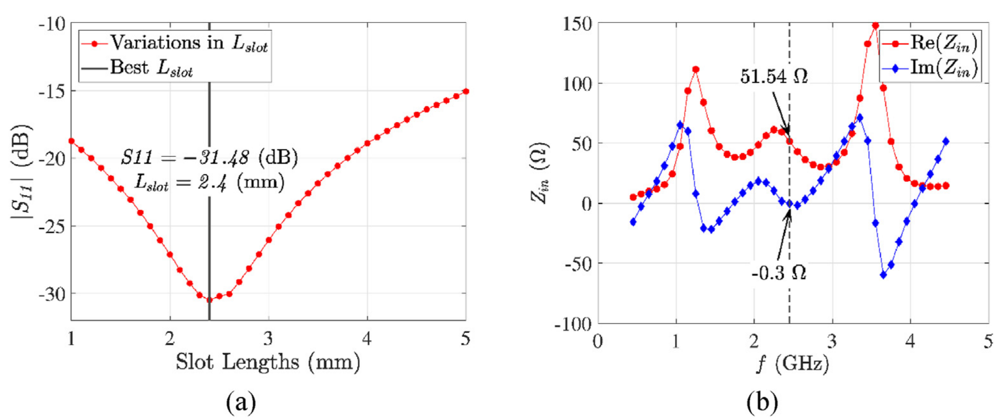

Fig. 3 – (a) Return loss, $|S_{11}|$ response respect to variation of the slot length, L_{slot}; (b) Antenna input impedance, Z_{in} of optimum design.

which only allowed the TEM wave to propagate along the coaxial line. The radiating part of the antenna applicator was immersed in the milk, which was considered to be a part of the antenna input impedance. The impedance-matching tuning was capable of optimising output microwave power released to milk which could save energy and milk heating time. The tuning setup consists of the applicator being immersed in 100 ml specimen of raw cow's milk, three-screw waveguide tuner, waveguide-coaxial adaptor, and portable Planar CABAN R54 vector reflectometer (Copper Mountain Technologies, Indianapolis IN, USA) as exhibited in Fig. 5.

Impedance matching of the system was achieved by manually adjusting the screws of the three-screw waveguide tuner and monitoring the return loss, $|S_{11}|$ of the system by the reflectometer until $|S_{11}|$ achieve lower than −20 dB at 2.45 GHz (resonance achieve). It should be noted that when impedance matching was done, the first screw was initially tuned, followed by a third and then the second. Laboratory heaters, thermocouple sensors, and a Pico technology TC-08 thermocouple data logger (Pico Technology, Cambridgeshire, UK) were used to observe the influence of milk temperature increase on system resonance, as shown in Fig. 5. The measurements were carried out over a wide range of milk temperatures from 25 °C up to 85 °C with interval of 5 °C. Figure 6a and b presents the simulated and measured thermal effects on antenna impedance matching covered frequencies from 1 GHz to 3.5 GHz.

Figure 6c shows the comparison between simulated and measured return loss, $|S_{11}|$ versus milk's temperature at 2.45 GHz. The heating milk causes some changes in its physiochemical and dielectric properties, which consequently, affect the antenna impedance as shown in Fig. 6d. Thus, the measurement presents supreme degradation that occurs at maximum temperature of 85 °C but it still gives a low return loss $|S_{11}|$ of −25.03 dB (still better than −20 dB).

2.4. *System power calibration*

The excited DC power, P_{DC} (in Watt), which was supplied by the Wepex DC power inverter, was used to generate the microwave output power, P_{MICRO} (W) by the magnetron. The relationship between microwave output power, P_{MICRO} at 2.45 GHz and supplied DC power, P_{DC} were calibrated using the Mini-Circuits PWR-SEN-6G + power sensor (Mini-Circuits, Brooklyn, New York, NY, USA) and 40 dB dual-loop waveguide coupler, as illustrated in Fig. 7a. The supplied DC power, P_{DC} was increased gradually using a potentiometer from 300 W to 1800 W, and the corresponding value of P_{MICRO} was measured using the power sensor, and their correlation is recorded and fitted with quadratic polynomial equation as shown in Fig. 7b.

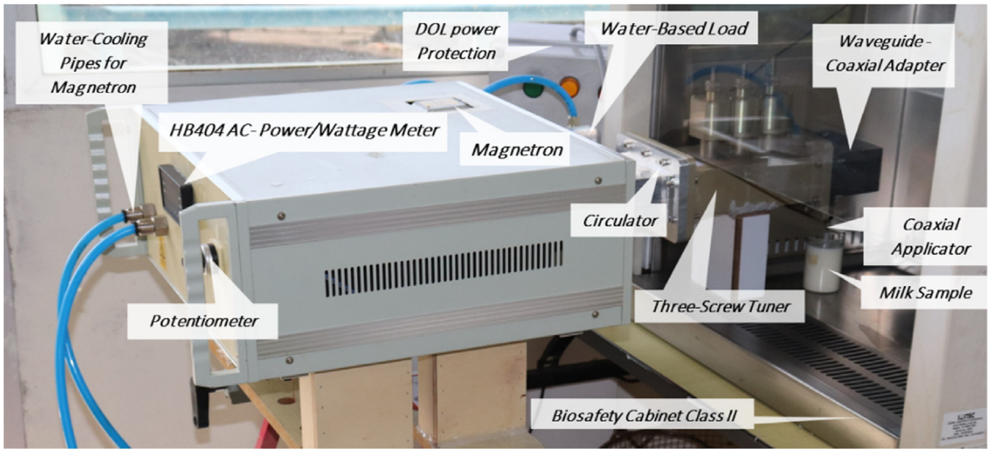

Fig. 4 – The microwave coaxial-antenna based pasteuriser (MAPS) system installed on Class II Type A2 Biosafety Cabinet.

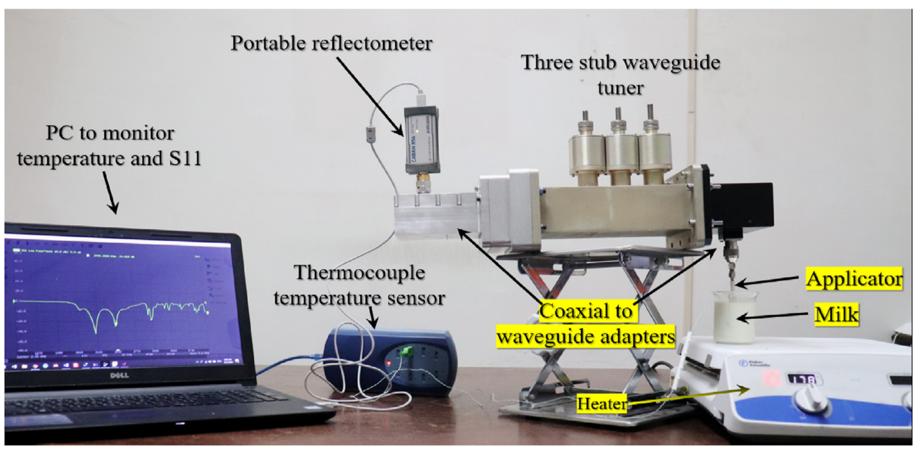

Fig. 5 – The impedance matching tuning set-up of the microwave milk pasteurisation system.

Based on the measurement, the output microwave power, P_{MICRO} (W) calibration equation is given as

$$P_{MICRO} = -0.0001715 \times P_{DC}^2 + 0.82822 \times P_{DC} - 94.93 \quad , r^2 = 0.973 \tag{1}$$

In addition, the uncertainties of the predicted microwave power, P_{MICRO} in Equation (1) is investigated and defined as:

$$\Delta P_{MICRO} = \sqrt{\left(\frac{\partial P_{MICRO}}{\partial P_{DC}}\Delta P_{DC}\right)^2 + \left(\frac{\partial P_{MICRO}}{\partial P_{SEN}}\Delta P_{SEN}\right)^2} \tag{2}$$

Based on Eq. (1) and the coupler factor, C formulation, the $\frac{\partial P_{MICRO}}{\partial P_{DC}}$ and $\frac{\partial P_{MICRO}}{\partial P_{SEN}}$ in Eq. (2) are given as:

$$\frac{\partial P_{MICRO}}{\partial P_{DC}} = -3.43 \times 10^{-4} P_{DC} + 0.82822 \tag{3a}$$

$$\frac{\partial P_{MICRO}}{\partial P_{SEN}} = 10^{\frac{C}{10}} \tag{3b}$$

The P_{SEN} is the coupled power detected by Mini-Circuits PWR-SEN-6G + power sensor and C (≈39.6 dB at 2.45 GHz) is the coupling factor of the dual-loop waveguide coupler. According to manufacturer's specifications, the supplied DC power from Wepex 1000B-TX digital controlled inverter provides maximum uncertainty of $\Delta P_{DC} = \pm 2$ W, whereas, the measured P_{SEN} using PWR-SEN-6G + power sensor contributes maximum uncertainty of $\Delta P_{SEN} = \pm 1.07$ mW (0.3 dBm). Let $P_{DC} = 300$ W was obtained by solving Eq. (2). The maximum uncertainty of the predicted output microwave power, ΔP_{MICRO} was approximately ±10 W. For instance, the supplied DC power, P_{DC} was set to 245 ± 2 W, 275 ± 2 W, and 315 ± 2 W, respectively, to generate microwave power, P_{MICRO} of 100 ± 10 W, 125 ± 10 W, and 150 ± 10 W at 2.45 GHz.

3. Microwave milk pasteurisation

3.1. *Milk samples preparation*

The raw cow's milk samples (milked at the early morning) were collected using sterilised (autoclaved) glass bottles from a local dairy farm based in Johor Bahru, Malaysia. The milk samples were stored at 4 ± 1 °C using icebox during transferring from the dairy farm to the lab and prior for processing. Later the stored milk was used for pasteurisation assessment tests with APC. The mean pH value of the collected milk samples was approximately 6.5.

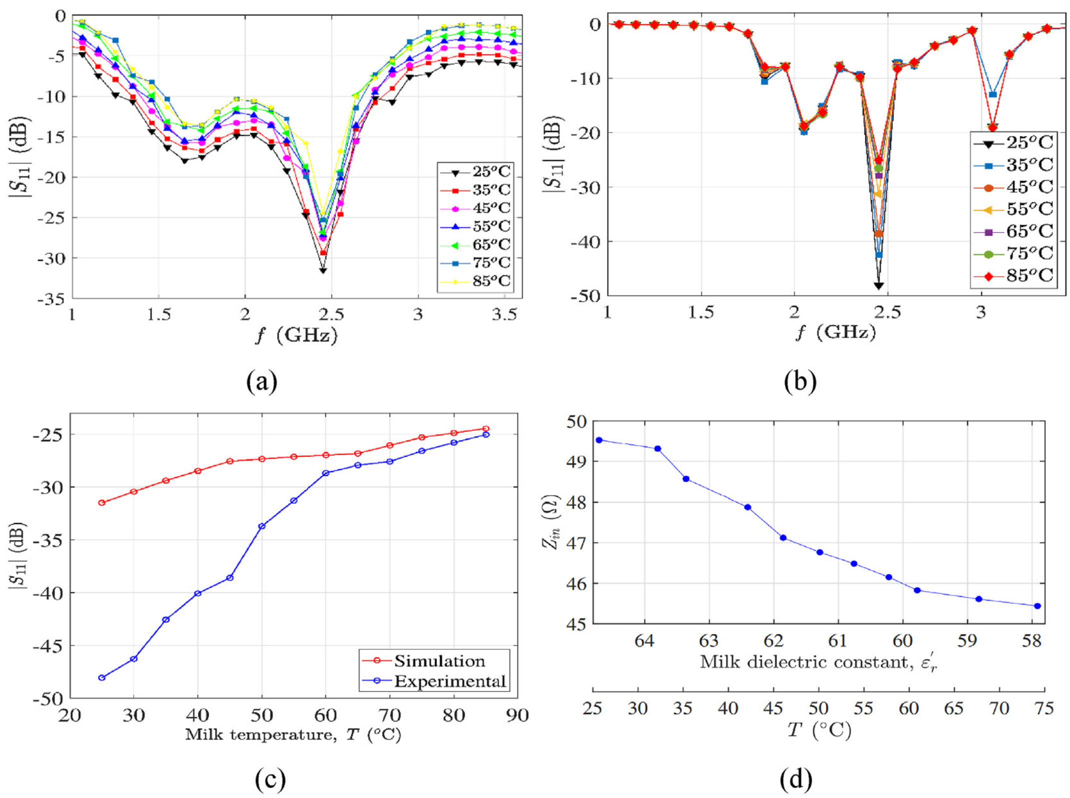

Fig. 6 – (a) Simulated and (b) measured $|S_{11}|$ of the applicator-system versus frequencies for various milk temperature, T; (c) The degradation in the simulated and measured $|S_{11}|$ for higher milk temperature, T at 2.45 GHz; (d) The relationship between antenna input impedance, Z_{in}, dielectric constant, ε_r' of the milk sample, and the temperature, T of the milk.

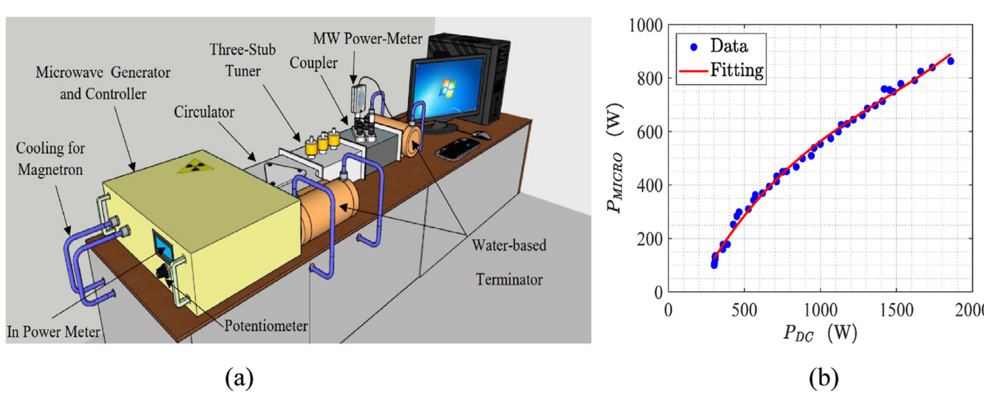

Fig. 7 – (a) Microwave power calibration set-up; (b) Correlation between microwave power, P_{MICRO} and supplied DC power, P_{DC}.

3.2. *Use microwave power and heating rate*

Collected cow's raw milk samples were pasteurized using three microwave powers, P_{MICRO}, namely 100 W, 125 W, and 150 W, respectively and the effect of use microwave power, P_{MICRO} respect to the heating rate is observed. The initial temperature, T of each 100 ml of milk sample is maintained at 25 °C using water bath. The microwave heating rates are determined using thermocouple temperature sensor located at position close to the slot. The results of heating rates at each microwave processing power show linear increasing, where the higher power is the faster process, as shown in Fig. 8.

3.3. *Thermal distribution measurement*

In this study, the VarioCAM infrared thermal imaging camera (InfraTec Infrared Ltd, Dresden, Germany) is used to monitor the surface temperature distribution of the 100 ml milk containing in glass beaker as shown in Fig. 9a. The TC-08 thermocouple sensor was used to measure the change of temperature in the milk sample (located near to the applicator) during the pasteurisation process as illustrated in Fig. 9b. Two thermocouple sensors were used to monitor the heat penetration in milk in off-line mode in order to avoid the interaction with radiated microwave. The two sensors were installed on a 3D-printed base which has level mount holders of equally distant points, as shown in Fig. 9c. For each point of temperature measurement, a new raw milk sample was used in order to avoid the errors caused by time–temperature degradation. In addition, the temperature measurement set is conducted immediately after turning off the microwave coaxial-antenna based pasteuriser (MAPS) system to avoid field distortion of *in situ* measurements (Pert *et al.*, 2004). The averages of three measurements were collected for a period of 3 s.

The simulated and measured thermal distribution of the applicator were immersed in 100 ml of milk samples after 7 min using microwave power, P_{MICRO} level of 100 W, 125 W, and 150 W are respectively shown in Fig. 10. Although there were small variations among different methods of temperature measurement, Fig. 10 shows significant improvement in temperature uniformity. According to the measurements of the thermocouple sensors, the maximum temperature differences, ΔT were 3.4 °C, 2.3 °C, and 2.2 °C within 20 mm radius area for corresponding used microwave power, P_{MICRO} of 100 W, 125 W, and 150 W, respectively.

4. Milk pasteurisation efficiency

4.1. *Microbial control analysis*

The minimum condition for successful pasteurization is to achieve the 5-log reduction of microorganisms, as defined in pasteurised milk ordinance (PMO), FDA (King & Bedale, 2017). Accordingly, milk samples were collected and processed using MAPS. At each processing power and time, three samples are pipetted into 20 ml of sterilised glass tubes and then immediately transferred to an enclosed and sterilised container and cooled down to 4 ± 1 °C using an ice bath to prevent post pasteurisation contamination and to avoid fat crystallisation (Sakata, 1977). Finally, the processed milk samples were stored at 4 ± 1 °C for the APC, pH, and physicochemical tests. Each processed sample of each processing power and time was triplicated and subjected to the APC test. The APC averages were calculated using spiral plate count (SPLC) (Donnelly et al., 1976), according to FDA/BAM 8th Edition (Chapter 3), the control (raw milk) and the processed milk samples are serially diluted with buffered saline peptone water (pH 7.0). Dilutions of the milk samples are plated on plate count agar media, and the plates are incubated for 48 ± 3 h at 35 ± 1 °C (Maturin & Peeler, 2001).

Lethality control analysis of the pasteurisation can be achieved using the decimal reduction time, so-called *D*-value analysis, which refers to the time required to kill 90% of existing microorganisms at a constant temperature, *T*. However, although, microwave heating does not maintain the temperature of the milk during the heating, several researchers have shown that the inactivation kinetics based on *D*-value analysis is applicable in microwave heating as long as the inactivation time exists (Benlloch-Tinoco et al., 2014; Heddleson et al., 1994; Pina-Pérez et al., 2014; Wu, 1996). Therefore, the inactivation kinetics based on *D*-value were conducted for all processing powers.

The pasteurisation process using the coaxial slot antenna immersed into a cow's raw milk sample was conducted inside Class II Type A2 biosafety cabinet as shown in Fig. 6. The sterilisation of the working area and the inserted part of the pasteurization system, including the applicator, was achieved using 90% alcohol steriliser followed by 20 min of UV light sterilisation (Bruscolini et al., 2015). The pasteurisation process was assessed based on an aerobic plate count (APC) test to monitor the microbial control of the MAPS heating system. Cow's raw milk samples were collected at three microwave power, namely 100 W, 125 W, and 150 W. The processing time started from 1 min up to 7 min in 1 min intervals with a new raw cow's milk sample used at each processing power and time.

4.2. *Aerobic plate count assessment*

The aerobic plate count (APC) assessments of the milk processed in MAPS showed a total elimination of microorganisms at each processing power. Significantly, the APC results indicate the high quality of microbial control despite the slight variances in the temperature distribution. Table 2 shows the microbial control using APC test for each processing power, where the 100 W- MAPS presents total elimination by 7 min. At the same time, the 125 W- MAPS effectively inactivates microbes at 6 min. While, the microbial destruction of 150 W-MAPS appears at 5 min.

The logarithmic determination of the aerobic plate count of the relative microwave processing powers is essential since the negative reciprocal of the corresponding linear regression slope values determines the *D*-value of the pasteurisation process (Mazzola et al., 2003). Figure 11 presents the microbial survival curves of raw milk pasteurised in MAPS based on the logarithm of the number of colony-forming units (CFU) in a 1 ml sample under test, namely $\log_{10}(\text{CFU ml}^{-1})$, whilst the corresponding curve fitting equations are expressed in Eqs. (4a), (4b), and (4c) for 100 W, 125 W, and 150 W, respectively. Thus, higher processing power requires less processing time.

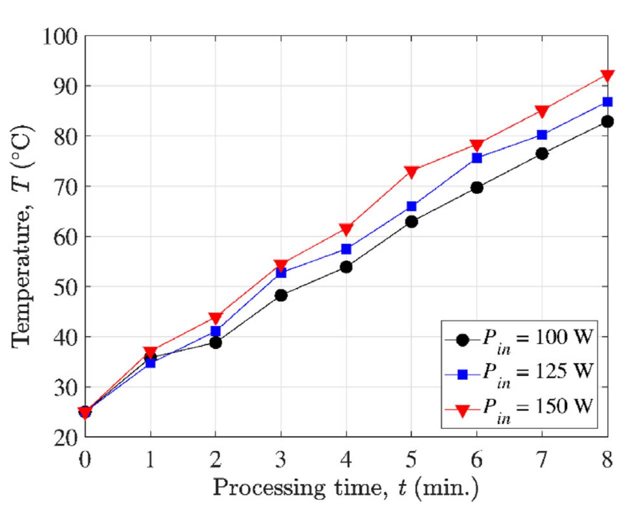

Fig. 8 – The microwave heating rates of the milk using different microwave powers, P_{MICRO}.

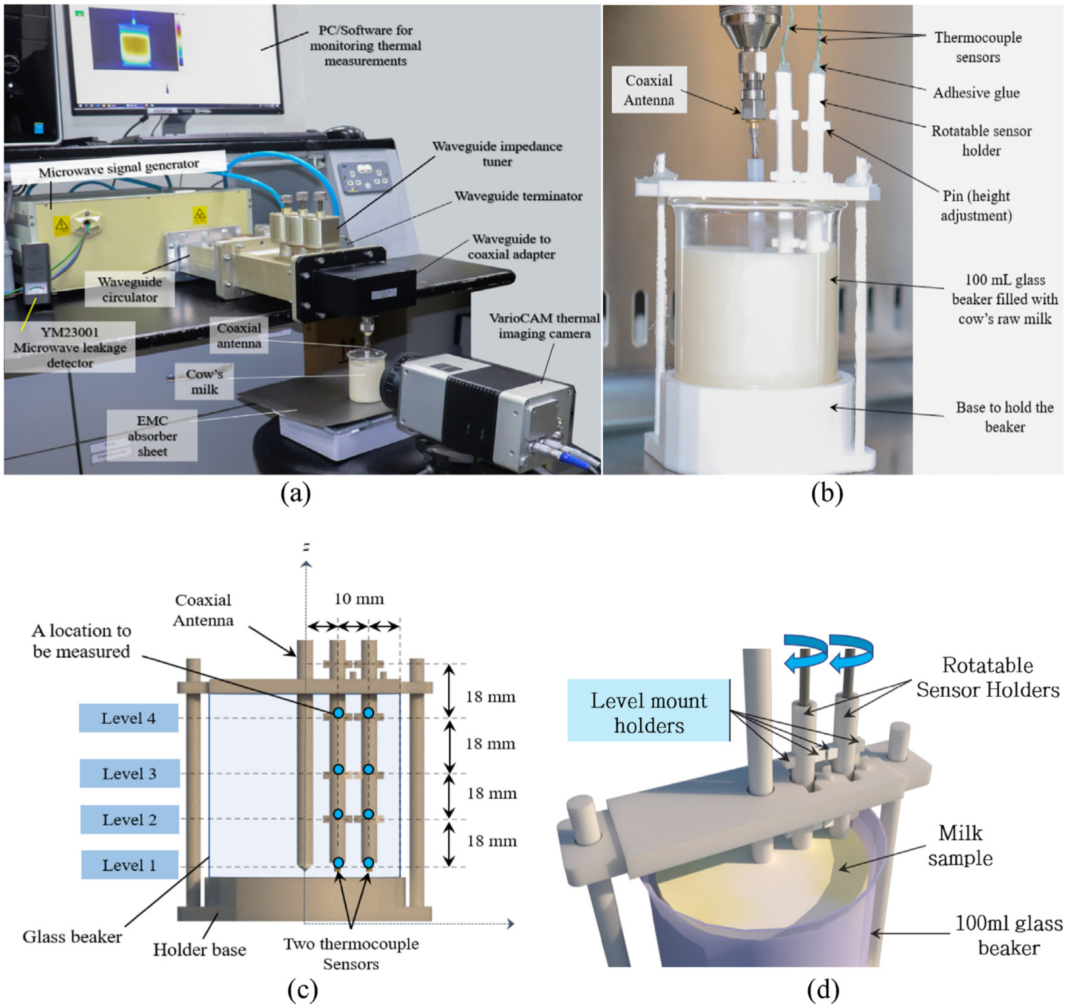

Fig. 9 – The measurement setup for depth temperature distribution using two thermocouple sensors. Illustration of the heating rate measurement setup.

Based on Eqs. (4a)–(4c), the decimal reduction times (*D*-values of MAPS) were 1.0773 min, 1.063 min, and 0.8338 min for 100 W, 125 W, and 150 W, respectively. Hence, the MAPS with 150 W requires about 50 s of heating time to cause one log cycle of microbial reduction, which is faster than for 100 W (63 s) and 125 W (64.6 s). However, Table 2 shows that MAPS is capable of achieving more than a 5-log as microbial reduction rate, which makes the inactivation efficiency to be higher than 99.999%, which meets the FDA-PMO requirements and standards.

$$\log_{10}\left(\frac{\mathrm{CFU}}{\mathrm{ml}}\right)\bigg|_{100W} = -0.9282 \times t + 7.1835 \quad , r^2 = 0.9889 \tag{4a}$$

$$\log_{10}\left(\frac{\mathrm{CFU}}{\mathrm{ml}}\right)\bigg|_{125W} = -0.9404 \times t + 6.5471 \quad , r^2 = 0.9652 \tag{4b}$$

$$\log_{10}\left(\frac{\mathrm{CFU}}{\mathrm{ml}}\right)\bigg|_{150W} = -1.1993 \times t + 6.3338 \quad , r^2 = 0.9457 \tag{4c}$$

where *t* is the heating time (in unit minute). Based on Eqs. (4a), (4b), and (4c), the $\log_{10}(\mathrm{CFU\ ml^{-1}})$ performance using study MAPS ($100\ \mathrm{W} \le P_{MICRO} \le 150\ \mathrm{W}$) can be represented as:

$$\log_{10}\left(\frac{\mathrm{CFU}}{\mathrm{ml}}\right) = \left(-1.0936 \times 10^{-4} P_{MICRO}^2 + 2.1918 \times 10^{-2} P_{MICRO} - 2.0264\right) t + \log_{10} N_o \tag{5}$$

where $\log_{10} N_o$ is the initial logarithm value of number of survivors (CFU $\mathrm{ml^{-1}}$) at $t = 0$ min.

5. Conclusion

The existing non-uniformities in the temperature distribution of microwave heating of milk result in failure pasteurisation. Because, in lower temperature regions, the milk does not reach the required temperature to inactivate the pathogens when compared with higher temperature regions. Increasing processing time to mitigate this problem will increase the deterioration of milk's nutritional value and flavour. This paper presents a possible novel solution based on isothermal heating using the omnidirectional coaxial slot antenna, where the milk is heated equally in all directions. The measurements

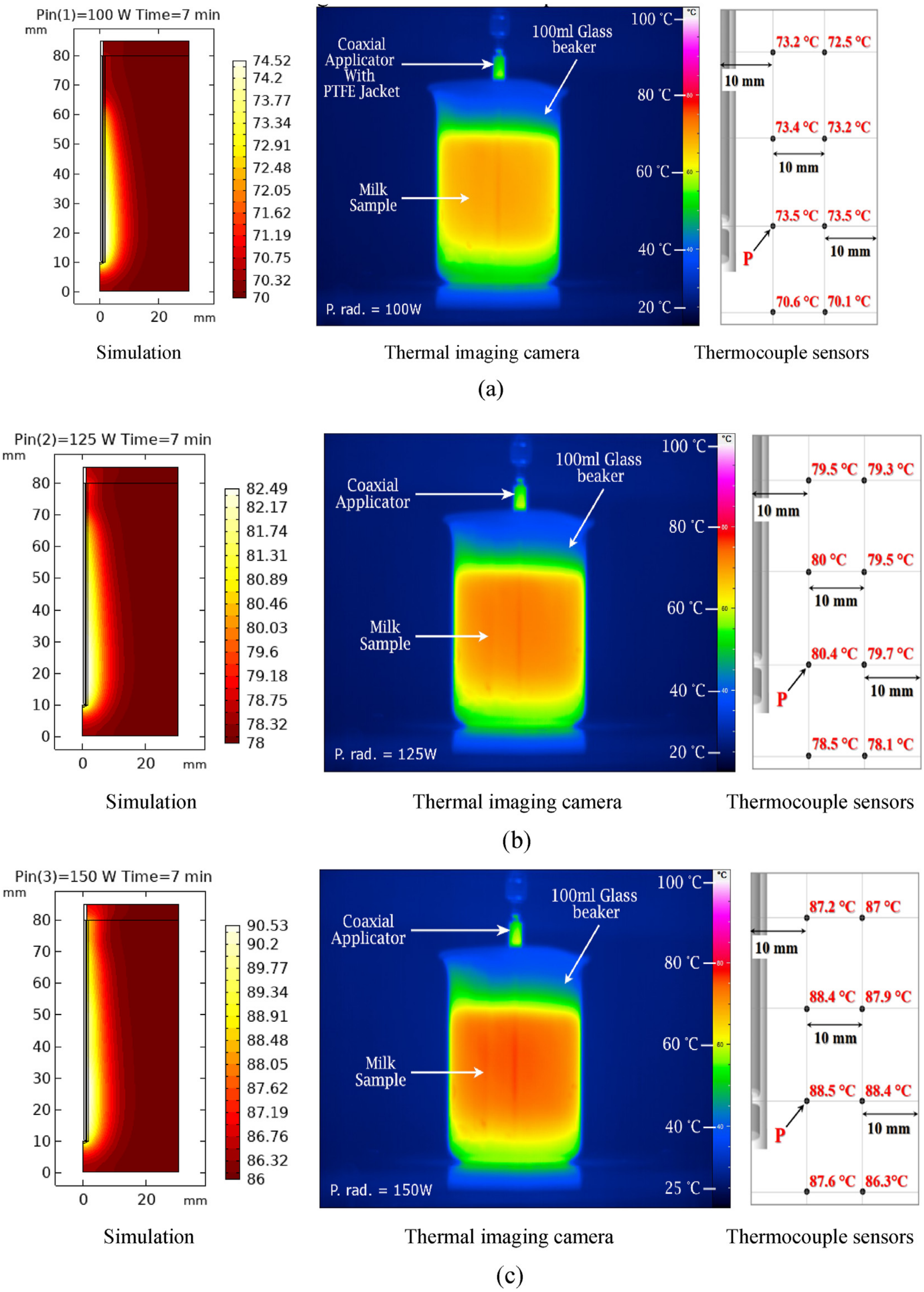

Fig. 10 – The temperature distribution of milk after 7 min heating process using microwave power, PMICRO of (a) 100 W (b) 125 W, and (c) 150 W, respectively.

of the temperature distribution on cows' raw milk samples show significant improvement in the temperature uniformity, with mean maximum temperature difference, ΔT of 2.6 ± 0.3 °C which is 89.2% better than the uniformity of previous milk microwave batch pasteurisation.

The simulation of the antenna applicator presented an optimised input impedance, Zin = 51.54 Ω and return loss, $|S_{11}|$ = −31.48 dB at 25 °C. In contrast, the implementation of the complete microwave heating system with the aid of tuning and resonance control subsystem maximises the coupling efficiency up to $|S_{11}|$ = −48.04 dB at 25 °C. However, as the temperature increases, the coupling efficiency drops linearly. Nevertheless, the maximum degradation in coupling efficiency, which occurs at 85 °C in both simulation and

Table 2 – APC results of the MAPS using 100 W, 125 W, and 150 W.

Processing time (min)	Number of survivors (CFU ml^{-1})		
	100 W	125 W	150 W
0	7.9×10^6	7.9×10^6	7.9×10^6
1	1.7×10^6	1.2×10^5	3.1×10^4
2	5.1×10^5	8×10^4	6.3×10^3
3	3.5×10^4	2.9×10^3	4.8×10^2
4	2.7×10^3	9.1×10^2	64
5	320	75	0
6	30	0	0
7	0	0	0

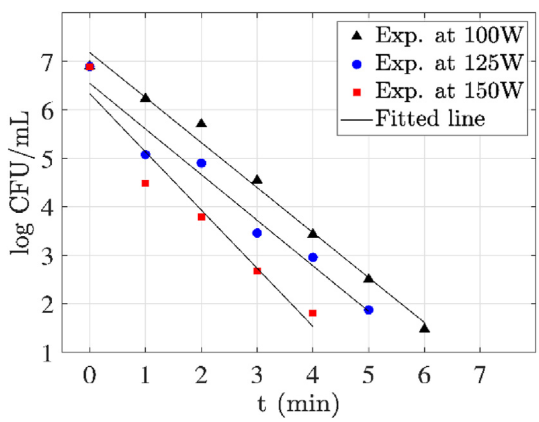

Fig. 11 – Linear curves of the experimental $\log_{10}$(CFU/mL) using microwave power, P_{MICRO} of 100 W, 125 W, and 150 W, respectively.

implementation is −24.45 dB and −25.03 dB, respectively, still indicates a good coupling factor. The temperature profiles provided by simulation and measurements of MAPS showed a uniform temperature distribution with a little contrast in the temperature profile as compared with existing microwave pasteurisation for milk applications.

The processed milk samples using MAPS system passed the pasteurisation test with an efficiency of 99.999% according to the APC test. The 100 W energy treatment showed complete microbial inactivation after the 7 min of treatment at an average temperature of 76.47 °C, whilst the same inactivation occurred after the 6 and 5 min at the temperatures of 75.62 °C and 73.08 °C when the treatment was done with the energies of 125 W and 150 W, respectively. Finally, further research and development of MAPS based on continuous flow pasteurisation are recommended for industrial applications. Also, the current processing time of 7 to 5 min is long as compared with existing microwave systems, hence, using a solid-state microwave system in the future should be investigated to further improve uniformity and increase the heating rate.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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