EXPERIMENTAL STUDIES ON LEAKED ELECTROMAGNETIC FIELDS AROUND RADIO FREQUENCY HEATING SYSTEMS

H. Zhu, R. Yan, Z. Huang, R. Li, S. Wang

ABSTRACT. *A safe operational environment is critical for industrial pasteurization and disinfestation applications of radio frequency (RF) treatments. To determine the maximum electric and magnetic field intensities around inlet and outlet openings for 27.12 MHz Strayfield and Jiyuan RF systems, an electromagnetic detector was used to measure the leakage electric or magnetic field intensity and estimate power density as a function of the distance from the opening, load type and electrode gap with shielding conditions in inlet and outlet openings. Results showed that both electric and magnetic field intensities increased with decreasing distance and electrode gap. With a load of 1 kg water, the RF power increased but the leaked electric or magnetic field intensity decreased, especially for the Strayfield system. After shielding was added around inlet and outlet openings for Jiyuan RF system, the leaked electric field intensity and the estimated power density were significantly reduced (P<0.05) at each location under each of the distances and electrode gaps. The averaged electric field intensity without shielding was 19.9 V/m for these two RF systems and the average magnetic one was 0.12 A/m for Strayfield system at the electrode gap of 130 mm, which were lower than the limited values allowed by International Commission on Non-Ionizing Radiation Protection (ICNIRP) and Institute of Electrical and Electronics Engineers (IEEE) standards. During the daily operations of the RF systems, the measures to reduce operators' radiation exposure include additional shielding of the interaction area, reducing exposure time, increasing the distance between the operator and the electrode, and avoiding empty-load running.*

Keywords. *Electromagnetic energy, Emissions, Leakage, Power density, Radio frequency.*

Most radio frequency (RF) systems in industrial applications are free running oscillator systems, which consist of transformer, rectifier, oscillator, an inductance-capacitance pair commonly referred to as the "tank circuit", and the work circuit. The transformer raises the voltage and the rectifier changes the alternating current to direct current, which is then converted by the oscillator into RF energy. Parallel plate electrodes with a sample load in between act as a capacitor in the work circuit. Thus, RF power into a specific load can be adjusted by changing the gap between the electrodes. RF treatments generally refer to dielectric heating of nonmetallic materials using electromagnetic energy between 10 and 300 MHz, and caused mainly by ionic conductance and dipole rotation (Nelson, 1996). Early RF applications for glue drying, plastic welding, and particle board curing result in exposure to high electromagnetic field strengths, which substantially exceed all existing safety standards (Hietanen et al., 1979; Stuchly et al., 1980; Eriksson and Mild, 1985). With improved shielded systems, RF heating technology has been used for post-baking of cookies and snack foods (Koral, 2004) and has also been studied for thawing/tempering (Farag et al., 2010; 2011), drying (Lee et al., 2010; Wang et al., 2014), disinfestation (Lagunas-Solar et al., 2007; Wang et al., 2007a, b), and pasteurization (Gao et al., 2011; Kim et al., 2012) of food and agricultural products. A major concern in the use of continuous processing with industrial RF systems is the operational safety of RF radiation emission levels near the conveyor belt openings through which loads pass into the system.

Although the load inlet and outlet openings are designed to be far away from the plate electrodes, the wavelength of the RF wave is long (e.g., 11 m at 27.12 MHz), and in spite of grounded shielding of the metal box, leaked radiation emissions still exist around the RF unit, especially near the openings. The emission radiation level depends on the size, and location of the openings, as well as the applied RF power and the electrode gap. Just as with treated products, this radiation energy is transformed into heat in the body as indicated by World Health Organization (WHO, 2010), especially in sensitive body parts, such as the eyes, testes, and brain. Long exposure to the high RF radiation may increase possible risks to the central nervous system of the body as reported by Heynick et al. (2003) and International Labor Organization (ILO, 1998) and increase the risk of breast cancer (Caplan et al., 2000). According to the Institute of Electrical and Electronics Engineers (IEEE) Standard C95.1 for safety issues with respect to human exposure to

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RF electromagnetic fields (IEEE, 2006), the safe level of the electric power density at 27.12 MHz should be less than 12.2 W/m^2 for 6 min exposure. It is, therefore, desirable to determine the RF radiation emission from the inlet and outlet openings of RF systems during processing.

Most studies are focusing on the possible radiation leakage from the home-use microwave oven door since its wavelength is only 0.12 m. The optimum door seal configuration to prevent radiation leakage from a microwave oven has been extensively studied using experiments and numerical simulation with finite-difference time-domain (FDTD) methods (Kusama et al., 1998). Several experimental results are reported on harmful effects of leaked electromagnetic radiation around microwave and RF ovens (Eriksson and Mild, 1985). For example, Alhekail (2001) found apparent correlations between measured leakage radiation and age of the oven based on 106 microwave ovens. Stuchly et al. (1980) surveyed industrial RF systems using frequencies between 4 and 51 MHz with output power ranging from 0.5 to 90 kW and reported that the biological effects would be negligible at relatively low average power density but would be clear at high power density levels without shielding. Wilén et al. (2004) reported the health problems of workers operating the RF plastic sealers based on the effects of measured electromagnetic field intensity on the exposed parts of the human body. Since most studies are conducted on the RF sealers, it is desirable to experimentally and systematically determine leaked electromagnetic field intensity and power density around inlet and outlet openings of the RF systems with conveyors for avoiding negative effects on operators in industrial plants and research labs.

The objectives of this study were to: (1) measure the electric or magnetic field intensity around inlet and outlet opening of the two different 27.12 MHz RF systems used in laboratory-scale food processing; (2) determine the leakage power density as a function of the distance from the opening, load type and electrode gap; and (3) compare the difference between two types of openings from the two RF systems and evaluate the effects of shielding strips installed at the openings on the leakage power density.

MATERIALS AND METHODS

DESCRIPTION OF THE TWO RF SYSTEMS

Two typical RF heating systems were selected to conduct measurements of radiation emission around the inlet and outlet openings and compare the difference between foreign and domestic systems. They were 6 kW (SO6B, Strayfield International, Wokingham, U.K.) and 10 kW (JYC, Jiyuan High-Frequency Electric, Shijiazhuang, China) pilot-scale systems, both operating at 27.12 MHz. The geometry of the two RF units and the measurement locations at the inlet (right) and outlet (left) openings are shown in figure 1. The maximum gap between the top and bottom plate electrodes was 190 and 259 mm for the Strayfield and Jiyuan RF systems, with the size of the top electrode to be 400 mm (W) × 830 mm (L) and 550 mm (W) × 750 mm (L), respectively. The inlet or outlet opening size was 250 mm (H) × 520 mm (L) and 360 mm (H) × 920 mm (L) for Strayfield and Jiyuan systems, respectively. At each of three distances from the opening, three points at the middle height of the openings (125 and 190 mm for Strayfield and Jiyuans, respectively) symmetrically distributed around the center of each opening were selected for measurements (fig. 1).

MEASUREMENT DEVICE AND CALCULATION OF POWER DENSITY

Electromagnetic radiation near RF units covers both electric (E, V/m) and magnetic (H, A/m) fields (Mantiply et al., 1997). Both the electric and magnetic field intensities were measured in this study according to standard (IEEE, 2005; 2006) and reported methods (Mild, 1980; Stuchly et al., 1980) using an electromagnetic detector (RJ-2, Jiande High-frequency Device, Jiande, China), which consisted of a probe, meter, and connecting the coaxial-cable. This device was operated at frequencies from 200 kHz to 30 MHz with a calibrated accuracy of ±2.3 dB. The probe was installed on a 0.5 m long wooden rod to avoid the measurement interference on the RF field. Usually, the electric field intensity and magnetic field intensity are defined within three-dimensional space, namely x, y, and z directions. By rotating the probe at three different directions, the three components of electric/magnetic field intensity were obtained and further used to calculate the general electric/magnetic field intensity (*E/H*) as follows (Stuchly et al., 1980; Wilén et al., 2004):

$$E=\sqrt{E_x^2+E_y^2+E_z^2} \quad \text{or}$$

$$H=\sqrt{H_x^2+H_y^2+H_z^2} \tag{1}$$

where E_x, E_y, and E_z or H_x, H_y, and H_z are the electric/magnetic field intensity values in x, y, and z directions, respectively.

Based on the protocol in IEEE Std C95.1 (IEEE, 2006), the safety level of leakage radiation around RF systems is commonly estimated by the power density. The obtained electric or magnetic field intensity was converted to the equivalent power density (W/m^2) as follows:

$$S_E=|E|^2/\eta \text{ or } S_H=\eta|H|^2 \tag{2}$$

where η is the wave impedance, which can be estimated as follows:

$$\eta=\mu_0 c_0 \tag{3}$$

where μ_0 is magnetic constant ($4\pi\times10^{-7}$ H/m) and C_0 is speed of light (3×10^8 m/s), resulting in η = 377 Ω in free space.

EFFECTS OF DISTANCE, LOAD AND ELECTRODE GAP

To clearly determine the effects of distance, load, and electrode gap on the radiation emission, the electric or magnetic field intensity was measured at three distances (100, 200, and 300 mm), with or without load of 1 kg tap water in a plastic container (170 ×170 ×85 mm), and three electrode gaps (130, 160, and 190 mm). Under stable RF

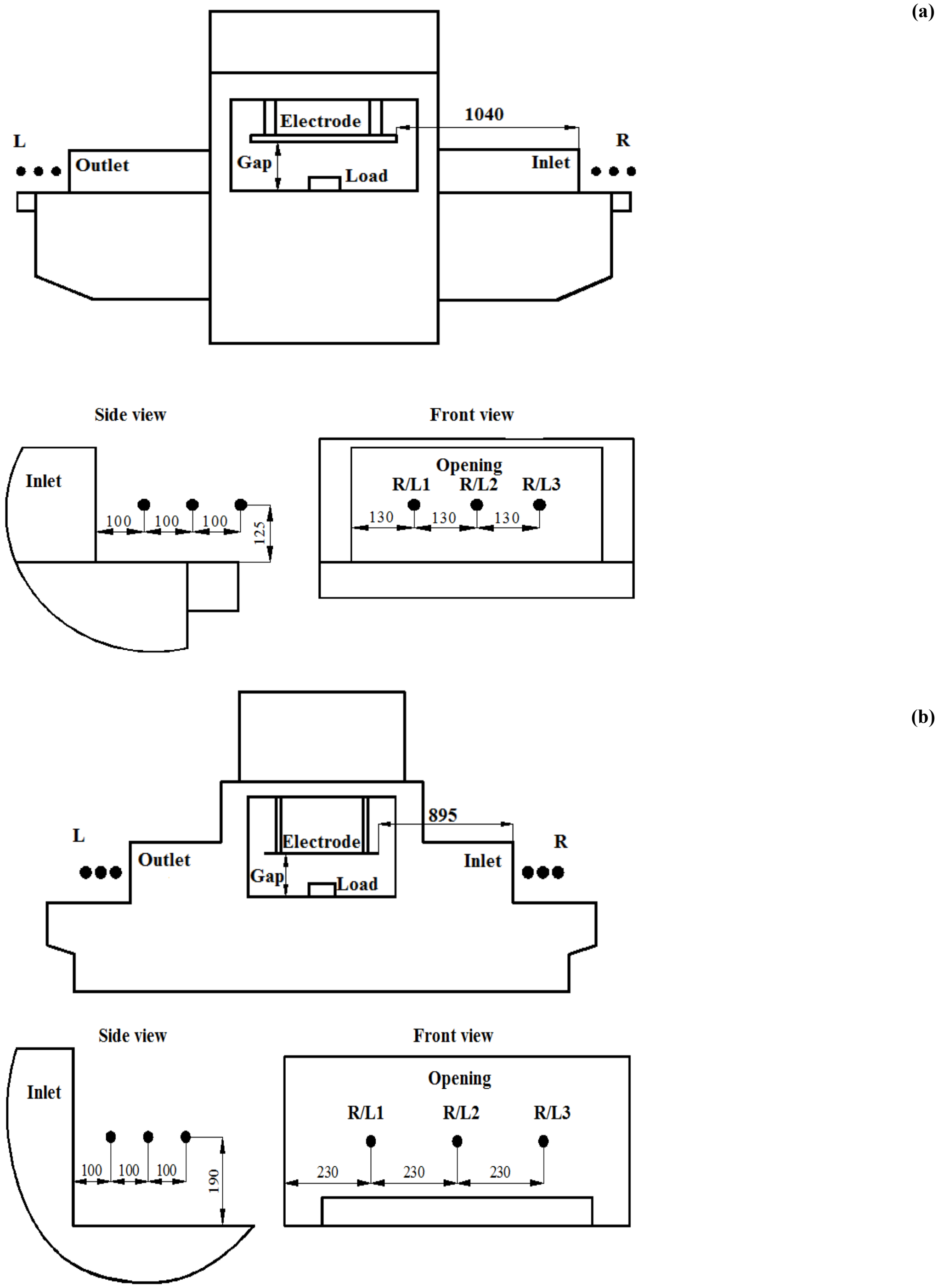

Figure 1. Schematic view of the radio frequency (RF) units showing the plate electrodes and the measurement locations at the inlet (right side: R) and outlet (left side: L) openings (all dimensions are in mm). (a) 6 kW Strayfield unit, (b) 10 kW Jiyuan unit.

heating conditions during the measurements, the magnetic field intensity and three components of the electric field intensity were completed at 9 locations in the inlet opening followed by those in the outlet opening. The measurement took about 5 min in each opening. The electric field intensity at positions R1-R3 (fig. 1) with or without load was regressed as a function of distance for both RF systems. Each of the independent tests was repeated two times.

Effects of Shielding

Shielding is generally designed to reduce the radiation emission from the RF applicators, especially the sewing and plastic-welding units, which directly expose to the operators. Now most of the commercial RF systems have been shielded with a metal box except for the openings, which still needed to be checked. For the Jiyuan RF system, 10 shielding strips (360 H×92 L mm^2) made of metal fabric and plastics were installed to hang freely at the inlet and outlet openings (fig. 2). The flexible shielding strips were used for containers on the conveyor to facilitate passing through. Because some leaking between the strips existed, the effect of the high conductance shielding on reducing radiation leakage was determined. The electric field intensity was measured with and without the shielding strips at nine locations as described in figure 1. The tests were conducted twice.

STATISTICAL ANALYSES

Mean values and standard deviations of electric or magnetic field intensity and power density were calculated from the two independent replicates for each given condition. The mean values were compared and separated at a significant level of P=0.05 with the least significant difference (LSD) t-test using the Excel variance procedure (Microsoft Office Excel, V2003, Seattle, Wash.). The maximum, minimum, and average electric field intensity was determined over the nine locations for each opening of the two RF systems under the no and with load conditions at the electrode gap of 130 mm.

RESULTS AND DISCUSSION

LEAKED RF POWER AS INFLUENCED BY THE DISTANCE

Figure 3 shows the electric field intensity leaked from two RF systems as a function of the distance at an electrode gap of 160 mm with load and no-load at three locations near the inlet opening. Due to symmetric conditions, the data in the outlet opening were not shown in the figures but partially listed in table 1. The electric field intensity leaked from both RF systems decreased dramatically with increasing distance at each load condition and location (fig. 3). The electric field intensity leaked from both RF systems located at the central point in the opening was larger than that at two sides and a distance of 100 mm. The maximum, minimum and average reduction rates of electric field intensity (E, V/m) against the distance (d, mm) for the Strayfield unit were E = -0.0569d + 30.396 (R^2 = 0.999), E = -0.0246d + 15.712 (R^2 = 0.984), and E = -0.0364d + 21.427 (R^2 = 1.000), respectively, as compared to E = -0.0605d + 24.551 (R^2 = 0.952), E = -0.0345d +17.328 (R^2 = 0.986), and E = -0.0465d + 20.950 (R^2 = 0.987) for the Jiyuan system. Based on the intercept, the electric field intensity leaked from Strayfield unit was slightly larger than that from the Jiyuan system. But in comparing slopes, the electric field intensity reduction rate for Strayfield unit was smaller than Jiyuan system. Specifically, the electric field intensity was reduced by 5.7, 2.5, and 3.6 V/m for maximum, minimum and average rate, respectively, as the distance increased by 100 mm for the Strayfield unit, as compared to 6.1, 3.5 and 4.7 V/m for the Jiyuan system.

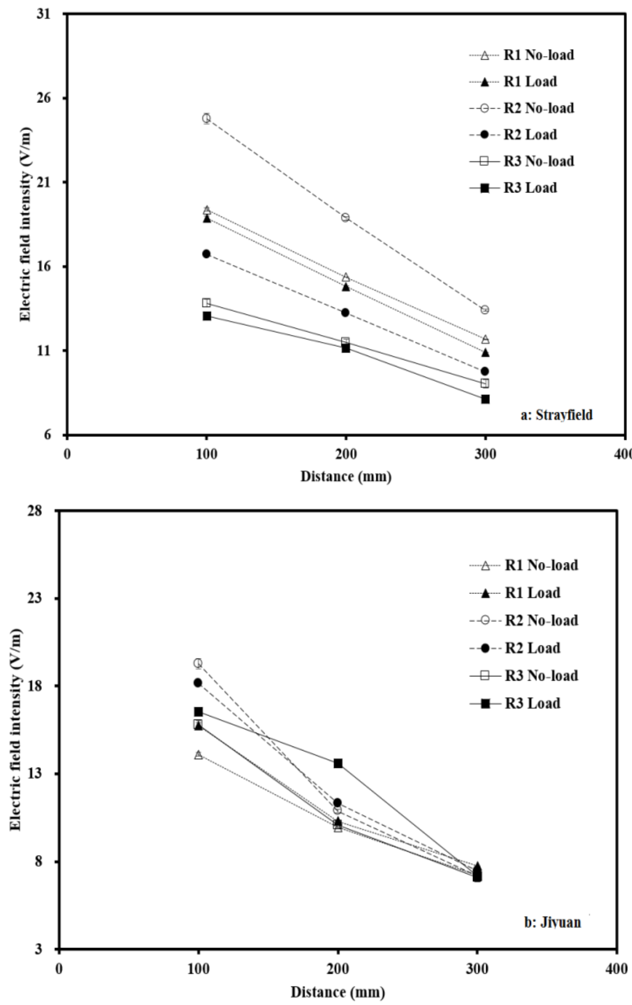

Figure 3. Electric field intensity from Strayfield (a) and Jiyuan (b) RF systems as a function of distance at an electrode gap of 160 mm with and without load at three locations (R1, R2, and R3) of inlet openings.

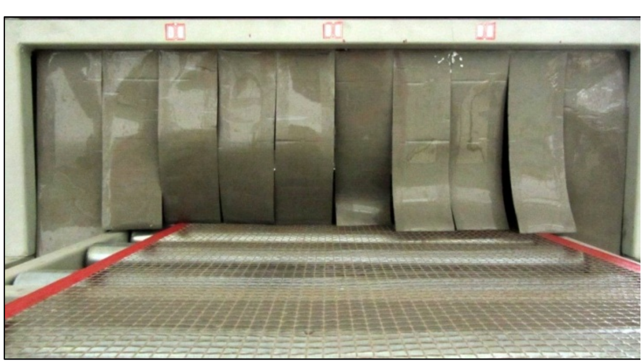

Figure 2. Shielding strips at the outlet and inlet openings for Jiyuan RF systems.

EFFECTS OF LOAD AND ELECTRODE GAP

Figure 3 also shows the effect of load on the electric field intensity leaked from the two RF systems. With the added load, the RF power increased but the leaked electric field intensity decreased, especially for the Strayfield system. But for the Jiyuan system, this decreasing trend was unclear. Figure 4 shows the electric field intensity from the two RF systems as a function of the electrode gap at the distance 100 mm and three locations from the opening with load and no-load. The electric field intensity clearly increased with decreasing gap for both RF systems. Specifically, the electric field intensity increased 15 to 16 V/m while the electrode gap was reduced from 190 to 130 mm.

Table 1. Comparison of electric field intensity and power density between uncovered and covered shielding at the outlet openings of Jiyuan RF systems without load.

(a) Electric Field Intensity (V/m)							
		Uncovered at Distance (mm)			Covered at Distance (mm)		
Positions	Gap (mm)	100	200	300	100	200	300
L1	190	7.8±0.0a[a]	6.1±0.0	4.7±0.1	6.9±0.2b	4.3±0.1	2.5±0.2
	160	12.1±0.0a	8.0±0.0	6.8±0.0	11.5±0.2b	7.8±0.0	5.8±0.2
	130	21.2±0.2a	13.9±0.1	9.6±0.0	21.0±0.3a	12.9±0.2	8.5±0.0
L2	190	9.0±0.1a	6.6±0.1	4.5±0.1	8.1±0.2a	4.8±0.0	2.3±0.2
	160	16.1±0.0a	10.0±0.0	9.1±2.5	13.1±0.1b	7.8±0.1	5.8±0.0
	130	25.3±0.1a	17.5±0.0	11.3±0.3	25.2±0.1a	13.7±0.1	8.6±0.0
L3	190	8.4±0.2a	6.5±0.1	4.4±0.4	6.8±0.0b	4.3±0.0	2.1±0.0
	160	12.9±0.0a	8.3±0.3	6.4±0.4	11.4±0.2b	7.2±0.1	4.1±0.0
	130	25.0±0.0a	15.2±0.5	9.4±0.1	22.0±0.2b	12.3±0.6	8.3±0.0
(b) Power Density (W/m^2)							
		Uncovered at Distance (mm)			Covered at Distance (mm)		
Positions	Gap (mm)	100	200	300	100	200	300
L1	190	0.16±0.00a	0.10±0.00	0.06±0.00	0.12±0.01b	0.05±0.00	0.02±0.00
	160	0.39±0.00a	0.17±0.00	0.12±0.00	0.35±0.01b	0.16±0.00	0.09±0.01
	130	1.20±0.02a	0.52±0.01	0.24±0.00	1.17±0.02a	0.44±0.02	0.19±0.01
L2	190	0.22±0.00a	0.11±0.00	0.05±0.00	0.17±0.01b	0.06±0.00	0.01±0.00
	160	0.69±0.00a	0.27±0.00	0.23±0.12	0.46±0.01b	0.16±0.00	0.09±0.00
	130	1.69±0.01a	0.81±0.00	0.35±0.02	1.68±0.01a	0.49±0.01	0.20±0.00
L3	190	0.19±0.01a	0.11±0.00	0.05±0.01	0.12±0.00b	0.05±0.00	0.01±0.00
	160	0.44±0.00a	0.18±0.01	0.11±0.01	0.35±0.01b	0.14±0.00	0.05±0.00
	130	1.66±0.01a	0.62±0.04	0.24±0.01	1.29±0.02b	0.40±0.04	0.18±0.00

[a] Different letters indicate that means are significantly different among shielding conditions, respectively, at P=0.05 using t-test.

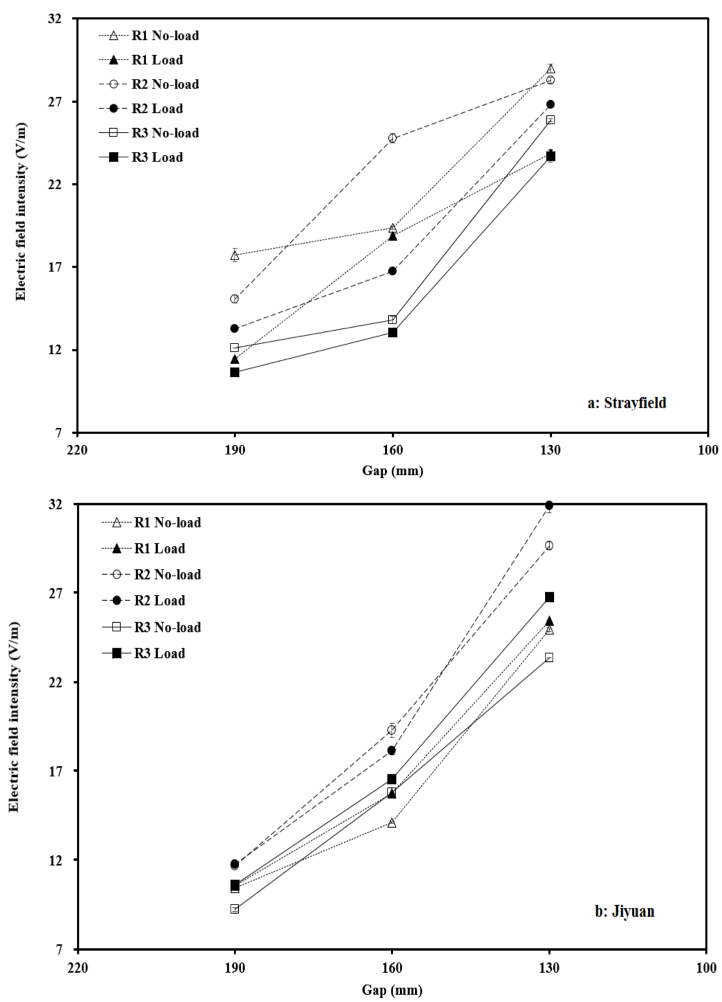

Figure 4. Electric field intensity from Strayfield (a) and Jiyuan (b) RF systems as a function of the electrode gap at a distance of 100 mm and three locations (R1, R2, and R3) from the inlet opening with and without load.

The largest estimated power density from the electric field intensity was found to be at the middle point of the opening at a distance of 100 mm with an electrode gap of 130 mm without loading (fig. 3). For the Strayfield system, the maximum value was 31.5 V/m and 2.5 W/m^2. But for the unshielded Jiyuan systems, the maximum value was 31.9 V/m or 2.6 W/m^2 (fig. 4). A similar reduction in electric field intensity with distance was reported by Eriksson and Mild (1985) and Stuchly et al. (1980). The maximum electric field intensity in this study was lower than those observed by Stuchly et al. (1980) (75 V/m) and Hietanen et al. (1979) (200 V/m) in sewing and plastic-welding RF units, respectively, which probably had less protective shielding. The values found in this study were also lower than the suggested maximum values of electric field intensity (69.9, 61.0, 67.9, and 61.0 V/m) or the estimated power density (12.2, 10.0, 12.3, and 10.0 W/m^2) issued by the Institute of Electrical and Electronics Engineers (IEEE, 1982, 2006) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP, 1998), respectively, according to the maximum permissible exposure (MPE) to 27.12 MHz RF electromagnetic fields.

Because the magnetic field intensity from Jiyuan RF system was not detectable (H<0.001 A/m), figure 5 presents the magnetic field intensity from the Strayfield RF system only both as a function of distance at an electrode gap of 160 mm and a function of electrode gap at a distance of 100 mm with load and no-load at three locations. The large difference of the magnetic field intensity between Strayfield and Jiyuan RF systems could be caused by the different design of tank and work circuits. The trend for the magnetic field intensity from Strayfield unit was similar to that for the electric field intensity (figs. 3 and 4). That is, the magnetic field intensity decreased dramatically with increasing distance at each load condition and location but increased with decreasing gap.

The most observable value of magnetic field intensity for the Strayfield unit was around 0.11 A/m at a gap of 160 and 190 mm even at a distance of only 100 mm. This was in agreement with those (0.3 A/m) observed by Stuchly et al. (1980) and was below the limit (0.16 A/m) required by ICNIRP (1998) and IEEE (2006). However, the only exceptional magnetic field intensity value (0.5 A/m) observed in this study appeared at a gap of 130 mm without loads. Although this was still lower than that (1.9 A/m) observed in plastic-welding RF units by Stuchly et al. (1980) and Wilén et al. (2004), it exceeded the standard value issued by ICNIRP (1998) and IEEE (2006). More attention should be paid to operators working close to the RF unit running

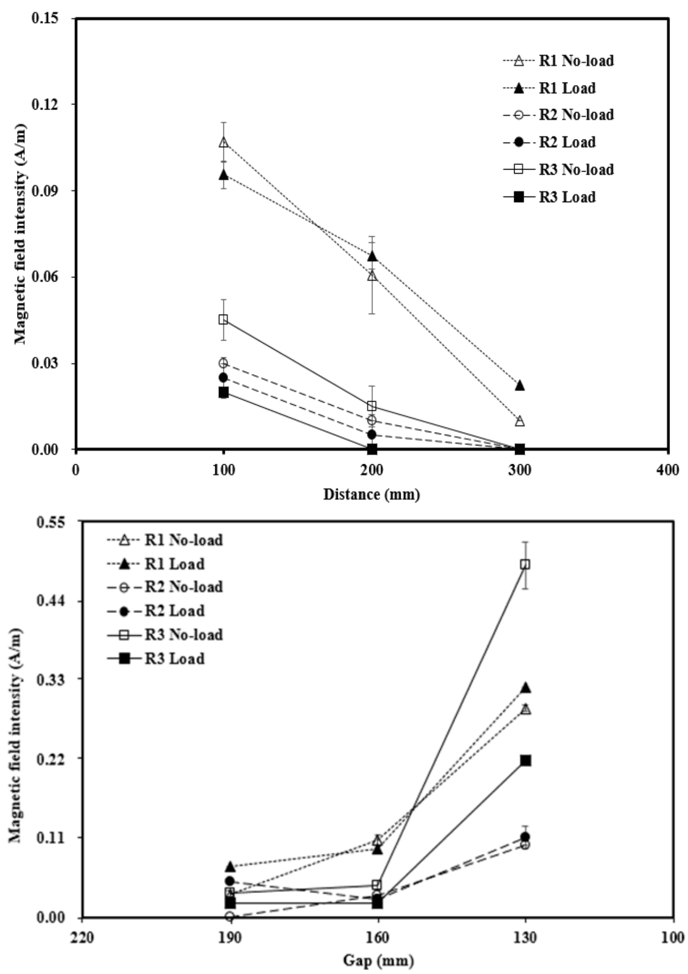

Figure 5. Magnetic field intensity from Strayfield RF systems as a function of the distance at electrode gap of 160 mm and the electrode gap at the distance 100 mm with and without load at three locations (R1, R2, and R3) of inlet openings.

without load and with high electrode gaps, suggesting that additional shielding of magnetic fields might be necessary for RF systems similar to the Strayfield unit.

Table 2 lists the electric field intensity of Strayfield and Jiyuan RF systems without shielding under no and with load conditions at electrode gap of 130 mm. Generally, the average leakage electric field intensity in Strayfield unit was larger than that in Jiyuan system and the average value without load was larger than that with load, which was also observed in Figs. 3-4. The maximum, minimum, and average electric field intensities were similar in inlet and outlet openings for the two RF systems and 31.9, 8.7, and 19.9 V/m at the worst scenario with the electrode gap of 130 mm over the 18 locations.

The effects of load in the Strayfield system was probably because the electromagnetic field in the RF oven was uniformly distributed around the plate electrodes when there was no load. However, the field was concentrated into any added load, resulting in less radiation emission from the openings. This phenomenon was also explained in a report by the Thermo Energy Corporation (TEC, 1987). The difference between the two systems was probably caused by the relatively higher measurement height of the Jiyuan system (190 mm) as compared to that (125 mm) used in Strayfield system, resulting in less of an effect when a load was added. Consequently running RF systems without a load should be avoided not only to lengthen the life of the triode tube but also to avoid high RF power emissions.

For the Strayfield system, the trend of decreasing electric field intensity with added load was true for each of the three given gaps. A similar trend was not observed when the electrode gap was reduced to 130 mm in the Jiyuan system. Similar results of the leaked electric field intensity were also observed at the outlet opening (table 1). The effect of various parameters such as different electrode geometry and size, opening area, and measurement locations on the distribution of electromagnetic fields should be further studied using finite element analyzing software.

EFFECTS OF SHIELDING

Table 1 shows the comparison of electric field intensity and power density between shielded and unshielded outlet openings of the Jiyuan RF system without load. The clear trend of increasing electric field intensity or power density with decreasing distance and gap was found again for covered and uncovered shielding. This was the same as observed in the inlet opening (figs. 3-4). The small standard deviation of electric or magnetic field intensity (table 1 and figs. 3-4) indicated the stable and repeatable measurement results over time. With shielding, the absolute value of the electric field intensity decreased by less than 3 V/m, but the electric field intensity or power density was reduced significantly ($P<0.05$) at distance of 100 mm for most of locations and electrode gaps except for position L2 and gap of 130 mm. The electric field intensity or power density was highest at the middle point of the opening, which was the same as observed in the inlet opening.

For short exposures, the leaked RF power density is completely safe since the maximum measured values were far below the permitted maximums. But for long exposures, the installation of shielding for additional protection would further provide for a safe environment. Eriksson and Mild (1985) proposed capacitive shielding for RF plastic sealer to avoid high-level electromagnetic emission from the dielectric heaters and sealers. The design and implementation of shielding was also described in detail by ILO (1998).

The leakage radiation level at openings of two RF heating systems did not exceed the standard level defined by International Commission on Non-Ionizing Radiation Protection and Institute of Electrical and Electronics Engineers standards (ICNIRP, 1998; IEEE, 2006). The leakage radiation level from conveyor RF systems is generally below that from the RF sealers, which is in good agreement with reports by Stuchly et al. (1980). The safety level of using commercial conveyor RF systems must be checked by manufacturers before delivery. During the daily operations of the RF systems, cares needed to take for reducing operators' radiation exposure include additional shielding of the interaction area, reducing exposure time, increasing the distance between the operator and the electrode, and avoiding empty-load running. Further research efforts should be directed toward the biological effects on the human body exposed to the near-field radiation of RF systems, especially for the less shielded RF sealers.

Table 2. Electric field intensity (V/m) of Strayfield and Jiyuan RF systems without shielding under no and with load conditions at electrode gap of 130 mm.

RF System	Opening	Value	No Load	With Load
Strayfield	Inlet	Max	29.0	26.8
		Min	18.9	15.6
		Average	23.7±3.6	21.1±3.4
	Outlet	Max	31.5	23.0
		Min	18.6	10.4
		Average	24.5±4.3	18.3±4
Jiyuan	Inlet	Max	29.6	31.9
		Min	8.7	11.5
		Average	18.2±6.7	16.5±6.0
	Outlet	Max	25.3	28.8
		Min	9.4	9.5
		Average	19.4±7.1	17.5±6.5

CONCLUSIONS

Leaked electric and magnetic field intensities were systematically measured using an electromagnetic detector around inlet and outlet openings of the two RF systems, then converted to RF power density and used to compare with the literature and standards for safe operation. The measured electric or magnetic field intensity was clearly reduced with added load, especially for the Strayfield RF system, which was probably caused by the electromagnetic field being concentrated into the load. Generally, the electric or magnetic field intensity increased with decreasing distance, electrode gap and lack of shielding. But the maximum RF radiation emission measured, even without shielding, was still lower than the limited value required by ICNIRP and IEEE Standards for a 6 min exposure. This study may provide solid data for ensuring operational safety when using industrial implementations of the RF heating systems.

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