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Original Article

Design and analysis of a doubly corrugated filter for a combined multi-feed microwave-hot air and continuous belt system

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Abstract

A doubly corrugated filter was designed for a combined multi-feed microwave-hot air and continuous belt system (CMCB). The proposed filter reduces microwave energy radiation from the open entry of the continuous belt system. Microwave radiation leakage that affects a human should remain below 10 mW/cm^2. The filter was designed for stop-band frequency range 2,300-2,600 MHz, while the operating frequency is 2,450 MHz, and for attenuation greater than 60 dB in this range. We report on optimizing all the design parameters of a doubly corrugated filter and on experimental verification after its installation at the Research Center of Microwave Utilization in Engineering (R.C.M.E) at Thammasat University, Thailand.

Keywords: microwave filter, microwave choke, corrugated choke, waffle-iron filter, radiation energy, drying kinetics

1. Introduction

A continuous microwave heating or drying process necessarily has entry and exit points for the material processed. These points leak microwaves that may interfere with electronic systems, such as communication systems, and might be hazardous to humans or animals. In particular, microwaves at the operating frequency 2.45 GHz of the currently considered equipment are absorbed by organic tissues. They penetrate, and can raise the temperature of blood and tissue, causing serious damage and danger. Therefore, most industrialized countries have established safety standards and limits for intensity of microwave radiation exposure (IEEE, 1992). For example, in the United States microwave energy exposure from microwave equipment at 2.45 GHz is limited to 5 mW/cm^2 at a distance of 5 cm from the equipment surface and the whole body exposure limit is 10 mW/cm^2 at 2.45 GHz. The same intensity limits have been adopted in many countries (Meredith, 1998). Many techniques to reduce or prevent microwave leakage are shown in textbooks (Meredith, 1998; Metaxas *et al.*, 1983), including partially filled choke tunnels (part filled height and part filled width) with a high loss material that absorbs residual microwave leakage. Moreover, a very effective method was proposed in Vankoughnett *et al.* (1973), which is commonly used in many practical system; reactive or reflective choking with a corrugated filter. The design of such filters is traditionally done by an approximate method based on monomode equivalent circuits (Matthaei, 1964; Young *et al.*, 1963). However, a doubly corrugated designed filter or a waffle iron

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filter has wide-band and stop-band characteristics. Such design of a high power L-band filter, as a singly or a doubly corrugated structure, is shown in Soto *et al.* (2000), and we also applied a multimode analysis method based on the generalized admittance matrix (GAM) (Melcon *et al.*, 1996).

Normally, researchers (De Paolis *et al.*, 2013; Jen-Tsai *et al.*, 2007; Manuilov *et al.*, 2005; Sharp, 1963; Young and Schiffman, 1963) designed and tested the performance of filters by using a waveguide scale, but they did not scaled-up their filters to an industrial scale. Thus, at the Research Center of Microwave Utilization in Engineering (R.C.M.E), we have a combined unsymmetrical multi-feed microwave heater and continuous belt system, which is a prototype of an industrial scale. It has two open entries with the geometry shown in Figures 1 and 2. The first is for workload input and the second for workload pass through the cavity. To address safety issues, we designed doubly corrugated filters. The advantage of doubly corrugated filter is that their periodic structure can be designed for pass-band and stop-band effects, and this paper shows a technique to optimize the design for the residual radiation energy, here with attenuation greater than 60 dB.

The designed filters were implemented at the open entries of the system, and their function validated by measurements. When the CMCB system with doubly corrugated filters was used to run some specimens for drying kinetics studies, also the microwave leakage from the system was checked by a microwave leakage detector. The results of experimental validation are discussed and summarized in the conclusions.

2. Design of Mechanical Blocking Filter (Corrugated Choke)

2.1 Theory

Normally a continuous microwave process has a rectangular open entry, as in Figure 1, and the doubly corrugated filter was designed to fit the open entry. The filter consists of a series of equal length stubs periodically in a grid layout, as shown in Figure 2. The traditional design method is based on a monomode equivalent representation of all the elements in the structure. We modeled the E-plane T-junction of the structure by the monomode equivalent circuit proposed in (Marcuvitz, 1951). The open entry port was considered a rectangular waveguide interconnecting such T-junctions, and was represented by a simple transmission line related to the fundamental mode. The periodicity of the monomode equivalent filter circuit is shown in Figure 3.

The attenuation α in the stop-band is given by the following equations (Matthaei, 1964).

$$A = \cosh^{-1}\left(\left|\cos(\beta l') - \left(\overline{X}_T + m^2{}_T \frac{b}{g}\tan(\beta d')\right)\cdot\frac{\sin(\beta l')}{2}\right|\right) \quad (1)$$

$$\alpha(dB) = 8.686 \cdot n \cdot A \quad (2)$$

Here A represents the attenuation constant in Np/m, *n* is the number of sections in the E-plane T-junction of filter, β is the propagation constant of fundamental mode ($\beta = \frac{2\pi}{\lambda}$), *b* and *g* are physical dimensions of the filter as shown in Figure 3 (a), and l', $\overline{X}_T$, $m^2{}_T$ and d' are electrical parameters derived from the equivalent circuit of a filter section in Figure 3 (b) (Marcuvitz, 1951).

2.2 Design of mechanical blocking filter

The geometry of the open entries is $a \times b$ shown in Figure 1, and x is 695 mm, y is 200 mm, and the web material is polypropylene. The electrical requirements for a filter are a high attenuation level (greater than 60 dB), and a wide stop-band response over ±150 MHz (2.30-2.60 GHz) centered at

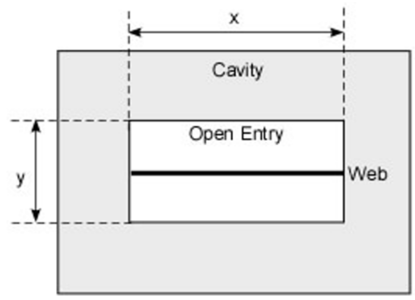


Figure 1. Geometry of open entry.

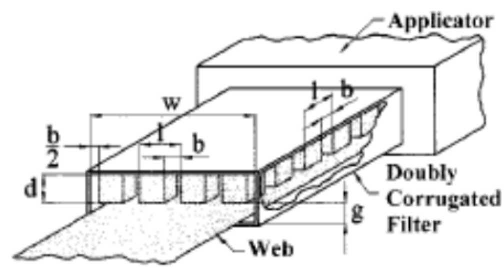


Figure 2. Open entry of the continuous microwave process and the doubly corrugated filter (Soto *et al.*, 2000).

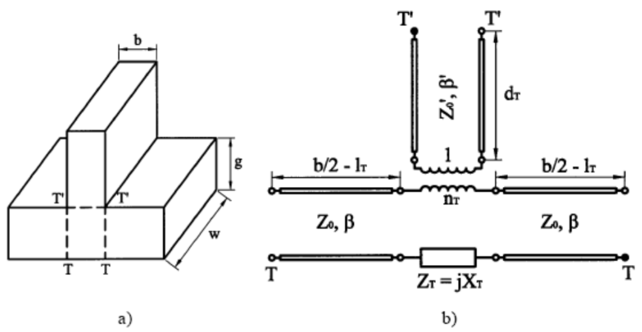


Figure 3. (a) General view and (b) equivalent circuit of E-plane T-junction.

2.45 GHz frequency. As a first step in the design of a doubly corrugated filter, we know from the conditions above that w equals x, and g is 135 mm. The w and g parameters are fixed by the material dimensions. We selected n to be 13, this is the number of sections of E-plane T-Junctions of the filter, and the period of rectangular posts per section was set to *l*, which should be as close as possible to 60 mm. Next we selected the stub height d to be approximately 30 mm, equal to a quarter wavelength (Matthaei, 1964). The last design parameter remaining is b, the stub width of the equivalent T-junction that needs to be carefully selected. When parameter b is one of 19, 21, or 23 mm, the corresponding *l* values are 53.38, 53.54 and 53.69 mm. The attenuation profiles computed for these values are shown in Figures 4, 5, and 6.

The parameters of doubly corrugated filter design given in Soto *et al.* (2000) (w = 172.72 mm, g = 13.97 mm, d = 29.21 mm, *l* = 17.27 mm, b = 6.29 mm, and material inside the waveguide is air with dielectric constant = 1) were used with our computing program to validate it. The design cutoff frequency and infinite attenuation at the operating frequency 2.45 GHz were checked. The given design rejects the energy related to the TE_{10} mode, propagating through the access ports, in the frequency band 2.30-2.60 GHz. The computed results in Figure 7 have the same trends as the graph in Figure 4 of Soto *et al.* (2000), serving as validation of our computations.

The difference between the current work and Soto *et al.* (2000) is in the dimensions of the open entry and the material inside it. Our material inside the open entry is not only air, but also the polypropylene belt (web) with a dielectric constant of 3.3. We performed some simulations based on Equation 1 with varying parameter values as discussed next.

Figure 4 shows the effects of varying parameters b and *l,* while keeping w, n, d and g fixed. When b equals 19 mm and *l* equals 53.38 mm, the line with symbols '*' shows a pass band of wavelengths from 125 mm to 130 mm (2.40-2.31 GHz). When b is increased, the attenuation also increases. In Equation 1 this increase in attenuation comes from the term $\tan(\beta d')$ that can become infinite; a higher value of b increases this term providing more attenuation. So the attenuation will increase with b but there is an upper limit for b from the equivalent circuit in Figure 3b. The computed attenuation is not valid if a higher order mode appears, and Equation 1 is no longer appropriate. If the number of sections (n) is changed from 10 to 13, or further to 15, while the other parameters are fixed, the attenuation loss increases. The results are shown in Figure 6, illustrating the effects of the stub height (d). Changing this value shifts the central frequency of the filter with the penetration of the stubs since d is also modified, and the attenuation and bandwidth of the filter are altered as well.

The design dimensions selected based on these simulations were: w = 675 mm, g = 105 mm, d = 30 mm, n = 13 mm, b = 21 mm and *l* = 53.54 mm, and the doubly corrugated filters were built accordingly as shown in Figure 8. These filters were installed at the open entry of the combined un-

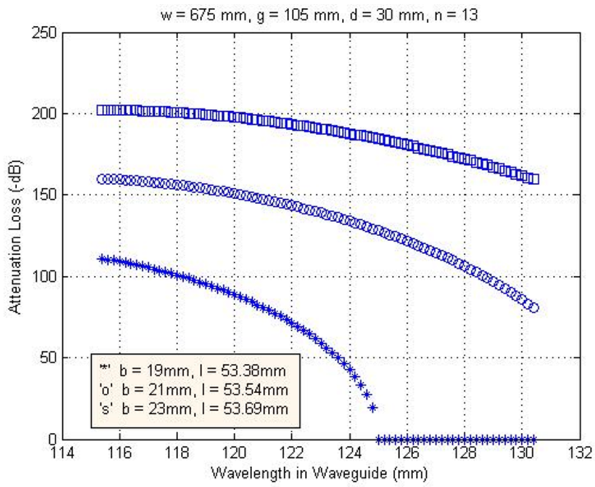


Figure 4. Attenuation loss of the doubly corrugated filter when b and l parameters are varied.

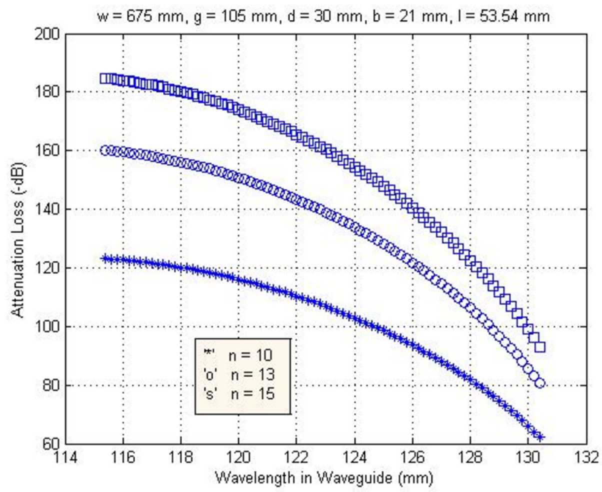


Figure 5. Attenuation loss of the doubly corrugated filter when n parameter is varied.

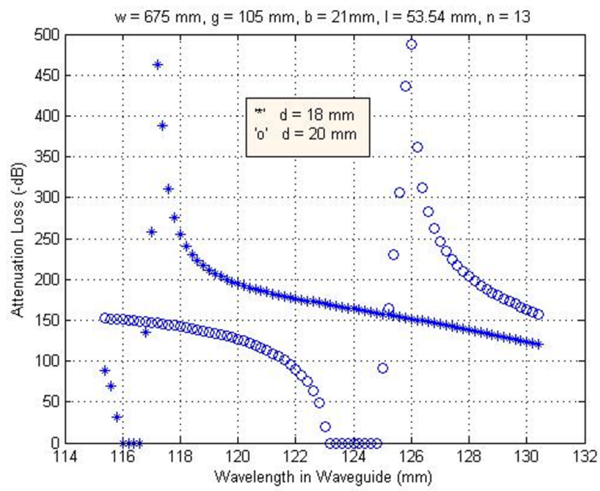


Figure 6. Attenuation loss of the doubly corrugated filter when d parameter is varied.

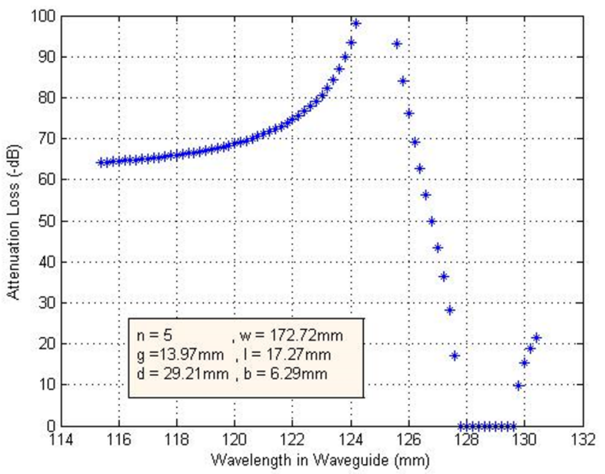
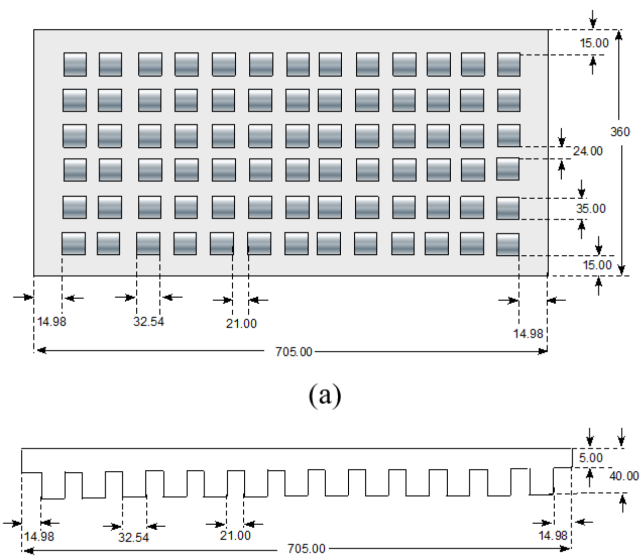


Figure 7. Attenuation loss of the doubly corrugated filter with the parameters from Metaxas *et al.* (1983).



(a)

(b)

Figure 8. General schematics of the R.C.M.E. doubly corrugated filter, (a) bottom view (b) side view.

symmetrical multi-feed microwave heater and continuous belt system at R.C.M.E., and microwave leakage measurements were done. Moreover, to confirm an attenuation performance of filters which were installed to open-end ports of the system, the commercial simulation software named COMSOL MultiPhysics^{TM}, which based on a finite element method (FEM), was applied. The simulation module that used to confirm the result is RF module >> Electromagnetic waves >> Harmonic propagation. The three dimensions of a doubly corrugated filter from Figure 5 of Soto *et al.* (2000) and R.C.M.E. doubly corrugated filter were created, then the transmission coefficient (S_{21}-parameter or attenuation [dB]) were carried out for both filters. The results are depicted in Figure 9. In this figure, it shows a good result trend of the doubly corrugated filter that is similar to the result from Figure 5 of Soto *et al.* (2000). Therefore, these results give more confidence in the R.C.M.E. doubly corrugated filter design, which can achieve the goal of the attenuation level around 60 dB.

3. Experimental Procedures

Microwave-convective air drying was carried out using a combined multi-feed microwave-convective air and continuous belt drier system (CMCB) as shown in Figure 10. The shape of microwave cavity is rectangular with dimensions 90 cm×45 cm×270 cm. The drier was operated at a frequency of 2.45 GHz with a maximum temperature of 180°C.

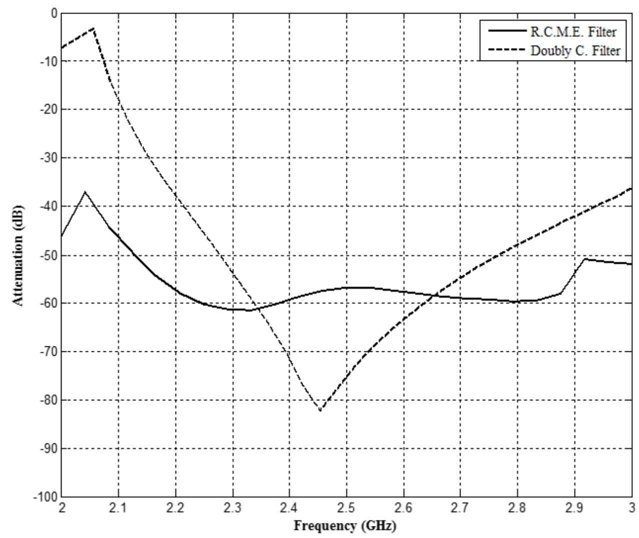


Figure 9. Attenuation results of a doubly corrugated filter with a geometry after Soto et al. (2000) and a R.C.M.E. doubly corrugated filter were carried out with COMSOL MultiPhysics^{TM}.

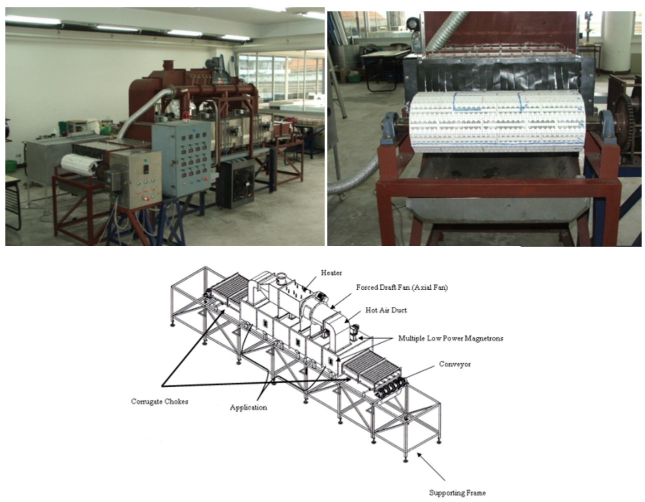


Figure 10. Photos and a schematic diagram of the experimental set-up of a combined multi-feed microwave-convective air and continuous belt system (CMCB).

The microwave power was generated by means of 12 compressed-air-cooled magnetrons. The maximum microwave capacity was 9.6 kW at the operating frequency. The power setting could be adjusted in 800 W steps by turning individual magnetrons on/off. The continuous belt conveyor necessitates two open ends for the material to enter and exit. The leakage of microwaves was prevented by a combination of mechanical blocking filter (corrugated choke) and microwave absorber zone filter, at each open end. The microwave leakage was controlled in compliance with the DHHS (US Department of Health and Human Services) standard to below 5 mW/cm^2. Multiple magnetrons were installed in asymmetrical positions around the rectangular cavity. The microwave power was then directed into the drier by waveguides.

The magnetrons and transformers were cooled down by fans. The belt conveyor system consisted of a drive motor, a tension roller, and the belt. During the drying process, the conveyor speed was held at 0.54 m/min and the motor speed was controlled by the VSD control unit. Hot air was generated using 24 electric heater units with a maximum capacity of 10.8 kW and a maximum working temperature of 240°C. The hot air was blown with a 0.4 kW fan through an air duct into the cavity. The hot air temperature was measured with a thermocouple.

As shown in Figure 11, the drying samples were non-hygroscopic porous packed beds, composed of two sizes of glass beads; fine bed (F-Bed) and coarse bed (C-Bed), with water and air in the pore space. A sample container of dimensions 14.5 cm×21 cm×4.5 cm was made from 2 mm-thick polypropylene. The polypropylene did not absorb microwave energy. In this study, the sample selected for a drying test was non-hygroscopic porous material with dimensions of 14.5 cm × 21 cm × 1.15 cm, and the 22 packed beds had a total weight of 11 kg.

4. Measurement of Microwave Leakages from Open Ends of Microwave Cavity

The measurement device can report whether or not the amount of radiation from a microwave oven is considered unhealthy, and is useful for testing for defects or problems with door seals. The business end of the MD-2000 and R.C.M.E. microwave leakage detector, Figure 12(a-b), is placed within a couple inches of the oven, along the seam where the door meets the oven's chassis. The device sniffs the oven and gives a reading from 0 to 9.99 mW/cm^2. If it senses levels over 5 mW/cm^2, it flashes a light and emits a warning beep. This usually means there is a problem with the door seal. The device is powered by a 9-Volt battery and comes with a wall-mounting bracket.

The device is zero calibrated before each use, and has sensitivity down to 0.01 mW/cm^2 at 2,450 MHz, giving readings in hundredths of mW/cm^2. The leakage of microwave radiation was measured during the drying trial. The distance (D) from an open end of the microwave cavity ranged from 0 to 200 cm, as shown in Figure 13.

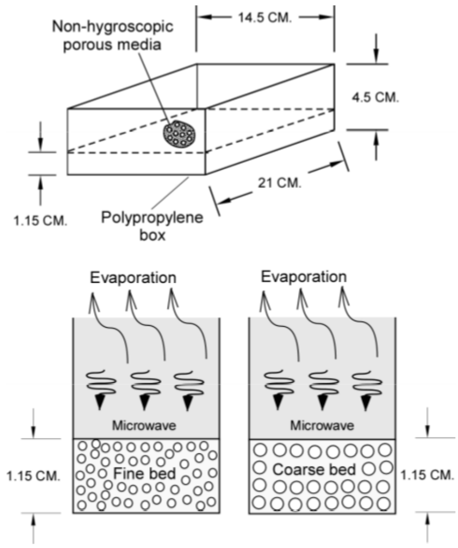


Figure 11. Schematics of a drying sample (packed bed)

(a) (b)

Figure 12. (a) Digital readout microwave leakage detector (MD-2000), and (b) digital readout microwave leakage detector (RCME).

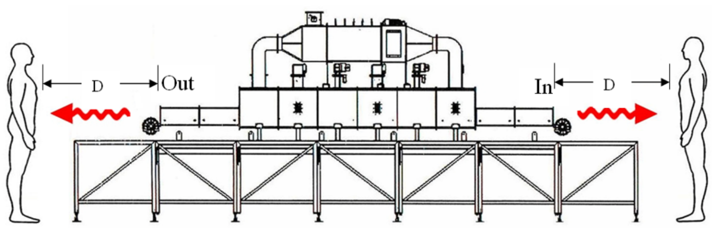


Figure 13. Distance definitions on measuring microwave leakage for CMCB.

The microwave operating power ranged from 0 to 4.8 kW; however, for the leakage experiments, the microwave operating power was fixed at 4.8 kW in all cases. The samples of two types described in the previous section were dried. The first sample type had coarse glass beads as porous substance, and these were labeled as C-Bed samples. They were loaded into the CMCB at the inlet open entry, and the conveyor carried the samples through to the outlet open entry, while the measurements of microwave leakage took place at various distances from the open entries. The experiments were replicated seven times. The other sample type had fine glass beads as the porous substance, and these cases were labeled as F-Bed. The drying and leakage measurements were similar with the C-Bed samples.

5. Results and Discussion

The measured microwave power leakage versus distance is shown in Figure 14. In the top panel, the microwave power leakage at the inlet ranged from 3 to 4 mW/cm^2 is decreasing exponentially with distance so that the leakage level was less than 1 mW/cm^2 for distances greater than 30 cm. There is only a slight difference between the C-Bed and F-Bed sample types, consistently but without statistical significance. In the bottom panel, the microwave leakage at the outlet ranged from 4 to 5 mW/cm^2 at the opening and qualitatively the leakage pattern is similar to the inlet.

Since the radiated power density decreases with distance, it is reasonable to assume that the exposure of a person within 10 to 200 cm from the open entry is much less than the maximum allowed by safety standards. The value 5 mW/cm^2 is considered harmless to humans by the DHHS (US Department of Health and Human Services). Therefore, it can be indicated that the designed doubly corrugated choke has good efficiency and performance.

6. Conclusions

Corrugated chokes are an effective means to reduce radiation leakage from open ports of microwave heating systems. The traditional analysis and design of these filters is based on monomode equivalent representations of the elements integrated in the filter structure. These representations give approximate responses, and particularly with multiple corrugations either multimode or more complete simulations are needed for accurate predictions. The designed corrugated choke was implemented in a combined multi-feed microwave-convective air and continuous belt system (CMCB). The proper function of the choke filter was experimentally established, using a handheld leakage detector. The filter design presented contributes to the safe operation of microwave equipment in industrial processes.

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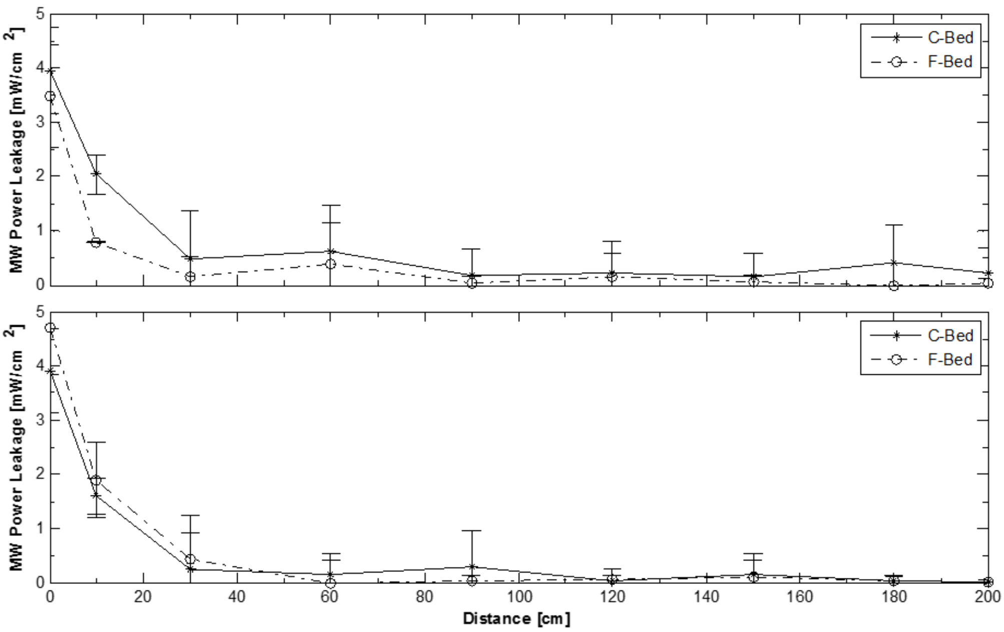

Figure14. Measured microwave power leakage versus distance from an opening to the "oven" cavity. The decaying curves differ slightly between two sample types shown in the labels. The top panel is for leakage at the inlet, while the bottom panel summarizes measurements at the outlet.

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