IOP Publishing Journal of Physics D: Applied Physics
J. Phys. D: Appl. Phys. **40** (2007) 6651–6656 doi:10.1088/0022-3727/40/21/026

Effective complex permittivity of a weakly ionized vegetation litter fire at microwave frequencies

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Received 21 April 2007, in final form 12 September 2007
Published 19 October 2007
Online at stacks.iop.org/JPhysD/40/6651

Abstract
Thermal ionization of alkali species emitted from thermally decomposing vegetative matter into the combustion zone of a fire makes the zone a weakly ionized gaseous medium. Collision between the medium electrons and neutral flame particles is a dominant form of particle interaction and incident microwave energy absorption process. Electromagnetic wave absorption properties of vegetation fire have implications for the safety of fire fighters during wildfire suppression where communication blackouts have been experienced. Propagation characteristics of electromagnetic waves in a vegetation fire could be deduced from its relative dielectric permittivity. In the experiment, a controlled fire burner was constructed where various dried natural vegetation could be used as fuel. The burner was equipped with thermocouples and used as a cavity for microwaves with a laboratory quality network analyser to determine effective complex permittivity from scattering parameters. A controlled vegetation fire with a maximum flame temperature of 1050 K was set in the burner and X-band microwaves (8.0–9.6 GHz) were made to propagate through the flame. For the flame, at temperatures of 800 and 1015 K, imaginary and real components of effective complex dielectric permittivity were measured to range from 0.113 to 0.119 and from 0.898 to 0.903, respectively.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The presence of electrons in a highly collisional atmospheric pressure gaseous medium such as vegetation fire may result in considerable signal intensity loss for microwaves propagating it. Illuminating the weakly ionized atmospheric pressure gas with microwave energy, electrons are accelerated by the electric field of the incident waves. Assuming that interaction between electrons and neutrals is an elastic one, the neutrals gain little kinetic energy during collisions mainly because they are relatively massive. Electrons are scattered isotropically such that the average velocity after collision is zero. In this way energy is transferred from the microwaves to the flame.

Eucalyptus forests of south eastern Australia are subject to recurring catastrophic wildfires during winter [1]. The wildfires can be very intense with maximum flame temperatures up to 1900 °C [2]. The wildfires often result in huge economic and social cost. During suppression of the threat, mobile radio communications are in constant use. There are anecdotal reports of failure to maintain (vhf–uhf) radio communication during wildfire suppression, e.g. in [3]. The problem could be severe at microwave frequencies. Research has shown that hot hydrocarbon flames at a temperature of about 1800 K significantly attenuate microwaves [4, 5]. Over the years, microwave communication efficiency in wildfire environments has been a concern, e.g. in [3, 6]. Microwave propagation tests carried out by [3] and [6] over vegetative matter flames showed no significant microwave loss. A search

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of the literature has revealed that no or few attempts have been made to investigate microwave propagation through the hottest part of a vegetation fire of at least moderate intensity (500 kW m^{-1}).

Mphale *et al* [19] have carried out a microwave propagation test in a moderate intensity pine litter fire using a network analyser. Using attenuation coefficients determined from *S*-parameters [19], graphically deduced momentum transfer electron-neutral particle collision frequency and electron density in the fire combustion. The method used to determine the electromagnetic constitutive parameters for the fire was rather crude. However, a slightly more accurate method would be to determine these parameters from network analyser measured complex relative dielectric permittivity for the combustion zone. Collision frequency and electron density are then determined from the real and imaginary parts of complex relative permittivity. Another advantage of the current method is that other flame constitutive parameters such as conductivity could be determined from these components. In the current work, microwave propagation coefficients for a vegetation (eucalyptus) fire are determined from real and imaginary components of complex relative dielectric permittivity measured by the network analyser. Average momentum transfer electron–neutral collision frequency and electron density in the vegetation fire are then calculated from the measured real and imaginary parts of complex relative dielectric permittivity.

2. Ionization in the fire

2.1. Thermal ionization

The reaction zone of a vegetation fire is very hot; flame temperatures could be up to 1300 °C [7]. The high temperature environment thermally excites some flame particulates to an unstable state. The excitation is on a selective basis determined by medium temperature and ionization potential of the incumbent particles. On collision with other energized flame particles, the excited particulates (A(g)) may shed their outer electrons to become ions according to the following reaction equation:

$$\mathrm{A(g)} \Leftrightarrow \mathrm{A^{+}(g)} + e^{-}. \tag{1}$$

Fire particulates that may appreciably ionize in the flame are alkali impurities and graphitic carbon (C_n). Alkalis have low excitation energy, e.g. potassium and sodium have excitation energies of 4.34 eV and 5.12 eV, respectively. The elements are present in significant quantities in vegetation, e.g. 3.4% of a plant's weight is potassium [8]. Carbon can exist in different polymeric forms in the vegetation fire. Graphitic carbon has a low work function (4.35 eV) and therefore it is an important contributor to thermal ionization in vegetation fires.

2.2. Chemi-ionization

Chemi-ionization is another mechanism by which flame particulates may be ionized in a vegetation litter fire (e.g. in [9]). In the process, dissociation reactions provide part of the energy required for ionization since they are exothermic and the rest is from the fire. Excited methyl radical CH^{*} is a known contributor to chemi-ionization in flames [10]. CH radical reacts with oxygen atoms in the flame to produce CHO^{+}, a primary ion in hydrocarbon flames [11] and electrons according to the following reaction equation:

$$\mathrm{CH^{*} + O} \Leftrightarrow \mathrm{CHO^{+}} + e^{-}. \tag{2}$$

The thermal and chemi-ionization processes create a weakly ionized environment in the combustion zone.

3. Microwave attenuation coefficient for a vegetation fire

Complex relative dielectric permittivity ($\tilde{\varepsilon}_{\mathrm{r}}$) for a weakly ionized gaseous medium such as fire is given by Sen and Mukhopadhyay [18] as:

$$\tilde{\varepsilon}_{\mathrm{r}} = 1 - \frac{Ne^2}{m\varepsilon_0\left(\omega^2 + \varphi_{\mathrm{eff}}^2\right)} - \mathrm{i}\frac{Ne^2}{m\omega\varepsilon_0\left(\omega^2 + \varphi_{\mathrm{eff}}^2\right)}, \tag{3}$$

where N, ω and ε_0 are electron density in the fire medium, propagation angular frequency and free space dielectric permittivity, respectively. φ_{eff}, m and e are momentum transfer electron–neutral particle collision frequency, electron mass and charge, respectively. The presence of free electrons in fire lowers its dielectric constant (real part of $\tilde{\varepsilon}_{\mathrm{r}}$ (equation (3))) to a value lower than unity (1). For example, if we are to consider a slightly ionized gas with an electron density of 1×10^{17} m^{-3} and a collision frequency of 1×10^{11} s^{-1}, its dielectric constant is 0.9683 for traversing electromagnetic wave at a frequency of 900 MHz.

The complex dielectric permittivity is related to the propagation constant (γ) for the weakly ionized fire medium by the relation [20];

$$\gamma = \mathrm{i}\frac{\omega}{c}\left\{\tilde{\varepsilon}_{\mathrm{r}}\right\}^{1/2} = \alpha_{\mathrm{f}} + \mathrm{i}\beta_{\mathrm{f}}, \tag{4}$$

where α_{f} and β_{f} are attenuation and phase coefficients for the fire. The attenuation coefficient for the fire can be determined from the equation given by Weir [21] as

$$\alpha_{\mathrm{f}} = \frac{\pi\left(2\tilde{\varepsilon}_{\mathrm{real}}\right)^{1/2}}{\lambda_0}\left\{\sqrt{1 + (\tan\delta)^2} - 1\right\}^{1/2}, \tag{5}$$

where $\tan(\delta) = \tilde{\varepsilon}_{\mathrm{imag}}/\tilde{\varepsilon}_{\mathrm{real}}$ is the loss tangent of the flame medium. $\tilde{\varepsilon}_{\mathrm{real}}$ and $\tilde{\varepsilon}_{\mathrm{imag}}$ are real and imaginary components of complex dielectric permittivity. Reflection coefficient and propagation factor can be measured by the use of a vector network analyser (VNA).

4. Experimental set up

4.1. Vector network analyser (VNA) and burner system

Vegetation litter fire was set in a specially constructed hexagonally shaped burner. The burner had a wooden casing and a thermal insulator (8 cm thick) was lined inside to protect it from the fire and heat. The insulator was a material which can withstand very high temperatures (>1200 K) called Fiberfrax®. The Fiberfrax® formed a combustion area that was circular in base cross-section and its internal diameter

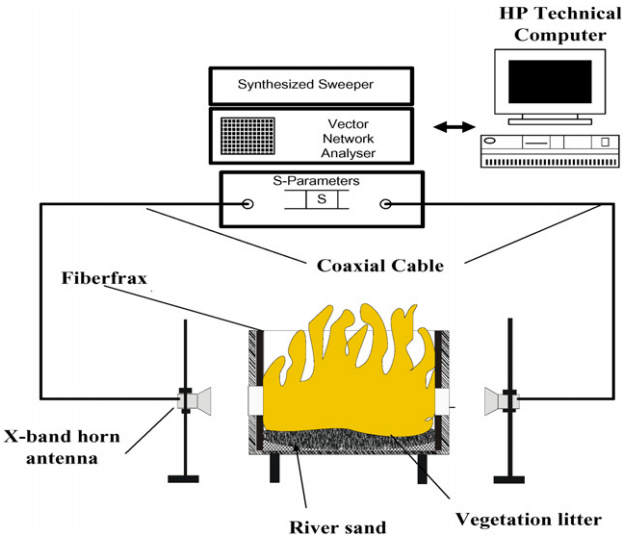

Figure 1. VNA set up for S_{21} and S_{11} parameter measurements.

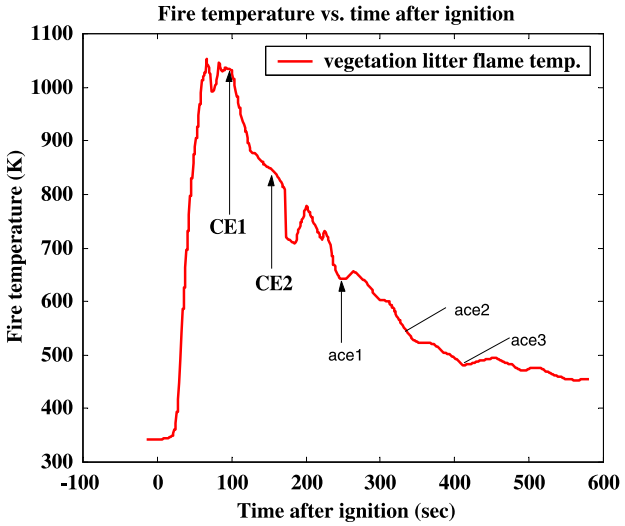

Figure 2. Vegetation litter fire temperature during the experiment.

was 50 cm. Vent holes, of 25 mm diameter, were drilled on each side of the burner to allow ambient air to enter into the combustion zone for efficient combustion. Two holes of horn dimensions were also cut out from the burner's wooden casing directly opposite to each other to allow microwaves to traverse the fire. Scattering parameter measurements, logging and analysis were carried out using a Hewlett-Packard 8577C VNA, *S*-parameter test set and computer system. X-band transmit-receive horns were connected to the VNA system through a two port *S*-parameter test set by means of coaxial cables. High quality mode transition adapters were used to make the connections between coaxial cables and the horns. The set up for the measurements is shown in figure 1.

4.2. Vegetation litter

The vegetation litter used in the experiment was 70% by volume of *Eucalyptus platyphylla* (poplar gum) leaves and the rest was eucalyptus tree bark, twigs and floral parts. The motivation in the volume mixing ratio was a study carried out by [12], who observed that the composition of surface vegetation litter in *Eucalyptus marginata* (jarra) forest in Western Australia was about 70% leaves and other plant parts making the rest. The vegetation litter in the experiment was, however, collected from open woodlands around James Cook University campus. After collection the litter was left to dry in a laboratory for 12 days. This was to maximize combustion efficiency during the experiment. The bulk density of the litter was 5.67 kg m^{-3}.

4.3. Flame temperature measurement

A thermocouple tree about 125 cm high was constructed from a steel pipe of diameter 2.5 cm with the capability to measure temperature at each 25 cm of its height. This was done by means of attaching side 'arms' of length 40 cm at the locations and thus the thermocouple tree could hold up to four thermocouples. The thermocouples used in the experiment were cut from a 100 m double braided fibreglass insulated chromel–alumel (24-G/G) thermocouple wire 50 μm in diameter. The thermocouple wire had a fibre glass shield which can withstand temperatures up to 450 °C. The type K thermocouple wires were then electro-fused at one end to make a perfect junction and then tested with a hot air gun and a multimeter. The thermocouples were then fixed to tree 'arms' by means of a muffler tape and the electro-fused junctions were left protruded 1 cm beyond the 'arm' length into the flame. The thermocouples were then wired to a PICO® Tech TC-O8 data logger to read the temperatures into a computer throughout the experiment.

4.4. S-Parameter measurements

The 8577C VNA system set sweeps from 50 MHz to 40 GHz logging in 601 *S*-parameter data points in each and every sweep. In the experiment, the frequency of our interest was in the X-band (8–9.6 GHz). Within this frequency band, *S*-parameter data was logged-in in each sweep. The *S*-parameter data was then uploaded and analysed by a HP technical computer. An automatic network analyser takes 2 s to sample over one sweep, and then there is a latency of about 50 s before the next sweep can be initiated. Before the VNA was used, it was calibrated first. The calibration method used in the experiment was the transmit-reflect-line (TRL). Varadan *et al* [13] give a full account of calibrating a network analyser using the TRL method. In the experiment, several sweeps and logging of *S*-parameters were carried out, but those for which flames filled the entire internal hollow space of the burner were chosen for *S*-parameter analysis. The selected logged in *S*-parameters were those at CE1 and CE2 (see figure 2), which respectively corresponded to the times 103 and 169 s after ignition.

4.5. Determination of propagation factor from S-parameter

The VNA measures the scattering parameters (*S*-parameters) from which the propagation factor can be calculated. The propagation factor is related to the S_{21} and S_{11} scattering

parameter by the relation [14]

$$T = \left[\frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\,\Gamma}\right], \tag{6}$$

where Γ is the reflection coefficient, which is given by the relation

$$\Gamma = \rho \pm \sqrt{\rho^2 - 1}, \tag{7}$$

where $\rho = ((S_{11}^2 - S_{21}^2 + 1)/2S_{11})$. The sign in (7) is chosen so that $|\Gamma| < 1$. With T determined from S-parameters using the network analyser, relative effective dielectric permittivity ($\tilde{\varepsilon}_r$) can be determined from the relation [14]

$$\tilde{\varepsilon}_r = \frac{\lambda_0}{\eta}\left(\frac{\mathrm{i}}{2d\pi}\ln[T]\right)^2, \tag{8}$$

where T, λ_0 and d are propagation factor, free space wavelength and propagation path length, respectively. In equation (8), $\eta = \lambda_0\{((\mathrm{i}/2d\pi)\ln[T])((1-\Gamma)/(1+\Gamma))\}$, where Γ is the reflection coefficient.

5. Experimental results and discussions

5.1. Flame temperatures

As ambient air entrained into the burner, flames as high as 0.75 m were observed. It took 7 min for the fire to smoulder. Initially the fire was turbulent; however it started to burn steadily after 82 s since ignition. Flames filled the inner space of the burner 12 s after it started to burn steadily. The experiment considered eucalyptus litter surface temperatures only, though it was possible to record fire plume temperature up to 100 cm above the vegetation litter. Eucalyptus litter surface temperature was observed to rise very fast to a maximum of 1050 K after 66 s since ignition (see figure 2). The temperature then started to change rapidly due to turbulence. After the turbulence, temperatures then steadily decreased from 1032 K after 100 s to 810 K at 171 s since ignition. The turbulent behaviour set in thereafter for 28 s. It then fell steadily until it smouldered after 7 min since ignition. A set of five S-parameter data was sampled during the experiment. The sampling was at CE1, CE2, ace1, ace2 and ace3 which correspond to temperatures 1015 K, 814 K, 643 K, 522 K and 481 K, respectively, in figure 2. This occurred at the times 103 s, 169 s, 247 s, 355 s and 413 s after ignition, respectively.

Though five sets of S-parameter data were logged-in, only two sets were considered for analysis. The two sets of data were sampled at CE1 and CE2. The rest were discarded between during the sampling vegetation litter fire did not fill the entire volume of the burner.

5.2. Real and imaginary flame permittivities

Eucalyptus litter fire was weakly ionized. The free electrons in the fire plume lowered the effective complex permittivity from what it would be for an unionized plume. Thus, fires with high electron content will have lower effective complex permittivities than those with the low electron concentrations. The amount of ionization in the fire is a factor of temperature and of the amount of alkali impurities (more especially potassium) in the flame. Potassium with other alkalis are

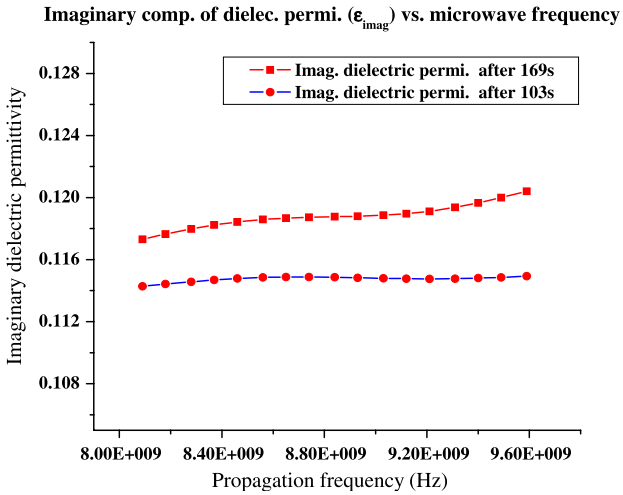

Figure 3. Variation of ε_{imag} with propagation frequency.

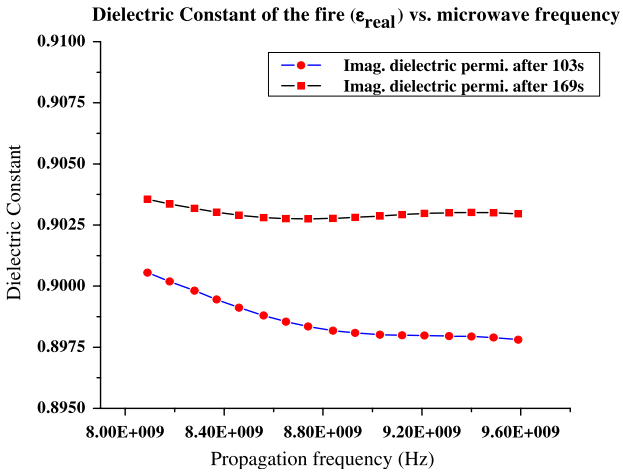

Figure 4. Variation of dielectric constant with propagation frequency.

emitted from the vegetation during combustion at temperatures as low as 400 K [15]. The most likely form of potassium released will be potassium atoms from a reduction reaction in which radicals displace potassium atom from carboxylate (K–O–C) complexes [16].

Microwave propagation through the hottest part of the flames has determined that the imaginary part of the effective dielectric permittivity (ε_{imag}) for a moderate intensity fire ranged from 0.114 to 0.115 at CE1 in the frequency range of interest (figure 3). At CE2, ε_{imag} ranged from 0.117 to 0.121 for the same frequency range. The real component of the effective dielectric permittivity (ε_{real}) behaved in a similar fashion. At CE1, ε_{real} decreased with the decrease in the propagation microwave wavelength. It decreased slightly from 0.901 to 0.897. At CE2 the trend was similar; ε_{real} decreased slightly from 0.903 to 0.902 for the same frequency range (figure 4).

5.3. Loss tangent and microwave attenuation coefficient

The loss tangent parameter indicates how much energy is lost to the vegetation fire. Through this parameter, the rate of energy

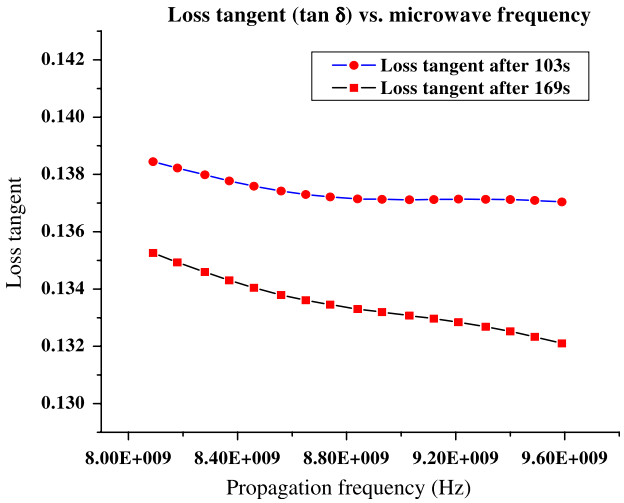

Figure 5. Variation of loss tangent with propagation frequency.

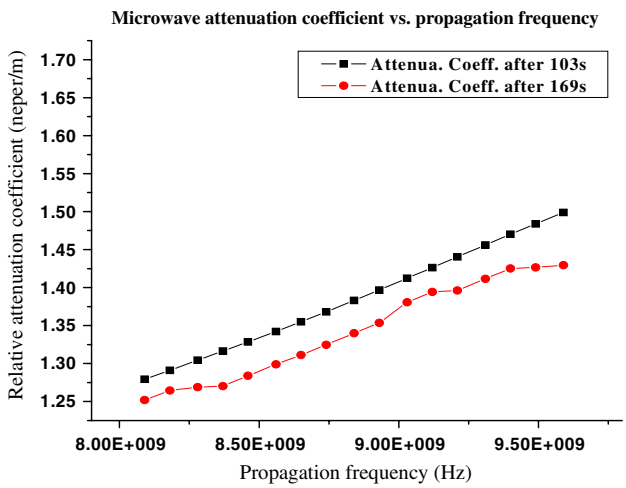

Figure 6. Variation of signal attenuation coefficient with propagation frequency.

loss per unit propagation path length (α), as per (12), can be determined. The measured real and imaginary components of effective dielectric permittivity were used to calculate the loss tangent and consequently the attenuation coefficient for the eucalyptus fire at CE1 and CE2. From the experiment, the loss tangent at CE1 was observed to decrease with the increase in propagation microwave frequency. It decreased from 0.138 to 0.137 for the frequency range 8.0–9.6 GHz, respectively (figure 5). At CE2 the loss tangent was observed to decrease from 0.135 to 0.132 for the same frequency range. For the fire, the loss tangent was observed to be a factor of fire intensity; a hot flame was observed to have a higher loss tangent than a cooler one. Microwave attenuation is a factor of ionization and also therefore of fire intensity. In the experiment, the hotter flame (CE1) produced relative attenuation coefficients in the range 1.28–1.51 neper m^{-1} while the cooler one (CE2) produced attenuation coefficients of 1.25–1.43 neper m^{-1} (figure 6). There was on average a difference of 0.02 neper m^{-1} at the each frequency for the flames. On comparing attenuation coefficients of hydrocarbon flames at high temperatures (≈1800 K) and probably with high alkali impurities, e.g. in [4, 5], with those considered in the experiment, it is observed that flames used by [4, 5] had high attenuation coefficients which ranged from 11.52 to 48.39 neper m^{-1} while attenuation coefficients of flames in the experiment were only up to 1.51 neper m^{-1}.

Alkali emission from combusting vegetation occurs at temperatures as low as 200 °C [14]. According to Vodacek *et al* [16], who carried out spectrometric studies on wildfires, 10–20% of the potassium that is present in vegetation is ionized at normal wildfire temperatures, thus at around 1000 °C. Therefore the measured attenuation coefficients are reasonable when recombination and electron scavenging radicals such as the hydroxyl (OH) radical are considered.

6. Estimation of collision frequency and electron density in the fire

Electron density and collision frequency are two parameters that determine the constitutive parameters of an ionized gas. They could be estimated from the measured dielectric permitivity. Electron–neutral collision frequency (φ_{eff}) can be estimated from the imaginary and real components of effective dielectric permittivity using the relation [18]

$$\varphi_{\text{eff}} = \frac{\varepsilon_{\text{imag}}}{1 - \varepsilon_{\text{real}}}\omega. \tag{9}$$

Using the measured real and imaginary components, average effective collision frequency at CE1 is estimated to be $5.84 \times 10^{10}\,s^{-1}$ while at CE2 it is $6.19 \times 10^{10}\,s^{-1}$. The average effective collision frequency calculated from (9) gives an estimation of electron density (Ned) from the relation [4]

$$\text{Ned} = \frac{2cm\alpha_{\text{f}}(\omega^2 + \varphi_{\text{eff}}^2)\varepsilon_0}{e^2\varphi_{\text{eff}}}, \tag{10}$$

where m is the mass of electron and c is the speed of light in vacuum. Using (10) together with the calculated average effective collision frequency, electron density at the flame temperature CE1 is $2.26 \times 10^{16}\,m^{-3}$ while at CE2 it works out to be $2.19 \times 10^{16}\,m^{-3}$.

7. Conclusions

The imaginary part of effective complex dielectric permittivity for the vegetation litter fire with a maximum temperature of about 1050 K was in the range from 0.114 to 0.115 for the frequency range 8–9.6 GHz for the fire at 1015 K. The imaginary component of effective dielectric permittivity was higher for the cooler flame (at 814 K) as it ranged from 0.117 to 0.121. The real component of effective dielectric permittivity behaved in a similar manner. It was high for the cool flame as it ranged from 0.903 to 0.902 and lower for the hot flame (at 1015 K) as it ranged from 0.901 to 0.897 for the same frequency range. The lowering of the microwave effective dielectric permittivity below unity is attributable to the amount of ionization. Free electrons in the flame decrease the dielectric permittivity of the flame. Therefore the high temperature flame which has a high ionization will have a dielectric constant which is lower than unity (1).

The loss tangent of the hot flame was higher than for the cooler flame. For the hotter flame the loss tangent ranged from 0.138 to 0.137 for the frequency range 8.0–9.6 GHz. The flame at 814 K had its loss tangent ranging from 0.135 to 0.132.

On average, the relative attenuation coefficient for the microwaves for the hotter flame ranged from 1.28 to 1.51 neper m^{-1} for the frequency 8.0–9.6 GHz while the cooler flame attenuated the microwave signals by 1.25–1.43 neper m^{-1} in the frequency range. On average, electron density in the hotter flame was $2.26 \times 10^{16}\ m^{-3}$ while in the cooler flame, the electron density was predicted to be $2.19 \times 10^{16}\ m^{-3}$. The collision frequency of the flame at 1015 K was predicted to be $5.84 \times 10^{10}\ s^{-1}$ while that of the flame at 814 K was $6.18 \times 10^{10}\ s^{-1}$.

Considering that the measured attenuation coefficients are up to 12 dB m^{-1}, significant radio communication efficiency impairments are possible for wildfires which have flame depths of more than 50 m. It should also be observed that the flames were only around 1000 K and therefore higher wildfire temperatures (≈1300 °C) could lead to higher attenuation rates.

Acknowledgments

We would like to gratefully acknowledge the Department of Electrical Engineering of JCU for providing the equipment for *S*-parameter measurement. The work is partly supported by the Staff Development Office of the University of Botswana and partly by Emergency Management Australia under project no. 60/2001.

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