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ChemTech

International Journal of ChemTech Research
CODEN (USA): IJCRGG ISSN: 0974-4290
Vol.7, No.2, pp 526-532, 2014-2015

ICONN 2015 [4th -6th Feb 2015]
International Conference on Nanoscience and Nanotechnology-2015
SRM University, Chennai, India

Effects of Microwave Heating of Human Blood in presence of Composite Materialsat 915 MHz

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Abstract: The increasing popularity of microwaves is primarily due to its volumetric heating. In engineering and medical fields, microwave energy is found spectrum of applications. It is a rapid volumetric heating technique and also known as pollution free technique. Due to its selective and uniform heating effects, it is commonly used in medical practices such as in warming and heating of human blood samples. This work has been carried out to analyze the effect of one dimensional (1-D) heating effect of microwaves on human blood samples placed in the layers of metallic and composite supports at Microwave frequency of 915 MHz with emphasis on the relation between average power vs sample thickness to estimate microwave power absorption within blood samples for various cases. In general, it is observed that microwave power absorption is enhanced in the presence of metallic and composite supports during both R1 and R2 modes. The efficient heating strategies characterized by large heating rates with minimal thermal runaway i.e. uniform temperature distributions within the sample have been assessed for both small and large blood sample thicknesses. Based on the detailed spatial distributions of power and temperature for various cases, suitable combinations of supports have been recommended as optimal heating strategies for human blood samples corresponding to both R1 mode and R2 mode.
Keywords: Microwave Heating, Power absorption, Composite Materials, Thermal runway, Temperature Distribution.

Introduction

Electromagnetic radiations in the frequency range 300 MHz to 300 GHz are known as microwaves (MWs). The material dielectric loss which is a function of frequency of MWs is responsible to convertelectrical energy into heat during MW heating. The detailed analysis of combined MW and thermal transport was studied by [1,4]. For heating of 1D slabs. The localized or non-uniform heating occurs due to volumetric heating effects. They established suitable relationships on the occurrence of resonance with sample size. MW heating and transport models were further applied for thawing and heating of multiphase systems in earlier studies[2] and greater rates in material processing are investigated. A large amount of the earlier work is done in the MW heating of pure substance or layered materials and a very few studies revolve around the MW heating or processing of multiphase systems, especially human blood samples. Blood samples (whole blood) are usually preserved at low temperatures (1 to 6 °C) with permitted storage periods of 2-4 weeks and for longer storage periods (more than months) blood samples need to be preserved at very low temperatures (-30 to -65 °C). In medical practice, warming and heating of human blood is a very common before blood transfusion. Conventional method may not be useful for emergency situations as it takes hours to heat the human blood sample. However, microwave heating could be extremely useful for human blood samples. Warming and heating of human blood, especially during emergency situations as it takes very less time. Microwave heating is based on thermal and dielectric properties of any substance and material.

This work has been carried out for the effective study of various combinations of Teflon, Alumina, SiC or metallic plates on MW heating of human blood samples in the shape of 1-D slabs in the presence of resonancesat 915 MHz. During heating of blood samples, a sample absorbs the power in presence of various supports which affects the power absorption during resonances.

A detailed studies of heating characteristics of blood samples placed in Teflon, ceramic and/or metallic supports as shown in Fig.1. The electromagnetic wave propagation due to uniform electric field *Ex*, given by Maxwell's equation[4] is

$$\frac{d^2E_x}{dz^2}+\kappa^2E_x=0 \qquad (1)$$

Where E_x lies in *x-y* plane and varies only in the direction of the propagation z axis (Fig.1). In Eq.1,

$\kappa=\frac{\omega}{c}\sqrt{\kappa^{'}+i\kappa^{"}}$ is the propagation constant which depends on the dielectric constant,

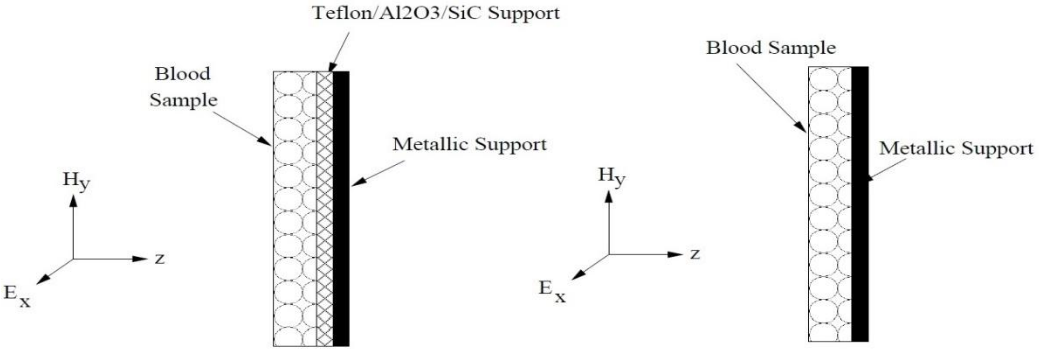

Figure 1: Schematic Illustration of a Human Blood Sample Placed on Composite Supports Exposed to Plane Electromagnetic Waves.

$\kappa^{'}$ and the dielectric loss, $\kappa^{'},\omega=2\pi f$, where *f* is the frequency of the electromagnetic wave and *c* is the velocity of light. In a multilayered sample the electric field for the l^{th}layer obtained from Eq.1 is

$$\frac{d^2E_{x,l}}{dz^2}+\kappa_l^{\,2}E_{x,l}=0 \qquad (2)$$

Where $z_{l-1}\le z\le z_l$ and l=1…n. Assuming each layer has constant dielectric properties, the general solution to Eq.2 represented as a linear combination of transmitted and reflected waves propagating in opposite directions is

$$E_{x,l}=E_{t,l}e^{i\kappa_l z}+E_{r,l}e^{-i\kappa_l z}, \qquad z_{l-1}\le z\le z_l$$

$$E_{x,n}=\begin{cases}E_{t,n}e^{i\kappa_n z}+E_{r,n}e^{-i\kappa_n z}, & z=z_n\left(air\right)\\ 0, & z=z_n\left(metallic\right)\end{cases} \qquad (3)$$

Where *Et, l* and *Er, l* are coefficients due to transmission and reflection, respectively. The general solutions (Eqs.3) andsuitable boundary conditions at the interface are used to obtain coefficients, *Et,l* and *Er,l* via solving the set of algebraic equations.

The absorbed power in l^{th}layer, obtained from Poynting vector theorem is[5]

$$q_l(z) = \frac{1}{2}\omega\varepsilon_0\kappa_{eff}^{"}E_{x,l}(z)E_{x,l}^{*}(z) \qquad (4)$$

Here ε_0 is the free space permittivity, and $\kappa_{eff}^{"}$ is the effective dielectric loss.

For human blood sample, effective dielectric properties and for supports are obtained from.[3] The average power obtained by integrating the power across the slab is

$$\bar{q} = \frac{1}{2L}\int_{-L}^{+L} q_l(z)dz \approx \frac{1}{2L}\sum_{z=0}^{2L} q_l(z) \qquad (5)$$

Here -*L* and +*L* denote the left and right faces of the slab respectively and $q_l(z)$denotes the power as a function of *z*

wherez is measured from the left edge of the slab or

sample assembly. The thickness of the entire slab is 2L. We denote *Ls* as the thickness of the sample and *L'* as the total thickness of supports such that $2L=L_s+L'$.

The average power for a sample of thickness *Ls* is

$$q_{av} = \frac{1}{n}\sum_{i=1}^{n} q_l(z_i), \qquad for\, 0 \le z_i \le L_s \qquad (6)$$

The energy balance equation due to microwave assisted heat source is

$$\rho c_p \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2} + q(z) \qquad (7)$$

where c_p,ρ and *k* are specific heat, effective density and thermal conductivity, respectively. Eq.7 can be solved using finite element method. In all these simulation works, dielectric properties at 915 MHz and thermal properties of human blood samples and support materials are obtained from the literature[2]. In all these cases, the human sample is exposed to MW radiation of intensity 2.5 Wcm^{-2}. We have assumed insulated boundary condition at outer surfaces. The temperature of the human blood sample and the support is 275 K at t = 0 s. It is important to note that, support thickness sensitivity analysis has been carried out to study microwave power absorption within blood samples with various support combinations and 0.15 cm support thickness is selected for support thickness.

Result and Discussions

The detailed analysis has been carried out to study the role of Teflon (transparent), metallic (reflective), and ceramic (Alumina and SiC are absorbed) supports on microwave power distributions for blood samples. In all cases, the supports are placed on the unexposed face of sample slab.

The average power obtained from Eq.6 is plotted as a function of sample thickness as seen in Fig. 2. The maxima in average power, also termed as 'resonances', are observed for specific sample thicknesses and consecutive resonance are termed as R1 modes. The significant resonances R1 are due to constructive interferences between transmitted and reflected waves. The amplitudes of the transmitted and reflected waves are generally larger for smaller sample dimensions corresponding to R1 mode. Based on these preliminary studies, specific sample thicknesses (L_s) are estimated corresponding to resonance (R1modes) for enhanced processing of blood samples.

Fig. 2 illustrates the average power distribution vs sample thickness for various blood samples placed on metallic support and composite supports. It is interesting to observe that human blood sample corresponds to greater average power and power absorption decreases with increase in during R1modes for sample with metallic support and composite supports as seen in Fig. 2. It isalso observed that average power is quite smaller with larger sample thickness for samples with ceramic supports than that for sample with metallic support, especially during R1 mode for all cases. Note that, fig.2, the average powers (qav) within blood samples at support thickness 1.5mm and intensity 2.5 Wcm-2 with metallic support, Alumina-Met support, SiC-Met support,Teflon-Met support are 2.259, 2.663, 2.634 and 2.662 Wcm-3 respectively and sample thicknesses corresponding to metallic support, Alumina-Met support, SiC-Met support,Teflon-Met support are 0.975, 0.825,0.825 and 0.825 cm respectively, during R1 mode.It is interesting to observe that the largest average powerwith Sic-Met support and the lowest average power with Metallic support is 2.634 and 2.259 Wcm-3 respectively.In the same fig.,the average powers (qav) within blood samples with metallic support, Alumina-Met support, SiC-Met support,Teflon-Met support are 0.465, 0.490, 0.488 and 0.490Wcm-3 respectively and sample thicknesses corresponding to metallic support, Alumina-Met support, SiC-Met support,Teflon-Met support are 2.975, 2.825,2.825 and 2.825 cm respectively, during R2 mode.It is interesting to observe that the largest average power with both Teflon-Met & Alumina-Met support and the lowest average power with Metallic support is 0.490 and 0.465 Wcm-3 respectively and intersting thing in the curve of both Teflon-Met & Alumina-Met support are meet at same point during R2 mode.

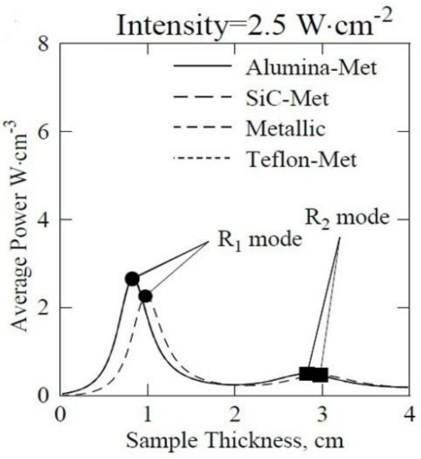

Figure 2: Average Power vs Sample Thickness Diagram for Blood Samples Placed on Composite and/or Metallic Supports Exposed to Microwaves.

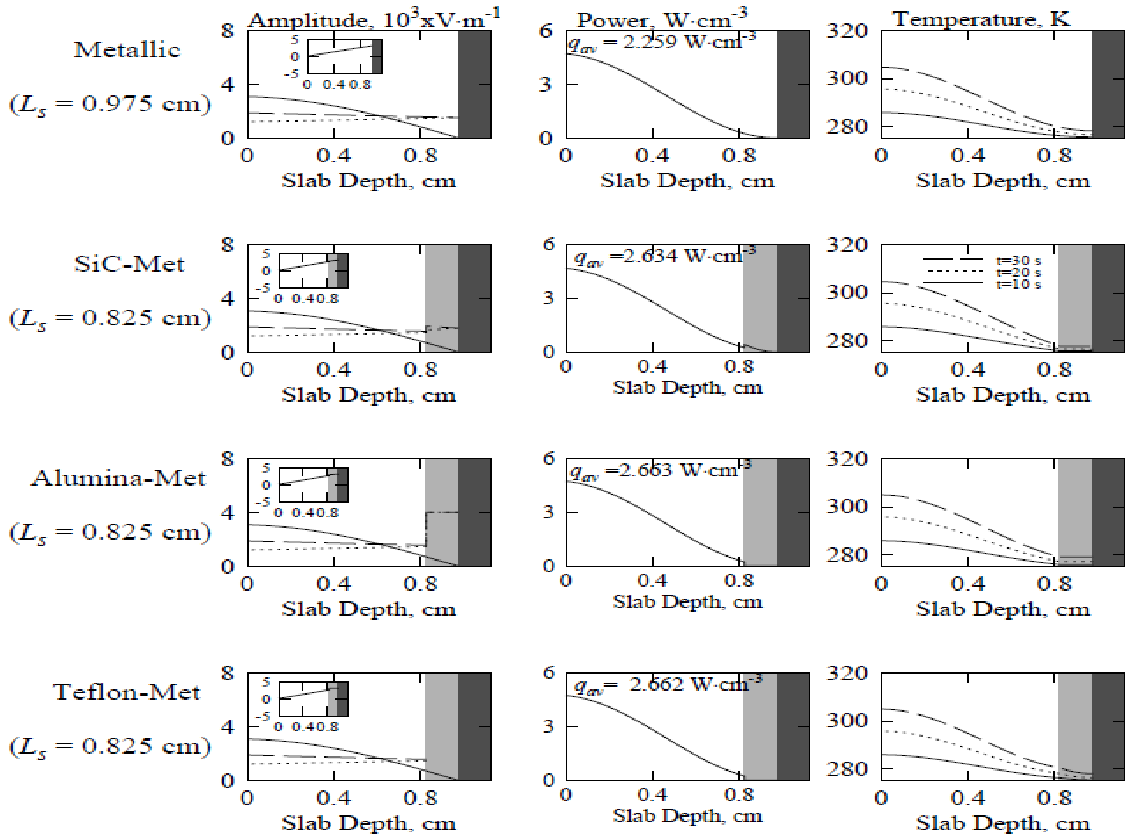

Figure 3: Spatial Distributions of Amplitudes of Electric Field, Power and Temperature for Blood Samples Placed on Metallic, SiC-Metallic, Alumina-Metallic and Teflon-Metallic Supports during R1 Mode at support thickness 1.5 mm and intensity 2.5Wcm^{-2}

Fig.3 illustrates that spatial distribution of amplitudes of the electric field, power distribution and temperature profiles for human blood sample with support thickness 1.5 mm and intensity 2.5Wcm^{-2} for Metallic, SiC-Met, Alumina-Met, Teflon-Met supports, during R1 mode. The human blood Sample thickness (L_s) corresponding to R1 mode are 0.975, 0.825, 0.825 and 0.825 cm for sample with Metallic support, SiC-metallic support, Alumina-metallic support and teflon-metallic support. The insets show the differences in the phase angle vs distance within the blood sample slabs. The difference in phase angles illustrates the strength of the stationary wave and zero phase difference signifies the constructive interference, which is also termed as resonance, whereas $\pm\pi$ phase difference signifies the destructive interference. The amplitude of the transmitted wave is a decreasing function of distance, whereas the amplitude of the reflected wave is an increasing function of distance within the blood sample for all the support cases.

The amplitude of the stationary wave is a decreasing function with distance within the sample slab for all the cases. It is interesting to note that, there is a significant jump in amplitude of the transmitted and reflected waves within the Alumina-Met support and there is a less significant jump in amplitude of both transmitted and reflected waves within the SiC-Met support. It may also be noted that, within the support the amplitudes of transmitted and reflected waves are almost equal.

Power distributions are seems to be qualitatively follow the stationary wave distributions within samples. It may also be observed that the magnitude of the stationary wave is quite high. In metallic support cases, only one maxima in spatial power occurs in the exposed face of the sample in all cases. Unlike the cases with metallic support, the unexposed face of the sample attached to composite support attains non-zero power absorption. It is also interesting to observe that the average power absorption with composite support is greater than that for the sample with metallic support for blood samples. Note that, the average powers (q_{av}) are 2.259, 2.634, 2.663 and 2.662 Wcm^{-3} for sample with Metallic, SiC-Met, Alumina-Met, Teflon-Met support respectively. It may also be noted that the sample thicknesses (L_s) corresponding to R1 mode are 0.975, 0.825, 0.825 and 0.825 cm respectively. As the average powers are larger and the sample thicknesses are smaller for composite support than that for metallic support, we have also calculated the effective power absorption in the sample for each case.

The spatial temperature distributions are illustrated for t= 10, 20 and 30 s as seen in Fig. 3. It is observed that, during 30 s, the temperature variation within 278.02–304.76 K for sample with metallic support , whereas that varies within 277.38–304.58 K ,278.84-304.93 K and 277.75– 304.93 K for sample with SiC-Met support, Alumina-Met support and Teflon-Met support, respectively. It is also interesting to note that, although the power absorption within the sample regime attached to the metallic support is insignificant, the spatial temperature is significantly higher within the regime due to high thermal conductivity of blood samples.

Fig.4 illustrates the spatial distributions of amplitudes of electric fields, power and temperature of human blood samples with support thickness 1.5mm and intensity 2.5mm for metallic support, Alumina-metallic support, SiC-metallic support and Teflon-metallic support during R2 mode. Unlike the cases during R1 mode where only one maxima in spatial power occurs, two maxima in spatial power are observed for all the support assemblies. Similar to previous cases, composite supports correspond to non-zero power absorption at the unexposed face of samples. It is interesting to observe that, average power absorption is enhanced with Alumina-metallic and Teflon-metallic support whereas it is reduced with metallic support compared to the case with SiC-metallic support. Note that, average powers (q_{av}) are 0.465, 0.488, 0.490 and 0.490Wcm^{-3} for sample with metallic support, SiC-metallic support, Alumina-metallic support and Teflon-metallic support, respectively, during R2 mode. Note that, the sample thicknesses (L_s) corresponding to R2 mode are 2.975, 2.825,2.825 and 2.825 cm for sample with metallic support, SiC-Metallic support, Alumina-Metallic supportand Teflon-Metallic support, respectively. Based on effective power absorption, it will be noticed that the average power is larger and the sample thickness is smaller for composite support than that of metallic support. Similar to previous cases, the spatial temperature distributions are illustrated for t = 10, 20 and 30 s as seen in Fig. 4. During 30 s, the temperature varies within 275.47–281.82 K, 275.37–281.80 K, 275.59–281.83 K and 275.42–281.83 K for blood with metallic support, SiC-metallic support, Alumina-metallic support and Teflon-metallic support, respectively. It is interesting to observe that, heating is quite uniform throughout the sample for all the support assemblies and this avoids local thermal runaway situation even at longer duration of heating time. This is in contrast for cases during R2 mode which corresponds to significant thermal runaway situation especially for samples with metallic and composite supports.

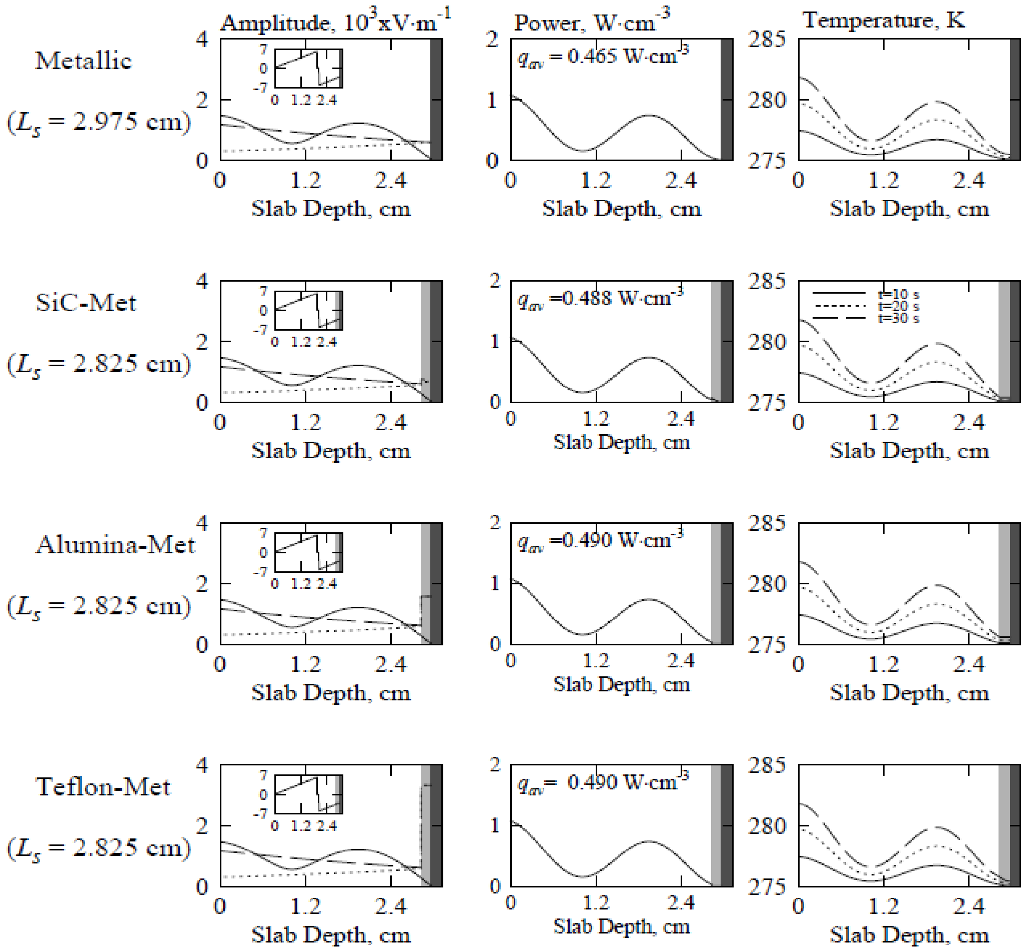

Figure 4: Spatial Distributions of Amplitudes of Electric Field, Power and Temperature for Blood Samples Placed on Metallic, SiC-Metallic, Alumina-Metallic and Teflon-Metallic Supports During R2 Mode.

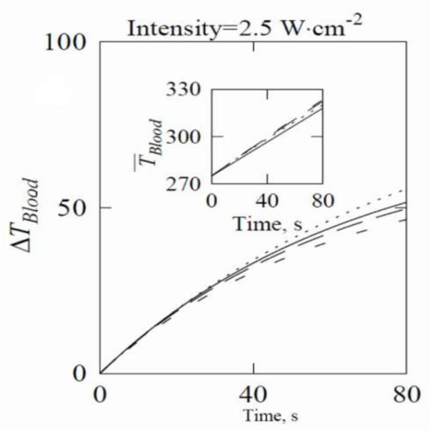

Figure 5: Average Temperature and Temperature Difference vs Time Profiles for Blood Samples Placed on Teflon-Metallic, Alumina-Metallic, SiC-Metallic, MetallicSupports exposed to Microwaves During R1 Mode.

Fig. 5 illustrates the temperature difference (ΔT_{Blood}) vs time distributions for various blood samples with metallic and composite supports during R1 mode at support thickness 1.5 mm and Intensity 2.5 Wcm^{-2}. Note that, temperature difference (ΔT_{Blood}) is defined as the difference between the maximum and minimum temperatures within the blood sample and it denotes the degree of thermal runaway. It is also observed that, thermal runaway is larger for samples with SiC-metallic supports whereas thermal runaway is slightly lesser for samples with metallic, Alumina-metallic and Teflon-metallic supports. Note that, when Intensity 2.5 Wcm^{-2}

during 80 s, ΔT_{Blood} reaches around51.60 K,49.67 K, 55.64 K and 46.41 K for samples with metallic**,** Alumina-Met, SiC-Met, Teflon-Met supports.The inset illustrates the average temperature ($\overline{T}_{Blood}$) vs time distributions for all the cases. Note that, the slope of the average temperature vs time denotes the heating rate which is directly proportional to the microwave power absorption as the heat loss to the ambiance is neglected. It is interesting to observe that, average temperature($\overline{T}_{Blood}$) increase with time for samples with metallic, Alumina-Met, Teflon-Met and SiC-Met supports. It is also observed that, samples with Teflon-metallic supports correspond to greater heating rates whereas heating rates with metallic, Alumina-Met, SiC-Met supports are quite small.Note that, for cases, average temperature ($\overline{T}_{Blood}$) reaches around 318.06 K, 322.44 K, 320.08 K and 323.48 K during 80 s when samples are processed with Metallic, Alumina-Met, SiC-Met and Teflon-Met support respectively.It may be inferred that, blood samples with SiC-metallic supports correspond to reasonably larger heating rates with lesser thermal runaway. An efficient heating strategy for the sample support assembly is characterized by higher rate of thermal processing with smaller thermal runaway. Based on the overall scenarios, SiC-metallic support may be chosen as the optimal heating strategy for blood samples.

Conclusion

These studies have been carried out for MW power absorption has been illustrated in the average power vs sample thickness diagram. The maxima in average power, also termed as 'resonances', are observed for specific blood sample thicknesses and the two consecutive resonances of significant magnitudes are termed as R1 and R2 modes. For all cases, it is observed that microwave power absorption is enhanced significantly in the presence of metallic and composite supports (Teflon-metallic, Alumina-metallic and SiC-metallic supports) during both R1 and R2 modes. The efficient heating strategies characterized by 'large heating rates' with 'minimal thermal runaway' i.e. uniform temperature distributions within the sample have been assessed for both small (during R1 mode) and large (during R2 mode) blood samples. Based on the overall scenarios, Teflon-Metallic composite support is recommended as the optimal heating strategy for 1-D blood samples corresponding to both R1 and R2 modes due to large heating rates with minimum non-uniformity in temperature distributions within blood samples.

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