Infrared Thermopile Temperature Measurement Technique in Microwave Heating Systems

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Abstract

Temperature measurement in microwave systems is essential for thermally driven processes, namely, catalytic reactions and ceramic sintering. Although, the application of direct thermometry methods, namely, thermocouples, have been commonly articulated in the available literature, however, contacted temperature measurement mechanisms have aroused concerns associated with the disruption of the electromagnetic field and local distortion of the field pattern leading to unprecedented measurement uncertainties. Consequently, the application of optical measurement methods has been advocated to diminish the associated concerns. However, due to the economic constraints and measurement range restrictions, the application of optical measurement systems, namely, pyrometers and optical fibers, has been deferred. In this study, an infrared thermopile, a precise and feasible temperature measurement system has been developed and calibrated to perform in microwave irradiation. Furthermore, the accuracy of the developed temperature system has been compared with the thermometry technique. It was concluded that thermopile stipulates unrivaled precision, succeeding a profound calibration procedure. It was further demonstrated that the thermopile is capable of the temperature measurement of the dielectric surfaces, exclusively, while the grounded thermocouple monitored the bulk temperature, a proportion of the gas phase and the solid phase temperature values. Consequently, the application of a thermopile coupled with a thermometry measurement method has been proposed to monitor the temperature of the dielectric catalyst active sites in gas-solid catalytic microwave-heated reactions.

Keywords

Microwave Heating;
Optical Measurement;
Temperature Measurement;
Thermometry;
Thermopile

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1. Introduction

The application of microwave heating method is promptly expanding in material processing and chemicals industry. In general, microwave heating technique stipulates multiple advantages over conventional heating methods, namely, uniform and volumetric heating, instantaneous temperature control, high power density, low energy consumption and process flexibility [1-6]. However, the most significant feature of the microwave heating method is the selective mechanism, whereas, electromagnetic wave interacts with a dielectric material, components with high relative permittivity, exclusively. Consequently, the microwave heating method has been distinguished for ceramic processing, gas-solid and catalytic reactions [7,8]. In microwave heating technology, the complex permittivity is the fundamental parameter to determine the thermal behavior of the material, while exposed to the electromagnetic field described as:

$$\varepsilon^* = \varepsilon' - j\varepsilon" \quad (1)$$

where ε', the real part of the equation, expressed as the *dielectric constant* represents the potential capacity of the exposed material to conserve the electric energy and $\varepsilon"$, the imaginary part of the equation, expressed as the *loss factor*, demonstrates the ability of the exposed material to dissipate microwave energy. The ratio of loss factor to dielectric constant, expressed as *loss tangent*, describes the portion of the dissipated microwave energy transformed into thermal energy in a dielectric material presented as:

$$tan\delta = \frac{\varepsilon"}{\varepsilon'} \quad (2)$$

The behavior of the material exposed to microwaves is determined and predicted according to the dielectric properties. Due to the insignificant dielectric properties, gases do not project sufficient interaction with microwaves and are regarded as transparent mediums, consequently.

The knowledge of temperature values in the microwave heated systems is crucial in chemical reactions and material processing domains. Application of microwave heating in ceramic sintering is expanding، while the proper *in-situ* temperature measurement is critical since the process is thermally driven [9,10]. Furthermore, in many chemical reactions, namely, gas-solid catalytic reactions, the reaction rate and pathway, and the development of secondary reactions are proportional to the system temperature [11]. Moreover, a distinguished temperature measurement system in multiphase reactions, namely, gas-solid catalytic reactions, is essential to determine the reaction mechanisms and the evolution of the products. However, temperature measurement in a microwave-irradiated environment is challenging. In general, *in-situ* temperature measurement methods, noncontact, namely, optical detection or blackbody irradiation, and contact, namely, electrical, mechanical and electrochemical thermometry methods, associated with the heat transfer mechanism can be extended to microwave systems, contemplating appropriate modifications. Although the application of thermocouples in microwave heating assisted processes is common, however, the presence of such a measurement device in an electromagnetic heating system could be problematic. Whereas, administering a metallic thermocouple in a microwave system may cause local distortion of the electromagnetic field, induction of thermal instabilities, conductive heat transfer from the cavity, extensive measurement errors and induction of thermal instabilities [12,13]. Consequently, in this study a novel temperature measurement system, a thermopile has been proposed for microwave heating applications. Thermopile, according to the radiation heat transfer mechanism, could measure the temperature of the solid surfaces irradiating visible light, exclusively. Moreover, the performances of the thermopile and thermocouple temperature measurement in a microwave heating assisted fluidized bed reactor have been utterly compared.

2. Fundamentals of Temperature Measurement in Microwave Systems

Although all common temperature measurement methods can be implemented in microwave-heated processes, however, thermocouples are favored due to the facilitated measurement mechanism, feedback control, and feasibility. However, effective and precise temperature measurement in a microwave environment compels the measurement device to diminish perturbation in the electromagnetic field, develop interruption by the field, disrupt the thermal distribution within the cavity or be susceptible by the cavity fluctuations in terms of geometry or emissivity shifts [14,15]. Table 1 demonstrates a concise assessment of common temperature measurement techniques exposed to microwave irradiation. Temperature measurement using a thermocouple in microwave-heated systems may exhibit one or many of the following concerns:

- *Field Enhancement:*

Independent of the sheathed or unsheathed (with a metal or ceramic) type, exposure of a thermocouple to microwave irradiation interrupts the local environment and intensifies the electromagnetic field patterns by the introduction of abrupt conduction boundaries. Consequently, the local disruption leads to massive variations in the locally absorbed power density, which is correlated with the square of the field intensity (E^2). This phenomenon significantly enhances at the tip of the thermocouple due to the charge accumulation.

- *Dielectric Breakdown:*

According to the dielectric *lens effect*, enhancement of the electric field due to the microstructural configurations in powder samples, the prospect of electrical discharges incidence at the tip of the thermocouple is inevitable. The electric discharge, regarded as the *dielectric breakdown*, supplies the emission of the electrons in the gap within the thermocouple and the workpiece, undertaking the arcing phenomenon, leading to carbon spotting. Whereas, the destructive effects of carbon spotting are demonstrated as enhanced densification at the tip of the thermocouple and cracking due to the imposed temperature gradient.

- *Ohmic Losses:*

The finite conductive metallic thermocouple sheath, regarded as a dielectric material, dissipates energy, while exposed to microwave irradiation, exhibiting undesired local heat gradient, leading to measurement uncertainties, described as the *ohmic loss*. The power loss is expressed as:

$$W_L = 0.5 R_s |J_S|^2 \quad (3)$$

where W_L is the power absorbed per unit area of the thermocouple, J_S is the current per unit depth of a conductor, and R_s is the surface resistance of the conductor termed as:

$$R_s = \pi f \mu / \sigma \quad (4)$$

Table 1. Summary of the available microwave temperature measurement methods [16-18]

	Pyrometer		Optical Fiber Thermometer		Thermocouple
	Monochromic Radiation	Two-color Radiation	Monochromic Radiation	Two-color Radiation	
Measurement Range (°C)	0 – 2800	400 – 4000	0 – 1900	500 – 1900	0 - 1600
Cost	$$ - $$$	$$$ - $$$$	$$$$		$ - $$
Accuracy	Moderate to High	High to Excellent	Excellent		Moderate
Issues	Large minimum spot size, sensitive to magnitude of sensitivity	Sensitive to slope of sensitivity	Delicate, cannot interchange readily, contamination of probe		Microwave interaction, high temperature unavailable, field perturbation, contamination of the cavity

where f is the microwave frequency, generally regarded as 2.45 GHz, and μ and σ are permittivity and conductivity of the thermocouple sheath material [19]. Deliberating a thermocouple with a stainless-steel sheath, exposed to a microwave irradiation field of 1000 V/m, the absorbed power per unit area of the sheath is estimated as <1 W/cm^2 according to Eq. 3 [20]. The ohmic loss phenomenon is significantly dominant in temperatures below 900 °C, where the emission of electrons from the metallic body is enhanced, explicitly [17].

- *Thermal Conduction*

According to the electrical conductivity, and thermal conductivity and radiation properties of the metallic thermocouples, a considerable heat flux is absorbed by the temperature measurement device. The thermal conduction is significantly enhanced if the thermal capacity of the thermocouple or sheath material is suggestively higher than the workpiece, stipulating that in a microwave heating system the heat generation is performed within the vicinity of the workpiece.

Consequently, due to the restrictions of the application of thermocouples for temperature measurement in microwave heating systems, further methods have been deployed to compensate for the thermometric (contacted) temperature measurement deficiencies.

The applications of optical temperature measurement methods, namely, fiber optic thermometers and radiation pyrometers, have been successfully reported in microwave heating systems [21-23]. In general, optical measurement methods perform an indirect temperature monitoring with the assistance of infrared blackbody irradiation emitted by the thermally processed material. Whereas, the corresponding signal is converted to temperature readings according to the calibration guidelines. Optical measurement methods require direct access to the cavity to monitor the workpiece temperature, thus, further amendments are necessary to the processing apparatus. However, the application of fiber-based systems is restricted to the maximum operating temperature associated with the structure of the fiber. Moreover, the metallic coating imposed on the tip of the optical-fiber measurement apparatus may utterly interrupt the electromagnetic field pattern and suffer from the induction of skin currents by the microwave field leading to direct heating, and contingent measurement uncertainties [24]. Furthermore, the sensitivity of the optical measurement system to the emissivity of the processing material and the transmission irradiation in the measurement path, despite the blackbody radiation detection mechanism, should be addressed by the disclosed calibration guidelines, accordingly [25; 26]. Ultimately, optical measurement methods require consistent maintenance and periodic re-calibration adjustments to sustain the optimal precision of the measurements [16]. However, the application of optical measurement techniques diminishes the destructive effects of thermometry measurement methods, namely, field enhancement, dielectric breakdown, ohmic losses, and thermal conduction. In this study, an optical temperature measurement device, an infrared thermopile, has been developed and the measurement precision has been compared with multiple thermocouple configurations.

3. Experiments

An infrared thermopile was developed to measure the temperature in microwave heating systems. Fundamentals of the thermopile temperature measurement have been thoroughly discussed in the available literature [27-29]. The thermopile measurement concept is according to optical temperature readings of the thermal irradiation emissions of solid surfaces exposed to a high-frequency electromagnetic field. Whereas, the thermopile correlates the visible light irradiations, the surface response to the thermal energy triggers, into an alternating voltage, consistent with the thermoelectric effect. Consequently, the developed signals are correlated to temperature readings with the assistant of calibration methods, to measure the thermal effects on the processing system. A microwave-heating fluidized bed setup was further developed to study the performance of the thermopile and calibrate the device for temperature measurements, demonstrated in Fig. 1. Carbon-coated silica (ρ_p=2650 kg/m^3, d_p= 212-250 μm, carbon composition = 0.25 wt% and coating thickness = 72±7 nm), developed by Hamzehlouia *et al.* was supplied as the dielectric microwave receptor and bed material, simultaneously, to provide sufficient microwave interactions (Bed properties: H_b=6 cm, D_b=2.2 cm and ε_b=0.45) [30]. To stipulate microwave irradiation, a single-mode 2.5 KW and 2.45 GHz frequency Genesys System microwave magnetron with a closed-loop water-cooling system was employed. The experiments were performed in a 20-cm height and 2.24-cm ID fused quartz tube to maintain negligible thermal interaction between the reactor and the electromagnetic waves. The developed experimental setup has been thoroughly described by Hamzehlouia *et al.*, correspondingly [8]. The dielectric properties of the experimental components have been summarized in Table 2. The C-SiO_2 receptors were the exclusive constituent that projected significant microwave interaction, accordingly.

The calibration of the thermocouple was performed in the microwave heating system, with the assistance of a K type thermocouple. First, a quartz filter was developed to minimize the wall effects corresponding to the quartz reactor, minimizing the lag associated with the temperature reading responses. Whereas, the wavelength range emitted by the quartz reactor was diminished [32]. For the calibration step, a K type thermocouple was arranged in the middle of the receptor bed, while the thermopile was aimed to the bed through the associated opening on the microwave metal shield. Next, the system was heated to the designated set point, 1000 °C, to cover the maximum processing range of the reaction system. Consequently, the microwave power was terminated and the temperature and the correlated voltage signals were recorded with the assistance of the K type thermocouple and the thermopile, accordingly. Ultimately, two mathematical correlations were developed to regulate thermopile voltage readings into the surface temperature of the solid particles. The thermopile provided temperature readings between 300 °C to 1000 °C, accordingly. The thermopile is incapable of monitoring temperatures <300 °C due to the low irradiation emissions from the dielectric surfaces and the low irradiance due to the application of the quartz filter [35].

Table 2. Dielectric Properties of the Employed Material at Ambient Temperature and 2.45 GHz Frequency

Material	Dielectric Constant (ε')	Loss Factor (ε'')	$tan\delta$
Silica Sand	3.066 [31]	0.215 [31]	0.070 [31]
Carbon	7 [32]	2 [32]	0.285 [32]
C – SiO_2	13.7*	6*	0.437*
Nitrogen	1.00058 [33]	-	-
Fused Quartz	4.0 [34]	0.001 [34]	0.00025 [34]

*Based on measurements reported in this study

The performance tests were executed in the microwave-assisted fluidized bed reactor, while nitrogen maintained with an initial superficial gas velocity of 10 cm/s at the ambient temperature as the carrier gas. In order to maintain the reactor in the bubbling fluidization regime, the nitrogen superficial velocity was constantly monitored and adjusted by a Bronkhorst F-201CV mass flow controller. Consequently, the performance of the thermopile and the K type thermocouple in the microwave environment was investigated at multiple configurations. In order to minimize the thermocouple effects, the K type thermocouple was promptly grounded to dismiss the corresponding interactions with the electromagnetic field. The experiments were attempted at the presence of the measurement devices, exclusively and simultaneously, to investigate the effect of the temperature measurement configurations. Ultimately, the effect of the operating conditions, system temperature and superficial gas velocity, at 500, 600, and 700 °C, and 3.4, 6.7 and 10 cm/s, was investigated correspondingly.

4. Results and Discussions

Thermopile calibration was performed in the absence of the carrier gas and in the cooling phase succeeding heating the bed to 1000 °C in the microwave system. Fig. 2 demonstrates the projected thermopile voltage response corresponding to the thermocouple temperature readings. It was concluded that the thermopile device was incompetent to monitor temperatures <300 °C due to the lack of irradiation emissions from the dielectric bodies. Consequently, with the application of data fitting methods, two correlations were developed to evaluate the dielectric surface temperatures according to the induced thermopile voltage expressed as:

$$T = +1359.34 - \frac{4621.04}{V} + \frac{15500.12}{V^2} - \frac{31559.36}{V^3} + \frac{39699.03}{V^4} - \frac{31869.86}{V^5} + \frac{16588.78}{V^6} - \frac{5566}{V^7} + \frac{1159.36}{V^8} - \frac{136.28}{V^9} + \frac{6.90}{V^{10}} \quad (5)$$

$$T = \left(\frac{V_n}{22 \times 10^{-13}}\right)^{\frac{1}{4.2}} \quad (6)$$

Where T is the corresponding thermopile temperature reading, V is the response voltage and V_n is the normalized response voltage, accordingly. The error temperature gradient, estimated by Eq. 5 an Eq. 6 has been exhibited in Fig. 3. It has been concluded that the average temperature gradient and standard deviation for Eq. 5 has been reported as 0.02 °C and 4.14, while the corresponding average temperature gradient and standard deviation for Eq. 6 has been calculated as -8.5 °C and 18.49. Thus Eq. 5 provides the precise prediction while Eq. 6 underestimates the temperature values, accordingly.

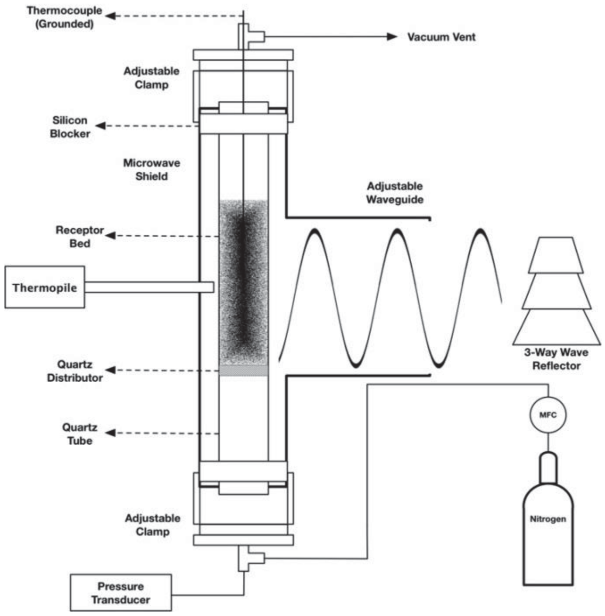

Figure 1. Schematic Diagram of the Microwave Heating-assisted Fluidized Bed Apparatus [8].

The thermopile corresponding voltage to the thermocouple temperature readings at different flow conditions of, 1) the presence of fluidizing and cooling gas, 2) the presence of fluidizing gas exclusively, 3) the presence of cooling gas exclusively, and 4) in the absence of any gas, was monitored and has been depicted in Fig. 4. It was concluded that during the fluidization state the measurements were severely affected by the movement of the particles, while in the absence of the gas, the voltage response distribution was evolved leisurely. Such an effect is associated with the difference in the optical measurement and conductive measurement concepts. While in the optical measurement, the device detects the corresponding temperature signals from emitting body surfaces, thermocouple measures an average local temperature of multiple phases, including gas and solids, while gases are considered as transparent mediums in optical measurement methods. Consequently, in the fluidization state, the thermocouple readings are associated with the gas temperature and solid temperature proportions, expressed as the bulk temperature, while the thermopile responds to the solid surface temperatures, exclusively.

Ultimately, the effect of process parameters, operating temperature, and superficial gas velocity was investigated in the thermopile and thermocouple measurements at different heights of the bed. The effect of the operating temperature on the temperature measurements has been demonstrated in Fig. 5. It was concluded that due to the appropriate particle mixing and uniform distribution of the microwave irradiation within the bed of particles the thermopile readings are utterly constant. While instantly above the distributor, due to the domination of the gas phase, the thermocouple reading values are minimized. However, the thermocouple temperature readings promptly intensify and stabilize within the bed until rigorously decline at the top of the bed, where the gas phase projected significant domination [8]. The effect of the gas superficial velocity on the thermopile and the thermocouple temperature measurement profiles within the bed has been exhibited in Fig. 6. It was demonstrated that since the thermal energy source evolves through the particles, according to the microwave irradiation principles, the thermopile readings are independent of the superficial gas velocity.

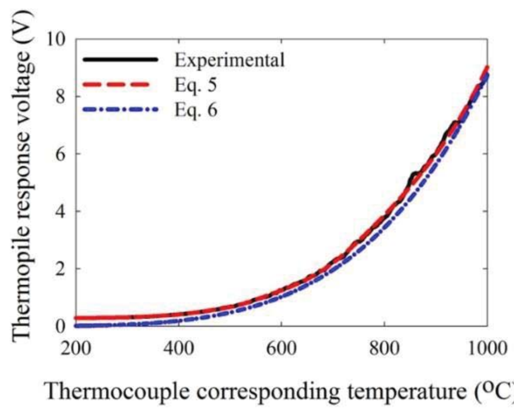

Figure 2. Thermopile calibration curves and curve fitting results associated with Eqs. 5 and 6

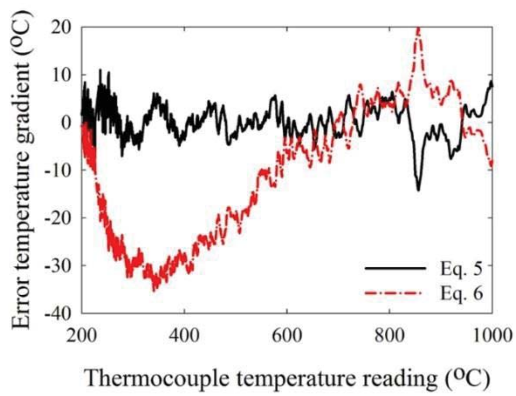

Figure 3. Predictions errors associated with the mathematically developed correlations

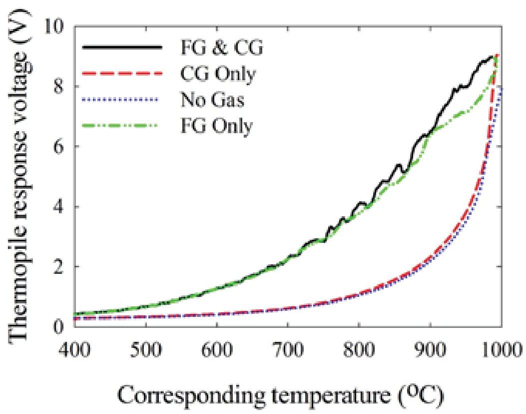

Figure 4. The effect of gas flow configurations on the temperature readings of the thermopile

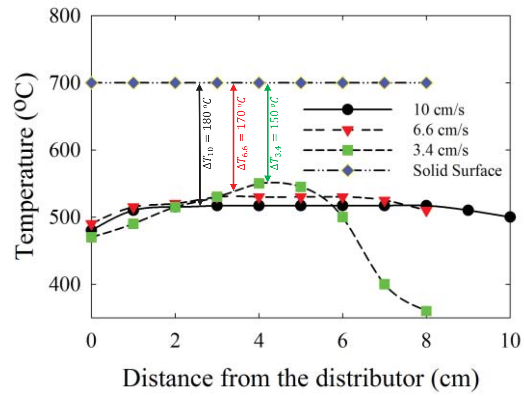

Figure 6. Effect of Superficial Gas Velocity on the Solids and Bulk Temperature Distribution in the C-SiO_2 Receptor Bed at Solid particles surface Temperature of 700 °C [8]

However, at lower superficial gas velocities, due to the declined bed height, and presence of a poor fluidization regime, the temperature profile was non-uniform, although, due to the lower volume of the gas, the solid phase was slightly dominant and the maximum bed temperature was marginally higher. Meanwhile, increasing the superficial gas velocity exhibited a significant decline in the thermocouple temperature measurements due to the increased gas volumes and domination of the gas phase and the enhancement of the convective heat transfer, correspondingly [36]. Furthermore, the results demonstrated that there is a significant temperature gradient between the solid and gas phases, associated with the high dielectric properties of the bed material and the insignificant dielectric properties the gaseous components, accordingly [7,8].

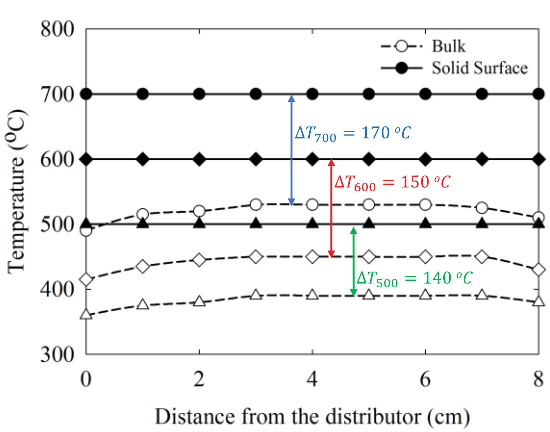

Figure 5. Effect of the Operating Temperature on the Solids and Bulk Temperature in the C-SiO_2 Receptor Bed at U_g = 6.7 cm/s [8]

5. Conclusions

A novel optical temperature measurement method, the infrared thermopile, was developed to address the deficiencies with thermocouple temperature measurements in microwave irradiation environments. The thermopile production cost is significantly lower than a traditional thermocouple, thus, is regarded as a promising feasible system. Following the accurate calibration of the corresponding thermopile voltage responses to the correlating temperatures, the thermopile demonstrated precise temperature measurement in fixed and fluidized operating states, in a microwave-heated system. Furthermore, due to the dielectric properties of receptor solids and gases, the thermopile monitored the surface temperature of the solid dielectric particles exclusively, while the thermocouple measured the bulk temperature, a proportion of the gas phase and the solid phase operating temperatures. The developed temperature gradient between the thermopile and the thermocouple temperature readings was associated with the insignificant dielectric properties of gaseous components restricting them to project substantial interaction with microwave irradiation. Furthermore, the effect of the operating parameters in the temperature gradient between the thermopile and the thermocouple readings were investigated, correspondingly. The evolution of a significant temperature gradient between the gas and solid phase, demonstrated by the thermopile and the thermocouple temperature measurements, promotes the prospect of the application of microwave heating systems for catalytic gas-solid reactions [7,8].

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Nomenclature

Symbols

d_p	Particle diameter (μm)
D_b	Bed diameter (cm)
E	Electromagnetic Field (V/m)
f	Microwave frequency (Hz)
H_b	Bed height (cm)
J_s	Current per unit depth of a conductor (Amps)
R_s	Surface resistance of the conductor (Ω)
T	System Temperature (°C)
V	Thermopile response voltage (V)
V_n	Normalized thermopile response voltage (V)
W_L	Power absorbed per unit area of the thermocouple (W)

Greek Letters

ε^*	Complex permittivity (-)
ε'	Dielectric constant (-)
ε''	Loss factor (-)
ε_b	Bed Voidage (-)
ρ_p	Particle density (kg/m^3)
μ	Permittivity (F/m)
σ	Conductivity (S/m)
$\tan\delta$	Loss tangent (-)

References

[1] Doucet, J., Laviolette, J. P., Farag, S. and Chaouki, J. (2014). “Distributed microwave pyrolysis of domestic waste.” *Waste and Biomass Valorization*, Vol. 5, No. 1, pp. 1-10.

[2] Farag, S., Sobhy, A., Akyel, C., Doucet, J. and Chaouki, J. (2012). “Temperature profile prediction within selected materials heated by microwaves at 2.45 GHz.” *Applied Thermal Engineering*, Vol. 36, pp. 360-369.

[3] Sobhy, A. and Chaouki, J. (2010). “Microwave-assisted biorefinery.” *Chemical Engineering Transactions*. Vol. 19, pp. 25-30.

[4] Farag, S. and Chaouki, J. (2015). “A modified microwave thermo-gravimetric-analyzer for kinetic purposes.” *Applied Thermal Engineering*, Vol. 75, pp. 65-72.

[5] Farag, S., Fu, D., Jessop, P. G. and Chaouki, J. (2014). “Detailed compositional analysis and structural investigation of a bio-oil from microwave pyrolysis of kraft lignin.” *Journal of Analytical and Applied Pyrolysis*, Vol. 109, pp. 249-257.

[6] Farag, S., Kouisni, L. and Chaouki, J. (2014). “Lumped approach in kinetic modeling of microwave pyrolysis of kraft lignin.” *Energy & Fuels*, Vol. 28, No. 2, pp. 1406-1417.

[7] Hamzehlouia, S., Jaffer, S. A. and Chaouki, J. (2018). “Microwave Heating-Assisted Catalytic Dry Reforming of Methane to Syngas. *Scientific reports*.” Vol. 8, No. 1, pp. 8940-8947.

[8] Hamzehlouia, S., Shabanian, J. and Latifi, M. and Chaouki, J. (2018). “Effect of microwave heating on the performance of catalytic oxidation of n-butane in a gas-solid fluidized bed reactor.” *Chemical Engineering Science*, Vol. 192, pp. 1177-1188.

[9] Katz, J. D. (1992). “Microwave sintering of ceramics. *Annual Review of Materials Science*.” Vol. 22, No. 1, pp. 153-170.

[10] Roy, R., Agrawal, D., Cheng, J. and Gedevanishvili, S. (1999). “Full sintering of powdered-metal bodies in a microwave field.” *Nature*, Vol. 399, No. 6737, pp. 668.

[11] Levenspiel, O. (1999). “Chemical reaction engineering.” *Industrial & Engineering Chemistry Research*, Vol. 38, No, 11, pp. 4140-4143.

[12] Wang, J., Binner, J., Vaidhyanathan, B., Joomun, N., Kilner, J., Dimitrakis, G. and Cross, T. E. (2006). “Evidence for the microwave effect during hybrid sintering.” *Journal of the American Ceramic Society*, Vol. 89, No. 6, pp. 1977-1984.

[13] Clark, D. E., Folz, D. C. and West, J. K. (2000). “Processing materials with microwave energy.” *Materials Science and Engineering: A*. Vol. 287, No. 2, pp. 153-158.

[14] Janney, M. A., Kimrey, H. D. and Kiggans, J. O. (1992). “Microwave processing of ceramics: Guidelines used at the Oak Ridge National Laboratory.” *MRS Online Proceedings Library Archive*, Vol. 269.

[15] Janney, M. A., Kimery, H. D., Allen, W. R. and Kiggans, J. O. (1997). "Enhanced diffusion in sapphire during microwave heating." *Journal of Materials Science*, Vol. 32, No. 5, pp. 1347-1355.

[16] Pert, E., Carmel, Y., Birnboim, A., Olorunyolemi, T., Gershon, D., Calame, J., Lloyd, I. K. and Wilson, O. C. (2001). "Temperature measurements during microwave processing: the significance of thermocouple effects." *Journal of the American Ceramic Society*, Vol. 84, No. 9, pp. 1981-1986.

[17] Dunscombe, P. B., McLellan, J., and Malaker, K. (1986). "Heat production in microwave-irradiated thermocouples." *Medical Physics*, Vol. 13, No. 4, pp. 457-461.

[18] Olmstead, W. E., and Brodwin, M. E. (1997). "A model for thermocouple sensitivity during microwave heating." *International Journal of Heat and Mass Transfer*, Vol. 40, No. 7, pp. 1559-1565.

[19] Jackson, J. D. (2012). *Classical electrodynamics*. John Wiley & Sons.

[20] Ramo, S., Whinnery, J. R., and Van Duzer, T. (2008). *Fields and waves in communication electronics*. John Wiley & Sons.

[21] Meek, T. T., Park, S. S., Nehls, M. A. and Kim, C. W. (1989). "Temperature Measurement for Microwave Processing of Advanced Ceramics." *MRS Online Proceedings Library Archive*, Vol. 155. pp. 267-274.

[22] Kappe, C. O. (2013). "How to measure reaction temperature in microwave-heated transformations." *Chemical Society Reviews*, Vol. 42, No. 12, pp. 4977-4990.

[23] Cuccurullo, G., Berardi, P. G., Carfagna, R. and Pierro, V. (2002). "IR temperature measurements in microwave heating." *Infrared Physics & Technology*, Vol. 43, No. 3-5, pp. 145-150.

[24] Matthew Gerbo, N., Boldor, D. and Mirela Sabliov, C. (2007). "Design of a measurement system for temperature distribution in continuous-flow microwave heating of pumpable fluids using infrared imaging and fiber optic technology." *Journal of Microwave Power and Electromagnetic Energy*, Vol. 42, No. 1, pp. 55-65.

[25] Svet, D. (1979). "The problems of radiation pyrometry and some new possibilities of their solution." *Acta IMEKO*, Vol. 1979, pp. 55-61.

[26] Nouaoura, M., Lassabatere, L., Bertru, N., Bonnet, J. and Ismail, A. (1995). "Problems relevant to the use of optical pyrometers for substrate temperature measurements and controls in molecular beam epitaxy." *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena*, Vol. 13, No. 1, pp. 83-87.

[27] Schieferdecker, J., Quad, R., Holzenkämpfer, E. and Schulze, M. (1995). "Infrared thermopile sensors with high sensitivity and very low temperature coefficient." *Sensors and Actuators A: Physical*, Vol. 47, No. 1-3, pp. 422-427.

[28] Dehe, A., Fricke, K. and Hartnagel, H. L. (1995). "Infrared thermopile sensor based on AlGaAs—GasAs micromachining." *Sensors and Actuators A: Physical*, Vol. 47, No. 1-3, pp. 432-436.

[29] Graf, A., Arndt, M., Sauer, M. and Gerlach, G. (2007). "Review of micromachined thermopiles for infrared detection." *Measurement Science and Technology*, Vol. 18, No. 7, pp. 59-75.

[30] Hamzehlouia, S. (2017). *Development of Microwave Heating-Assisted Catalytic Reaction Process: Application for Dry Reforming of Methane Optimization* (Doctoral dissertation, École Polytechnique de Montréal). Montreal, Canada.

[31] Ma, J., Fang, M., Li, P., Zhu, B., Lu, X. and Lau, N. T. (1997). "Microwave-assisted catalytic combustion of diesel soot." *Applied Catalysis A: General*, Vol. 159, No. 1-2, pp. 211-228.

[32] Vos, B., Mosman, J., Zhang, Y., Poels, E. and Bliek, A. (2003). "Impregnated carbon as a susceptor material for low loss oxides in dielectric heating." *Journal of Materials Science*, Vol. 38 No. 1, pp. 173-182.

[33] Uhlig, H. H. and Keyes, F. G. (1933). "The dependence of the dielectric constants of gases on temperature and density." *The Journal of Chemical Physics*, Vol. 1, No. 2, pp. 155-159.

[34] Wong, W. L. E. and Gupta, M. (2007). "Development of Mg/Cu nanocomposites using microwave assisted rapid sintering." *Composites Science and Technology*, Vol. 67, No. 7-8, pp. 1541-1552.

[35] Leclerc, P., Doucet, J., and Chaouki, J. (2018). "Development of a microwave thermogravimetric analyzer and its application on polystyrene mi-

crowave pyrolysis kinetics." *Journal of Analytical and Applied Pyrolysis*, Vol. 130, 209-215.

[36] Kim, S. W., Ahn, J. Y., Kim, S. D. and Lee, D. H. (2003). "Heat transfer and bubble characteristics in a fluidized bed with immersed horizontal tube bundle." *International Journal of Heat and Mass Transfer*, Vol. 46, No. 3, pp. 399-409.