TEMPERATURE DISTRIBUTION IN MONOLITHIC CERAMIC SUBSTRATE OF SELECTIVE CATALYTIC REDUCTION SYSTEM ACTIVATED WITH MICROWAVE FOR REDUCING POLLUTANT EMISSIONS FROM COMBUSTION ENGINES OF INLAND SHIPS

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Cordierites are one of the most used ceramic composites materials in SCR applications. The thermal field evolution in cordierites placed in microwave field is studied in order to prove the sustainability of the NOx reduction technology when the high frequency of the electromagnetic field is applied to monolithic ceramic substrate from the selective catalytic reduction device. This paper intends to simulate the thermal field in cordierite and then to certify the simulation through experimental program. The samples used in research were cordierite composites materials with cylindrical shapes having the ratio diameter/height 0,78 which are similar with real ceramic substrate from SCR applications. The microwave injected power was set to 1200 W and the heating source position on cordierite material was established based on previous research in microwave heating mechanism. The simulation was developed based conduction heating laws for 350°C, 375°C, 400°C, 425°C and 450°C, taking into consideration the temperatures required by selective catalyst reduction device for reducing the nitrogen oxides. The simulation has shown that temperature distribution in the center of material presents increased values of the temperature for different exposure times of the cordierite to the microwave beam. However, even the simulation provides the same pattern models for temperature distributions on hot and cold surfaces, the surface exposed to microwave beam presents a peak of temperature and for the same location, the cold surface has a lowest point in terms of temperature. The validation of the simulation model has been done using a Muegge microwave generator containing a water-cooled magnetron that provides 6 kW net power. The temperatures on the hot and cold surfaces of the cordierite have been monitored by two infrared pyrometers Optris G5H having the range temperature from 250°C to 1650°C. The values obtained by experimental program validate the simulation model on the surface of cordierite.

Keywords: cordierite, microwave heating, pollutant emissions, NOx reduction, inland ships

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1. Introduction

The emissions from exhausting systems of the inland ships are subject of current research in order to obtain cost effective solutions for retrofitting the fleets. Besides the new technologies, i.e. Liquefied Natural Gas (LNG) engines, electrical propulsions or dual fuel applications, the selective catalytic reduction (SCR) technology represents one of the cheapest solutions for NOx reduction. However, even the SCR technology reduces up to 90% of emissions, the reduction process starts after 170°C, in the best-case scenarios when a ceramic core is used, but in most of cases the reaction temperature is set to 250°C. The heating time of the ceramic substrate causes delays in SCR functioning and the effect occurred is called Cold Start Effect (CSE). Culbertson [1] studied the effects of additional heating source on SCR performance by introducing a resistance heater with 1000 W net power for heating the exhaust gases for the transition period from CSE to normal operating regime. Due to CSE occurrence the NOx emissions are very high until the reaction temperature is reached. He obtained a significant reduction of NOx after 5 minutes of heating. Previous research has shown that microwaves can be used to preheat the ceramic substrate, in order to reduce the CSE near to zero. The microwave heating [15, 16, 17] represents a new technology applied for fast heating of materials, waste treatment and other advanced applications [15, 16, 17, 18]. However, the process is unstable for most of the dimensions and shapes of cordierites used as ceramic substrate in SCR applications [2-4]. Both unwanted phenomena characteristic to microwave heating of ceramics, thermal runaway [5] and plasma microwave, occurred and the samples have been destroyed. The thermal runaway occurs when the samples suffer local overheating due to microwave interaction with ceramic materials. The thermal field evolution can be modelled in order to improve the microwave heating mechanism and to obtain uniform heat in cordierite cylindrical shapes. Navarro [6] solved the heat equations in microwave field by taking into consideration the electric field distribution as a source term in the heat transfer equation. Navarette [7] and his collaborators also developed mathematical models for predictive approach to the microwave extraction of essential oils by including the interaction between electromagnetic energy and material. Hossan [8] obtained a mathematical model and simulation of the temperature distribution under microwave heating by computing the nonhomogeneous heat equation through separation of variables and integral transform techniques. The temperature distribution has been presented as a function of cylinder length, radius heat transfer coefficient and microwave frequency. Tamang and Aravindan [9] concluded that the temperature reached after 5 minutes increases from 191°C to 246°C for the increase in height from 38 mm to 44 mm respectively.

2. Simulation of temperature distribution

This paper intends to elaborate and validate the temperature distribution into cordierite material when a high frequency electromagnetic field is applied to samples. The developed by the interaction of the microwaves with ceramic monolith represents is given by the friction between electrical dipoles when they change their direction after the direction lines of the electromagnetic field. According to the simplified Maxwell' equations, the electrical field inside cordierite with cylinder shape is perpendicular on magnetic field. The case taken into consideration was that the microwave incident rays are propagating in the axial direction as presented in Fig. 1.

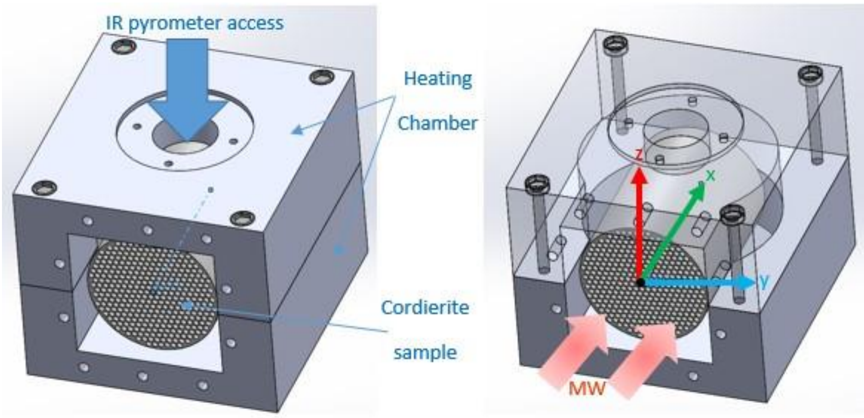


Fig. 1. Conversion mechanism of the microwaves into heat in cordierite ceramic core

The equation of the electric field can be written taking into account a uniform plane wave:

$$\frac{d^2E}{dz^2} + \chi^2 \cdot E = 0 \tag{1}$$

where E is the strength of electromagnetic field and χ represents the propagation constant that can be expressed as function of phase factor and attenuation factor [10, 11]. The dissipated power is assumed in the heat transfer equation according to heat transfer in solid materials [13].

$$\rho \cdot C_p \cdot \frac{\delta T}{\delta t} - \nabla \cdot (k\nabla T) = Q \tag{2}$$

where ρ = 2,505 g/cm^3 is the calculated density, C_p = 839-900 J/KgK is the specific heat at constant pressure and k = 3 W/mk is the thermal conductivity of the cordierite. The heat flux boundary condition is given by the following equation:

$$-n \cdot (-k\nabla T) = h \cdot (T_c - T_h) \tag{3}$$

where T_c = 250°C is the cold temperature considered to be the ambient temperature and T_h = 350 – 450°C represents the hot point on the surface of cordierite taking into consideration previous research related to thermal runaway and plasma arc discharge. The simulation of the thermal field has been done using these values for temperatures.

The sample used for simulation of the thermal field had cylindrical shape with diameter equal 250 mm and height 320 mm placed in microwave reaction chamber with overall dimensions 150 x 140 x 120 mm. The position of the sample was axially with microwave incident beam. The simulation process has been performed using thermal analysis module from SolidWorks application. The results of simulations obtained for different values of incident temperature are presented in Fig. 2.

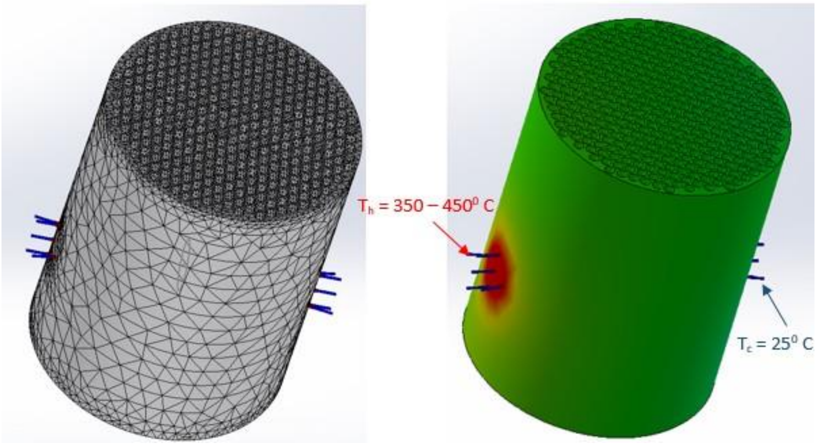
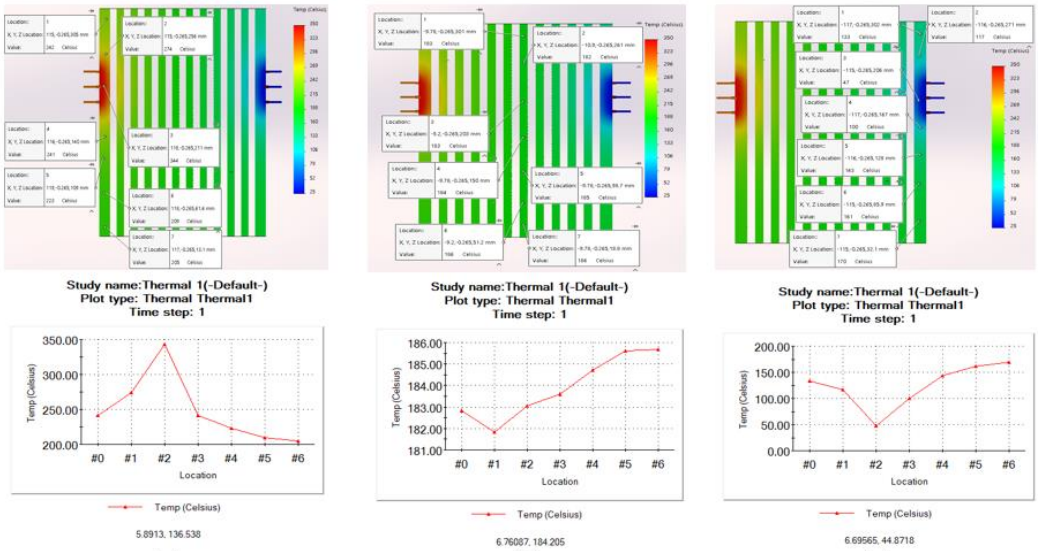


Fig. 2. Temperature distribution in cordierite cylindrical shape (left: mesh, right: simulation)

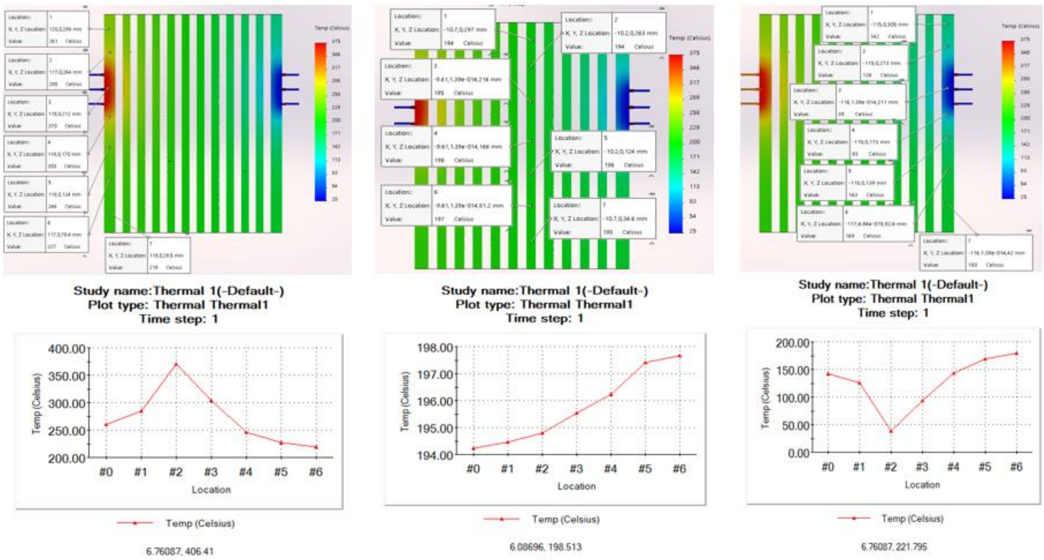
The temperature distribution inside the cylindrical sample has been determined by pointing different nodes on the surface and inside the material. The section plane has been designed through center of the cylinder in order to cover the diameter length. The results of the simulation for temperature distribution using conduction heating equations are presented in Figs. 3, 4, 5, 6 and 7.

The validation of the simulation model has been done using a microwave installation consisting of a Muegge microwave generator containing a water-cooled magnetron that provides 6 kW net power [19]. Tristan automatic tuner for matching load the impedance performed the optimization of the power transfer from magnetron to samples. The process has been monitored and controlled by Homer software.



(a) (b) (c)

Fig. 3. Simulation of temperature distribution for T_h = 350°C
(a) on hot surface, (b) in the center of cordierite, (c) on cold surface



(a) (b) (c)

Fig. 4. Simulation of temperature distribution for T_h = 375°C
(a) on hot surface, (b) in the center of cordierite, (c) on cold surface

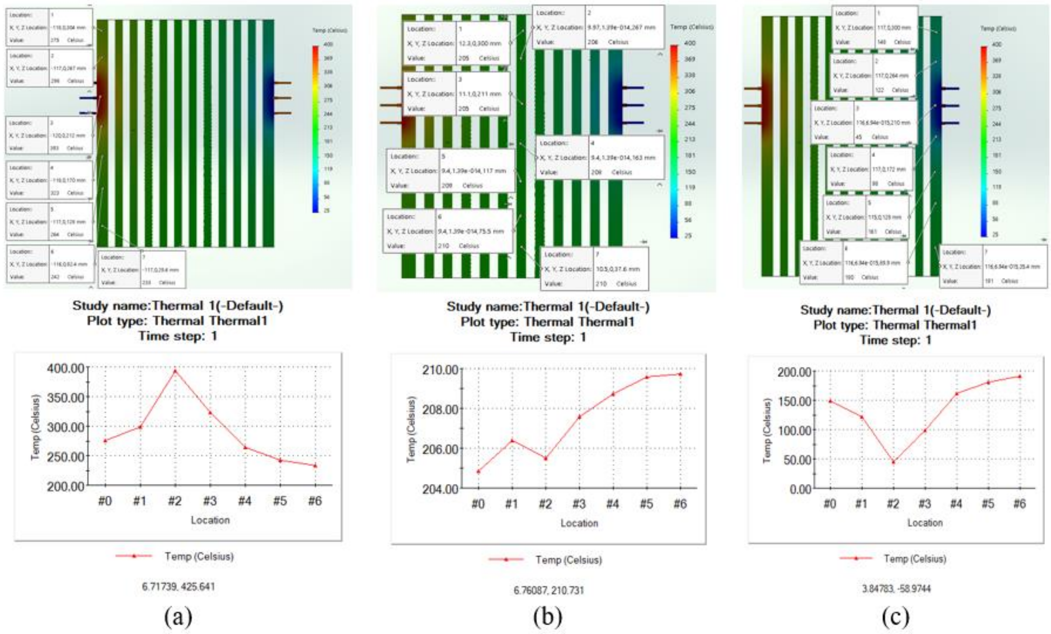


Fig. 5. Simulation of temperature distribution for T_h = 400°C
(a) on hot surface, (b) in the center of cordierite, (c) on cold surface

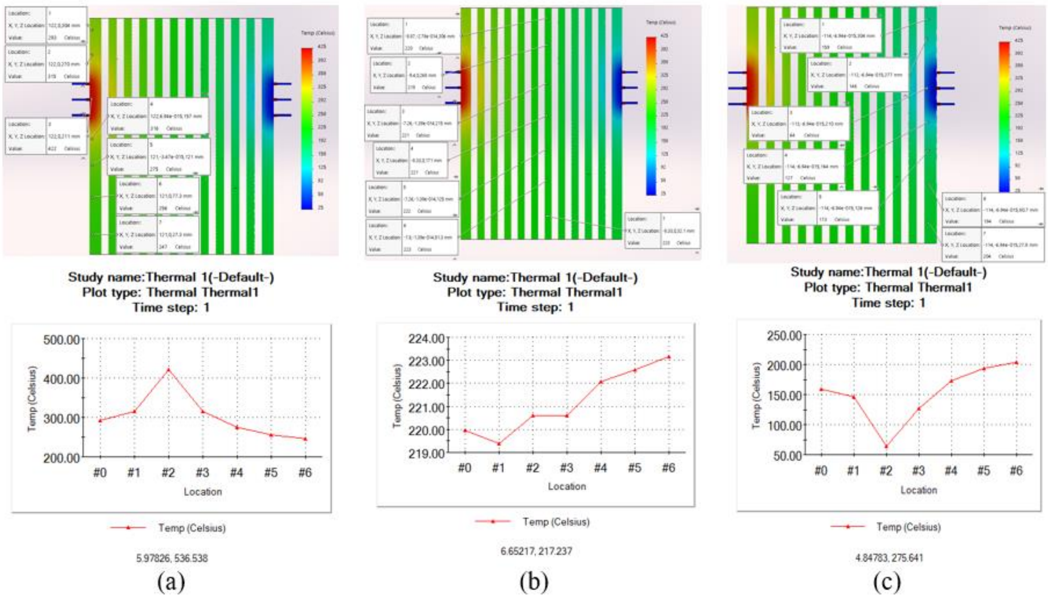
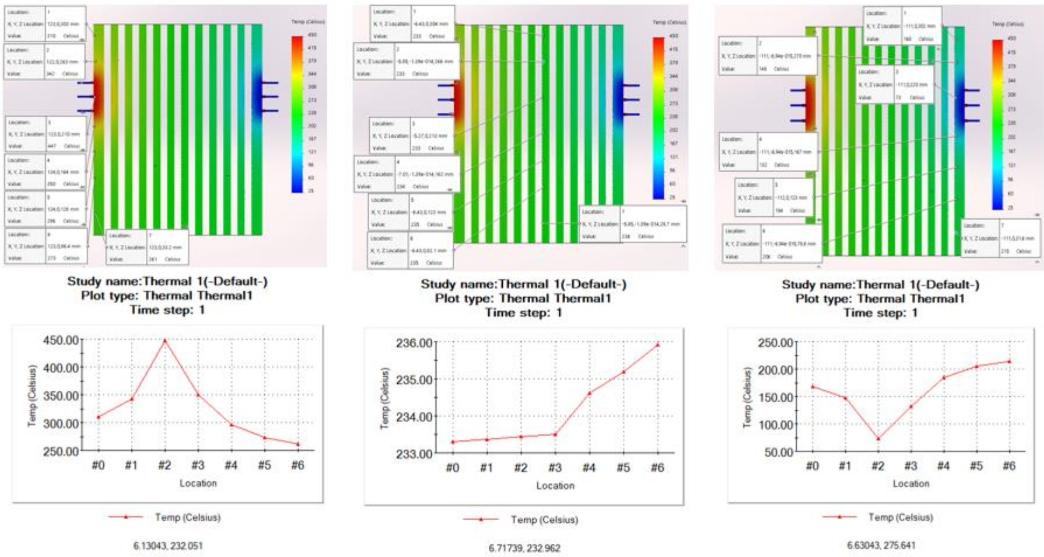


Fig. 6. Simulation of temperature distribution for T_h = 425°C
(a) on hot surface, (b) in the center of cordierite, (c) on cold surface



(a) (b) (c)

Fig. 7. Simulation of temperature distribution for T_h = 450°C
(a) on hot surface, (b) in the center of cordierite, (c) on cold surface

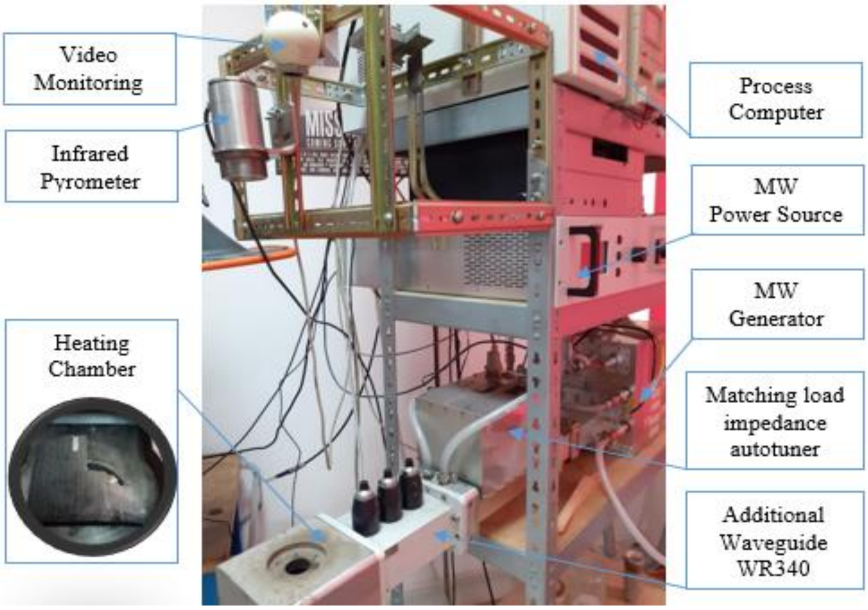


Fig. 8. The microwave heating installation

The temperatures on the hot and cold surfaces of the cordierite have been monitored by an infrared pyrometer Optris G5H having the range temperature from 250°C to 1650°C and a thermo-couple K-type with range domain between 0°C and 1300°C. The microwave installation is presented in Fig. 8.

3. Results and discussions

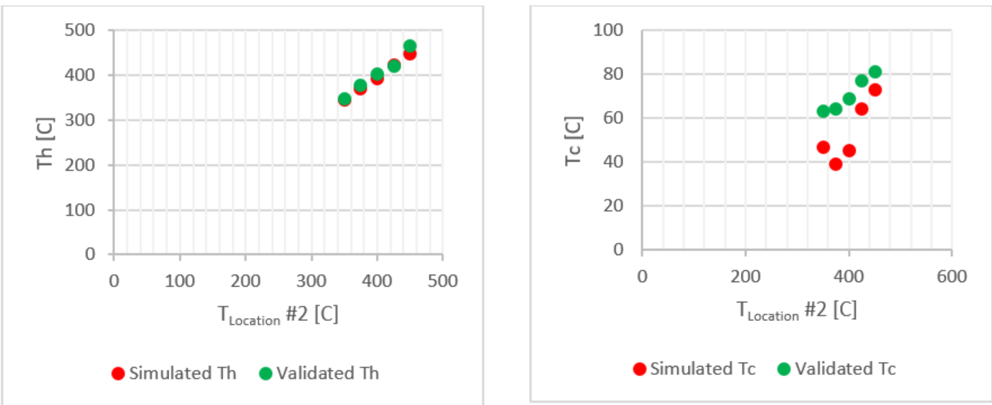
The heating process started with net power set at 1200 W and the temperatures were recorded from 350°C to 450°C in order to be compared with values provided by simulation model. The cordierite sample has been obtained from a real ceramic monolith used in selective catalyst reduction process as substrate for reactive materials. The total heating time was less than 4, 5 minutes and the results can be consulted in the table below. The location of the infrared spots were selected in order to be the same as in the simulation model.

Table 1

Temperature distribution in microwave heating of cordierite

Position	T [°C]	T_h [°C]		T_c [°C]	
		Simulated	Recorded	Simulated	Recorded
Location #2	350	344	348	47	63
	375	370	377	39	64
	400	393	402	45	69
	425	422	419	64	77
	450	447	465	73	81

According to table 1, the experimental program validates the simulation model in case of temperature distribution on the hot and cold surfaces of the cordierite sample heated in microwave field. The values of the temperatures recorded on the cold surface has suffered a small alteration as follow as the delayed measurement of the temperature provided by the thermocouple. The graph of the temperature distribution is presented in Fig. 9.



(a) (b)

Fig. 9. Temperature distribution for the simulation model validated experimentally
(a) hot surface, (b) cold surface

4. Conclusions

Temperature distribution during microwave heating of cordierite materials can be numerically simulated in order to predict the evolution of the temperatures. The simulation model has been successfully validated by the experimental program. The research has been conducted starting from a heated point on the cordierite surface where the incident ray is higher according to the Maxwell' equations. The differences between simulated and validated temperatures are small, but the model can be applied for temperatures below 600°C, due to the thermal runaway phenomenon that usually occurs at microwave heating of ceramics, after this value of the temperature [5, 14].

The evolution of the temperature inside the cordierite material could not be evaluated experimentally due to the limitations of measurement technology. The non-contact measurement sensors as IR pyrometers requires a hole in material in order to avoid any objects between pyrometer and material. On the other hand, by using a thermocouple, the values of temperatures recorded are altered by the influence of the microwaves on hot junction of the thermocouple. In addition, the presence of metallic object inside the heating chamber could lead to arc discharge due to reflection coefficient of the metallic materials.

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