Influence of convection at outer ceramic surfaces on the characterization of thermoelectric modules by impedance spectroscopy

Braulio Beltrán-Pitarch, Jorge García-Cañadas*

Department of Industrial Systems Engineering and Design, Universitat Jaume I, Campus del Riu Sec, 12071 Castellón, Spain

**E-mail: garciaj@uji.es*

Impedance spectroscopy is a useful method for the characterization of thermoelectric (TE) modules. It can determine with high accuracy the module dimensionless figure of merit (zT) as well as the average TE properties of the module thermoelements. Interpretation of impedance results require the use of a theoretical model (equivalent circuit) which provides the desired device parameters after a fitting is performed to the experimental results. Here we extend the currently available equivalent circuit, only valid for adiabatic conditions, to account for the effect of convection at the outer surface of the module ceramic plates, which is the part of the device where convection is more prominent. This is performed by solving the heat equation in the frequency domain including convection heat losses. As a result, a new element (convection resistance) appears in the developed equivalent circuit, which starts to influence at mid-low frequencies, causing a decrease of the typically observed semicircle in the impedance spectrum. If this effect is not taken into account, an underestimation of the zT occurs when measurements under room conditions are performed. The theoretical model is validated by experimental measurements performed in a commercial module with and without vacuum. Interestingly, the use of the new equivalent circuit allows the determination of the convection heat transfer coefficient (h) if the module Seebeck coefficient is known and an impedance measurement in vacuum is performed, opening up the possibility to develop TE modules as h sensors. On the other hand, if h is known, all the properties of the module (zT, ohmic (internal) resistance, average Seebeck coefficient and average thermal conductivity of the thermoelements, and thermal conductivity of the ceramics) can be obtained from one impedance measurement in vacuum and another measurement at room conditions.

Keywords: Convection heat transfer coefficient, thermoelectric module zT, frequency domain, convection resistance, impedance spectroscopy

I. INTRODUCTION

Impedance spectroscopy has been proved to be an accurate and quick method to measure the dimensionless figure of merit of thermoelectric (TE) modules.[1–7] In addition, it also allows a complete characterization of these devices if the thermal conductivity of the ceramics is given, providing the ohmic (internal) resistance, the module zT, and the average thermoelements Seebeck coefficient and thermal conductivity.[6,8,9] Interpretation of impedance results typically require the use of a theoretical model (equivalent circuit) which provides the desired device parameters after a fitting is performed to the experimental results. We have recently developed the equivalent circuit for suspended TE modules under adiabatic conditions, which consists of the ohmic module resistance connected in series with a parallel combination of two Warburg elements.[8,10] However, this equivalent circuit, since considers adiabatic conditions, does not take into account the effect of convection at the outer surface of the ceramic plates, which is the part of the device where convection is more prominent. This can significantly influence the impedance response when measurements are not performed in vacuum and provide an inaccurate module characterization.[5]

In this work, we extend the previously reported equivalent circuit to include the effect of convection at the outer surface of the ceramics. This is achieved by solving the heat equation in the frequency domain with convective heat fluxes at the ceramic boundaries. The complete analysis provides three new elements which for standard commercial TE modules can be simplified to only one, a convection resistance, which is connected in parallel to the two Warburg elements. An experimental validation of the new equivalent circuit is performed with a commercial TE module, which is measured in vacuum and at room conditions. Finally, new possibilities of the developed equivalent circuit for module and convection characterization are discussed.

II. THEORETICAL MODEL

In order to calculate the impedance function of the system a monodimensional model as shown in FIG 1 is considered. This model consists of a TE material of cross-sectional area A and length L contacted by two ceramic contacts of similar area, simulating a TE leg inside a TE module. The thermal influence of the copper interconnects is neglected due to the high thermal conductivity of copper and their short length.[2,8] In addition, the model does not consider spreading-constriction effects of the heat flow due to the dissimilar areas between the TE elements and the ceramics.[11] On the other hand, due to the small ac amplitude used in the impedance measurements and the high electrical conductivity of the TE materials the Joule effect is neglected. Finally, the TE properties are considered independent on temperature T and the system is considered adiabatic, except at the outer surfaces of the ceramics, where the convection influence is evaluated. It should be noted that this model only considers a single TE leg, so the final impedance response should be multiplied by the number of legs of the TE module ($2N$, being N the number of couples).

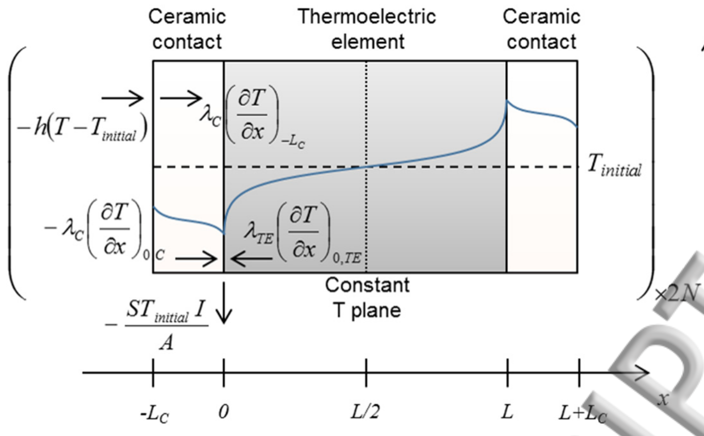

FIG 1. Thermal model employed in the theoretical analysis. A positive value of both the current and the Seebeck coefficient is considered. The arrows indicate the direction of the heat fluxes appearing at the boundaries. For the Peltier heat, the arrows point out of the junction when the electrons absorb heat from the lattice. The solid line depicts qualitatively a possible thermal profile. The dotted line shows the plane where the temperature remains constant at any time and the dashed line indicates the initial temperature.

The impedance function $Z=V/I$ of a TE module under the above considerations is given by,

$$Z=\frac{V(0)-V(L)}{I_0}=R_\Omega+2N\frac{|S|\left[T(L)-T(0)\right]}{I_0}=R_\Omega-2N\frac{2|S|\left[T(0)-T_{initial}\right]}{I_0}, \quad (1)$$

where $V(0)$ and $V(L)$ are the voltages at x=0 and x=L, respectively, I_0 is the electrical current flowing through the device at x=0, R_Ω is the total ohmic resistance, which includes the contribution of all the TE legs, the copper interconnects, the wires, and the contact resistances, S is the average Seebeck coefficient of each thermoelement, and $T(0)$ and $T(L)$ are the temperatures at $x=0$ and $x=L$, respectively. It should be noted in Equation (1) that due to the symmetry of the system with respect to the constant temperature plane (see FIG 1), the temperature difference across the thermoelement can be determined from the temperature value at x=0.

To determine the variation with frequency of $T(0)$, the heat equation of the system in the frequency domain must be solved,[8]

$$\frac{\partial^2\theta}{\partial x^2}-\frac{j\omega}{\alpha_i}\theta=0, \quad (2)$$

where θ is the Laplace transform of the temperature with respect to the initial temperature ($\theta=L[T-T_{initial}]$), j is the imaginary number, ω is the angular frequency (defined as $\omega=2\pi f$, where f is the frequency) and α_i is the thermal diffusivity of the TE leg ($i=TE$) or the ceramic ($i=C$).

The solution of Equation (2) and its derivative is given by,

$$\theta = C_{1,i} \sinh\left[\frac{x}{L_i}\left(\frac{j\omega}{\omega_i}\right)^{0.5}\right] + C_{2,i} \cosh\left[\frac{x}{L_i}\left(\frac{j\omega}{\omega_i}\right)^{0.5}\right] \tag{3}$$

$$\frac{\partial\theta}{\partial x} = \frac{1}{L_i}\left(\frac{j\omega}{\omega_i}\right)^{0.5}\left\{C_{1,i} \cosh\left[\frac{x}{L_i}\left(\frac{j\omega}{\omega_i}\right)^{0.5}\right] + C_{2,i} \sinh\left[\frac{x}{L_i}\left(\frac{j\omega}{\omega_i}\right)^{0.5}\right]\right\}, \tag{4}$$

where L_i is the half the length of the thermoelement ($i=TE$) or the thickness of the ceramic contact ($i=C$), ω_i is the characteristic angular frequency of each material (being $\omega_i=\alpha_i/L_i^2$), and $C_{1,i}$ and $C_{2,i}$ are constants.

From the thermal model in FIG 1, four boundary conditions can be formulated,

$$\theta(L/2,\omega) = 0 \text{, at } x=L/2 \tag{5}$$

$$-\frac{ST_{initial}i_0}{A} - \lambda_C\left(\frac{\partial\theta}{\partial x}\right)_{0,C} + \lambda_{TE}\left(\frac{\partial\theta}{\partial x}\right)_{0,TE} = 0 \text{, at } x=0 \tag{6}$$

$$-\frac{h}{\eta}\theta(-L_C) + \lambda_C\left(\frac{\partial\theta}{\partial x}\right)_{-L_C} = 0 \text{, at } x=-L_C \tag{7}$$

$$\theta(0)_{TE} = \theta(0)_C \text{, at } x=0 \tag{8}$$

where i_0 is the Laplace transform of the current at x=0 ($i_0=L[I_0]$), h the convection heat transfer coefficient, η the TE module filling factor, which is given by the ratio of the total area of the TE legs (2NA) to the total area of the ceramic plate, λ_C the thermal conductivity of the ceramic, and λ_{TE} the average thermal conductivity for each thermoelement. Equation (5) defines the constant temperature at the half-length plane due to the symmetry of the system. Equations (6) and (7) show the energy balance at x=0 and $x=-L_C$, respectively, where the convective heat flow is included in the latter. It should be noticed that the filling factor in this equation accounts for the convection produced in the area of the ceramic which differs from the area of the TE legs (2NA). In commercial modules η can take values around 0.3, which represents a significant part of the ceramic outer surface where convection occurs which should be taken into account. Finally, Equation (8) shows the temperature continuity at the contacts,

Using these boundary conditions and Equations (3) and (4), $\theta(0)$ can be determined,

$$\theta(0)=\frac{-ST_{initial}i_0}{A}\left\{\frac{\lambda_{TE}}{(L/2)}\left(\frac{j\omega}{\omega_{TE}}\right)^{0.5}\coth\left[\left(\frac{j\omega}{\omega_{TE}}\right)^{0.5}\right]+\frac{\frac{\lambda_C}{L_C}\left(\frac{j\omega}{\omega_C}\right)^{0.5}\cosh\left[\left(\frac{j\omega}{\omega_C}\right)^{0.5}\right]+\frac{\lambda_C^2}{hL_C^2}\left(\frac{j\omega}{\omega_C}\right)^{0.5}\sinh\left[\left(\frac{j\omega}{\omega_C}\right)^{0.5}\right]}{\sinh\left[\left(\frac{j\omega}{\omega_C}\right)^{0.5}\right]+\frac{\lambda_C}{hL_C}\left(\frac{j\omega}{\omega_C}\right)^{0.5}\cosh\left[\left(\frac{j\omega}{\omega_C}\right)^{0.5}\right]}\right\}^{-1} \tag{9}$$

As shown in Equation (1), the impedance function in the frequency domain can be obtained once $\theta(0)$ is known,

$$Z=R_\Omega+\left\{Z_{WCT}{}^{-1}+\left[\left(Z_{Wa}{}^{-1}+R_{Conv}{}^{-1}\right)^{-1}+\left(Z_{WCT,C}{}^{-1}+Z_{C_{Conv}}{}^{-1}\right)^{-1}\right]^{-1}\right\}^{-1}, \tag{10}$$

where the different elements in Equation (10) are defined as,

$$Z_{WCT}=\frac{2NS^2T_{initial}L}{\lambda_{TE}A}\left(\frac{j\omega}{\omega_{TE}}\right)^{-0.5}\tanh\left[\left(\frac{j\omega}{\omega_{TE}}\right)^{0.5}\right] \tag{11}$$

$$Z_{Wa}=\frac{4NS^2T_{initial}L_C}{\lambda_C A}\left(\frac{j\omega}{\omega_C}\right)^{-0.5}\coth\left[\left(\frac{j\omega}{\omega_C}\right)^{0.5}\right] \tag{12}$$

$$R_{Conv}=\frac{4NS^2T_{initial}\eta}{hA} \tag{13}$$

$$Z_{WCT,C}=\frac{4NS^2T_{initial}L_C}{\lambda_C A}\left(\frac{j\omega}{\omega_C}\right)^{-0.5}\tanh\left[\left(\frac{j\omega}{\omega_C}\right)^{0.5}\right] \tag{14}$$

$$Z_{C_{Conv}}=\frac{4NS^2T_{initial}L_C{}^2h}{\lambda_C{}^2A\eta}\left(\frac{j\omega}{\omega_C}\right)^{-1}. \tag{15}$$

The equivalent circuit corresponding to Equation (10) is show in FIG 2a. This equivalent circuit includes three new elements in addition to the R_Ω, the constant-temperature Warburg (Z_{WCT}) and the adiabatic Warburg (Z_{Wa}), which form the previously reported equivalent circuit which discarded convection effects.[8,10] The first new element, given in Equation (13), is defined as a convection resistance R_{Conv} and can be represented by a resistor, since it takes a constant value and shows no dependency on frequency. It can be seen that R_{conv} depends neither on the thermal properties of the thermoelectric material nor the ceramic, but it is influenced by the convection heat transfer coefficient. The physical meaning of R_{conv} is related to the loss of heat energy from the ceramic produced by convection. These losses reduce the heat accumulation in this material and hence the temperature increase at the junction. The second element $Z_{WCT,C}$, defined in Equation (14), takes the form of a constant-temperature Warburg[8] but with all its parameters corresponding to the ceramic material and multiplied by two, since two ceramic layers are present. The last new element C_{Conv}, given in Equation (15), shows the typical relationship with frequency of a capacitor ($Z_{Cconv}=(j\omega C_{conv})^{-1}$, being $C_{conv}=(\lambda_C{}^2 A)/(4NS^2 T_{initial} L_C{}^2 h\omega_C)$) and it is defined as a convection capacitance. It should be noted that when the convection effect does not take place (h=0) Z_{Cconv}=0, which creates a short circuit replacing the capacitor in FIG 2a, making irrelevant the presence of $Z_{WCT,C}$. On the other hand, R_{conv} becomes infinite and consequently the equivalent circuit in FIG 2a reduces to the parallel combination of Z_{WCT} and Z_{Wa} in series with R_Ω, which is the previously reported equivalent circuit with no influence of convection.[8]

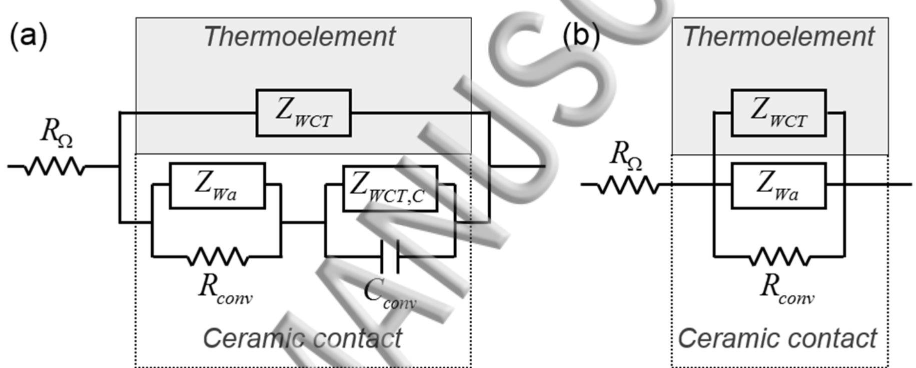

FIG 2. (a) Equivalent circuit obtained when convection effects are considered at the outer surface of the ceramics in a thermoelectric module. (b) Simplified equivalent circuit for standard commercial thermoelectric modules. The equivalent circuit elements framed in the dotted line are related to the ceramic plates. The ones framed by the solid line in grey correspond to the thermoelement.

If the opposite case is considered, i.e. a huge convection ($h\rightarrow\infty$) at the outer surface of the ceramics occurs, $R_{conv}\rightarrow 0$ and $Z_{Cconv}\rightarrow\infty$, thus, the equivalent circuit in FIG 2a reduces to the parallel combination of $Z_{WCT,C}$ with Z_{WCT}, connected in series with R_Ω. In this case, the $Z_{WCT,C}$ element represents the diffusion of heat within the ceramic from the junction, which is completely removed by the effect of the convection when it reaches the outer surface of the ceramic, producing no temperature change at this surface (constant-temperature boundary).[10]

For the case of TE modules with ceramic plates ($\lambda_C\approx$35 WK^{-1}m^{-1}) and conditions where the convection heat transfer coefficient is approximately h<500 WK^{-1}m^{-2}, Equation (10) can be simplified as,

$$Z = R_\Omega + \left(Z_{WCT}{}^{-1} + Z_{Wa}{}^{-1} + R_{Conv}{}^{-1}\right)^{-1}, \tag{16}$$

since the impedance of the parallel combination of $Z_{WCT,C}$ and C_{Conv} is much lower than the impedance of the parallel combination of Z_{Wa} and R_{Conv}. The equivalent circuit obtained from Equation (16) can be seen in FIG 2b. In any case, it should be taken into account that this approximation is not valid if the convection heat transfer coefficient takes significantly higher values, or the TE module is formed by electrically insulating plates of thermal conductivity significantly lower than typical values of ceramics (e.g. polymers where $\lambda \approx 0.2$ WK^{-1}m^{-1}), although this is not usually the case.

Some simulations of the equivalent circuit elements from FIG 2b were performed to understand the effect of convection in the impedance spectra, which are shown in FIG. 3a. As described in our previous article,[10] Z_{Wa} would be obtained in the impedance spectrum in the hypothetical case where there conduction of heat towards the TE elements is not produced (λ_{TE}=0) and convection effects are neglected. In this case, all the Peltier heat diffuses from the junction towards the outer surface of the ceramic (slope 1 line from Z_{Wa} in the higher magnification inset of FIG. 3a). Then, once the heat reaches the outer surface, it is accumulated in the ceramic, since it cannot escape due to the adiabatic conditions, producing the capacitive (vertical line) feature in the impedance response. However, when convection effects are considered, part of the heat reaching the outer surface can escape by convection, and the impedance response induced by the ceramic layers is now given by the parallel combination of Z_{Wa} and R_{conv}, which produces the closing of the vertical line at mid-low frequencies, as shown by the green line from FIG. 3a. The effect of convection is not sensed at high frequencies (see FIG. 3a), since for the convection to occur it is required that the heat reaches the outer surface of the ceramics and also certain temperature increase in this material, which does not take place at high frequencies. For this reason the Z_{Wa} element and the parallel combination of Z_{Wa} and R_{conv} provide the same impedance response at mid-high frequencies (see the overlap in the insets of FIG. 3a).

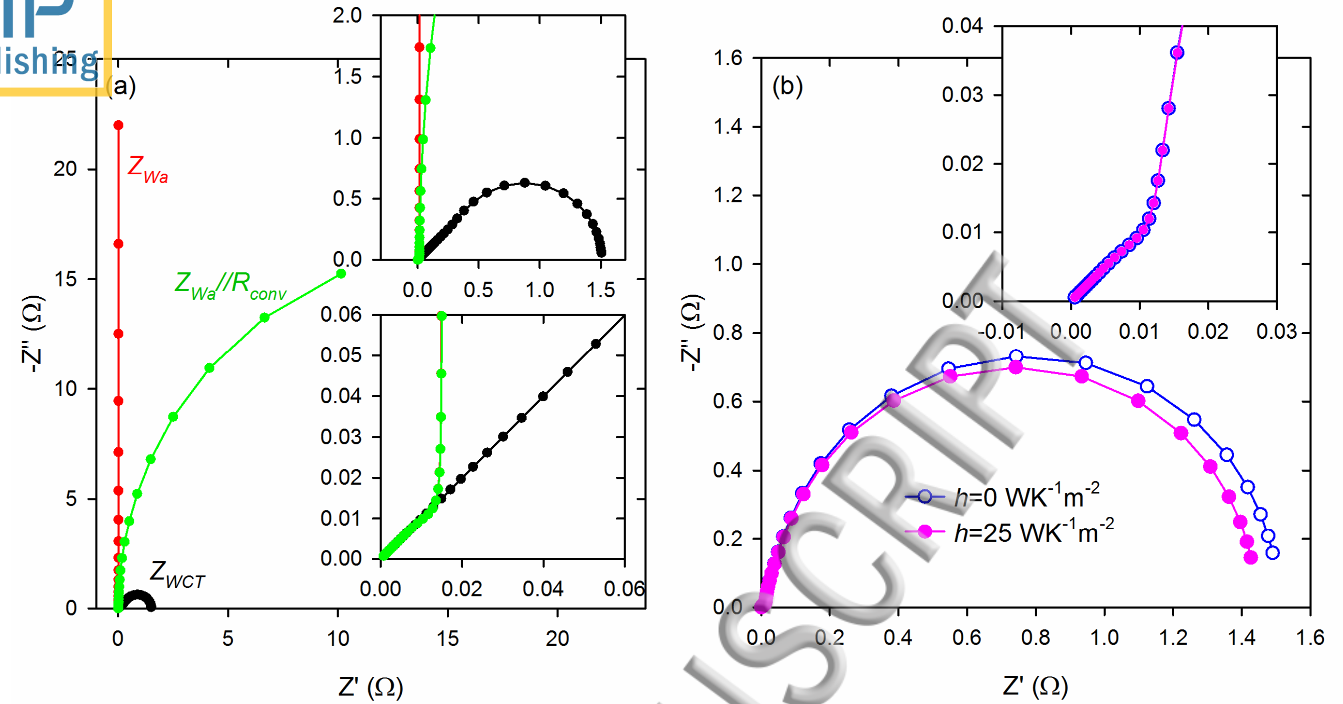

FIG. 3. (a) Impedance simulations in the 10 mHz to 10 kHz frequency range of the equivalent circuit elements Z_{Wa} (red), Z_{WCT} (black) and the parallel combination of Z_{Wa} and R_{conv} (green). The plots in the inset show magnifications at medium and high frequencies. Simulations in (b) represent the complete equivalent circuit for a thermoelectric module (FIG 2b) under high vacuum (h=0 WK^{-1}m^{-2}) and room (h≈25 WK^{-1}m^{-2}) conditions. R_Ω=0 is considered for simplicity and typical values for commercial thermoelectric modules were used (S=190 µVK^{-1}, λ_{TE}=1.5 WK^{-1}m^{-1}, α_{TE}=0.37 mm^{2}s^{-1}, L=1.6 mm, λ_C=35 WK^{-1}m^{-1}, α_C=10 mm^{2}s^{-1}, L_C=0.6 mm, N=127, A=1.94 mm^2, $T_{initial}$=294.7 K, η=0.3).

FIG. 3b shows the total impedance response (equivalent circuit in FIG 2b) for the cases of high vacuum (h=0 WK^{-1}m^{-2}) and room conditions (h=50 WK^{-1}m^{-2}).[12] As previously discussed, the convection effect does not make any influence at high frequencies, thus, the impedance response only differ at mid-low frequencies, as observed in FIG. 3b. It can be also observed from FIG. 3b that the main difference in the impedance response produced by the convection is a reduction of the semicircle. This reduction can be quantified by the dc (steady state) limit (ω→0), which is given by $R_\Omega+(R_{TE}^{-1}+R_{conv}^{-1})^{-1}$, being $R_{TE}=2NS^2T_{initial}L/(\lambda_{TE}A)$, and becomes reduced with respect to the high vacuum (adiabatic) case ($R_\Omega+R_{TE}$) by the presence of R_{conv}. It should be noticed that if the module $zT=R_{TE}/R_\Omega$ is calculated by impedance spectroscopy[6,13] at room conditions by considering R_{TE} as the difference between the low and high frequency intercepts of the spectrum with the real impedance axis, or using the adiabatic equivalent circuit (R_{conv}=0), a lower value of R_{TE} will be obtained as shown in FIG. 3b, consequently producing an underestimation of the zT.

III. EXPERIMENTAL VALIDATION

In order to validate the new equivalent circuit (FIG 2b), impedance measurements were performed to a 40 mm x 40 mm commercial TE module from Interm (Ref. TECB1-1, power generation) formed by 127 couples with 1.4 mm x 1.4 mm x 1.64 mm legs and 0.57 mm of ceramic thickness. Two different measurements were performed to the module under suspended conditions in a vertical position. A first measurement was carried out at room conditions (ambient pressure) and a second one under high vacuum ($3.4x10^{-5}$ mbar) in order to completely remove convection losses. These impedance measurements were performed using a PGSTAT30 potentiostat equipped with a FRA2 impedance module (Metrohm Autolab B. V.) at 0 A dc current and 40 mA ac current amplitude, employing a frequency range from 10 mHz to 10 kHz. All the measurements were performed inside a vacuum chamber and at the same ambient temperature of 21.2 ºC.

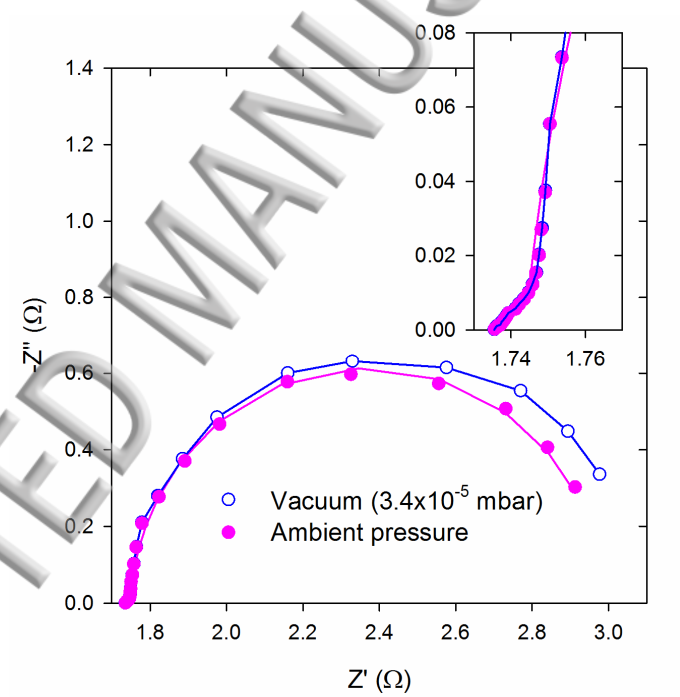

FIG. 4. Experimental impedance spectra of a suspended commercial thermoelectric module at room (ambient pressure) and high vacuum conditions (dots) and their corresponding fittings to the equivalent circuit of FIG 2b (lines). The convection resistance was not considered for the vacuum case (h≈0 $WK^{-1}m^{-2}$). The quantity of 13.8 mΩ was subtracted to the real impedance part of the vacuum measurement in order to match the ohmic resistances (R_{Ω}) and obtain a clearer comparison.

FIG. 4 shows the experimental measurements and their corresponding fitting to the equivalent circuit of FIG 2b. Zview software was used to perform the fittings. It can be observed that the results obtained are quite similar to the simulations performed using the theoretical model (FIG. 3b). As expected from the above theoretical analysis, both measurements overlap at the highest frequencies (inset of FIG. 4) and the differences due to the effect of convection appear at the mid-low frequencies.

Since $h \approx 0$ WK^{-1}m^{-2} for the measurement under high vacuum, the fitting to this result was performed considering R_{conv}=0, which allows obtaining R_Ω, R_{TE}, ω_{TE}, R_C ($R_C=4NS^2T_{initial}L_C/(\lambda_C A)$), and ω_C, whose values are shown in Table I. The resistances R_{TE} and R_C depend on the properties of the materials, which do not change with the pressure of the environment. These two resistances were fixed when the fitting was performed to the high vacuum measurement, otherwise the fitting is not possible and very high errors will be obtained. All the fitting results are shown in Table I. As it can be seen from Equation (13), h can be obtained from R_{conv} if the average Seebeck coefficient of the module is known. In order to determine the value of h in this way, the Seebeck coefficient of the module was measured from an open-circuit voltage vs. temperature difference curve, obtaining a value of 192.14 µVK^{-1} (see Table I). Using this value of S, a convection heat transfer coefficient h=40.12 WK^{-1}m^{-2} was obtained, which although somewhat higher than the typical values for natural convection at ambient pressure (2-25 WK^{-1}m^{-2} [12]) it is not very far and in the same order of magnitude.

TABLE I. Fitting parameters obtained from the fittings to the experimental measurements in FIG. 4 of a commercial thermoelectric module under high vacuum and ambient pressure conditions (no vacuum). The errors provided from the fitting are given in brackets. The Seebeck coefficient was experimentally obtained and the convection heat transfer coefficient calculated from the no vacuum fitting result.

	R_Ω (Ω)	R_{TE} (Ω)	ω_{TE} (rads^{-1})	R_C (Ω)	ω_C (rads^{-1})	R_{Conv} (Ω)	S (µVK^{-1})	h (WK^{-1}m^{-2})
Vacuum	1.75 (0.09%)	1.33 (0.37%)	0.33 (10.3%)	0.036 (25.9%)	11.72 (26.7%)	---	192.14	---
No vacuum	1.74 (0.06%)	---	0.32 (9.5%)	---	11.66 (3.0%)	21.75 (6.1%)	---	40.12

A possible reason for the deviation observed could be attributed to convection effects that are also produced in other parts of the TE module, such as the surface at the side of the ceramics where the thermoelements are attached that is not covered by them. It should be noted that the mentioned approach to determine h when the properties of the TE module are known can potentially offer the possibility to use TE modules as h sensors.

On the other hand, if the value of h of the measurement system is known (40.12 WK^{-1}m^{-2} in our case), the Seebeck coefficient can be obtained from the convection resistance if measurements under high vacuum (which provides R_{TE} and R_C) and at room conditions are performed. Once S is known from R_{conv} all the average properties of the TE module can be obtained (λ_{TE} from R_{TE}, R_Ω, zT, and λ_C from R_C), without the need of knowing the thermal conductivity of the ceramic plates, which was a requirement in a previous approach.[6,8]

As it was mentioned above, if the measurement at room conditions had been used to determine zT, a value of R_{TE}=1.25 would have been obtained, instead of the correct value from the vacuum measurement (1.33). This provides a zT=0.718 which is 6% lower than the accurate vacuum result (0.764). Hence, in order to accurately determine zT from measurements under room conditions, the new model developed here (FIG 2b) should be employed.

IV. CONCLUSIONS

A new theoretical model (equivalent circuit) to interpret impedance spectroscopy measurements of TE modules has been developed. The new model includes convection effects at the outer surface of the module ceramic plates, which introduces three new elements (R_{Conv}, $Z_{WCT,C}$ and C_{Conv}) in the equivalent circuit. However, for standard commercial TE modules the equivalent circuit can be simplified when h<500 WK^{-1}m^{-2}, only requiring to introduce the convection resistance (R_{conv}). This new element, which depends on the convection heat transfer coefficient h, influences the mid-low frequency part of the spectrum, producing a reduction of the typically observed semicircle. The theoretical model was experimentally validated by performing impedance spectroscopy measurements under high vacuum and at room conditions (ambient pressure) to a commercial TE module. The experimental measurements were found to be in agreement with the predicted results from the theoretical model and allowed the determination of the convection heat transfer coefficient, which was in the same order of magnitude than literature values.

The determination of the convection heat transfer coefficient is possible if the module average Seebeck coefficient is known and an impedance measurement in vacuum is performed, which opens up the possibility to develop TE modules as h sensors. On the other hand, if h is known, all the properties of the TE module (zT, ohmic (internal) resistance, thermal conductivity of the ceramics, average Seebeck coefficient and average thermal conductivity of the thermoelements) can be obtained from one impedance measurement in vacuum and another measurement at room conditions. A final analysis also showed that an underestimation of the module zT of 6% can be produced if the new equivalent circuit is not employed when the characterization of the TE module is performed at room conditions.

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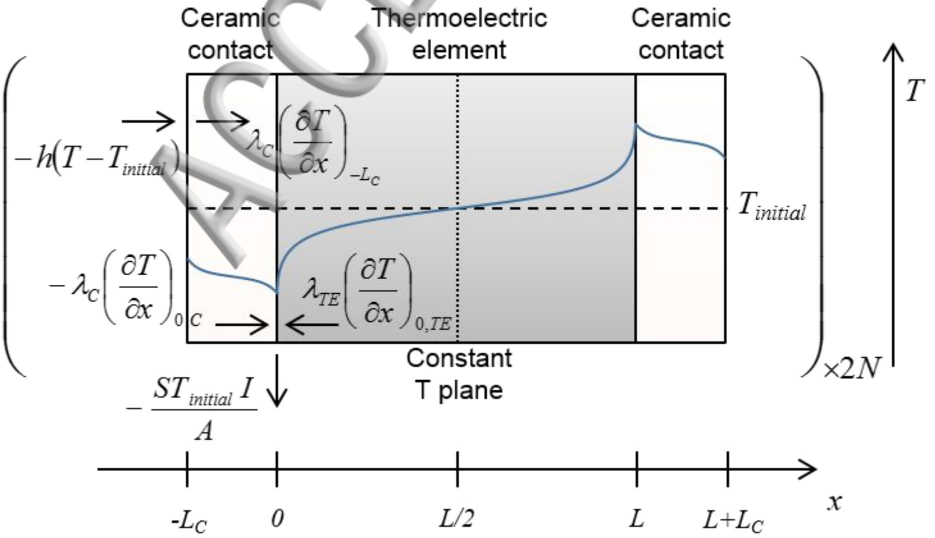
Ceramic contact
Thermoelectric element
Ceramic contact
T
$-h(T-T_{initial})$
$\lambda_C\left(\frac{\partial T}{\partial x}\right)_{-L_C}$
$T_{initial}$
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$\lambda_{TE}\left(\frac{\partial T}{\partial x}\right)_{0,TE}$
Constant T plane
$\times 2N$
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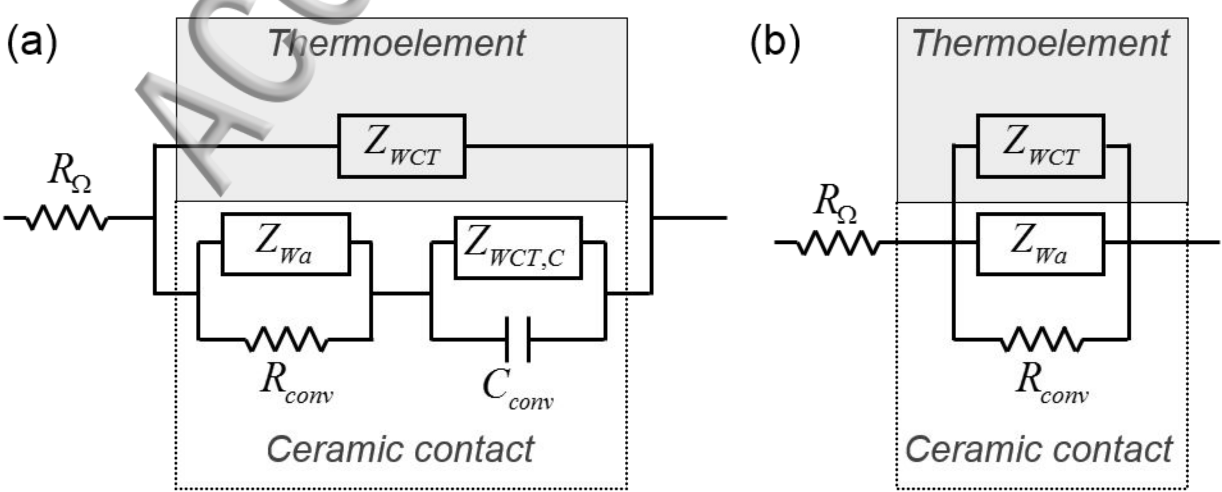
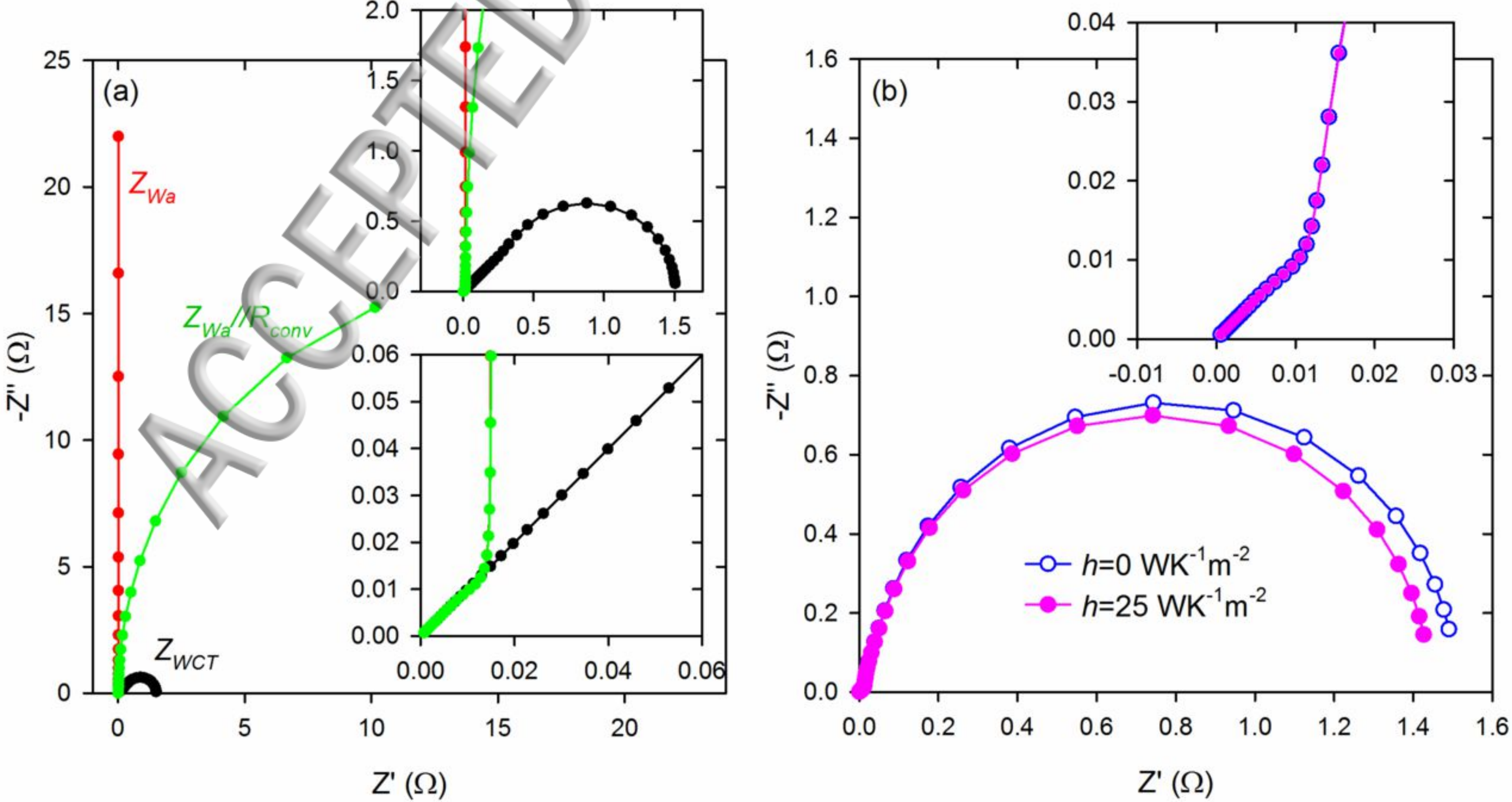
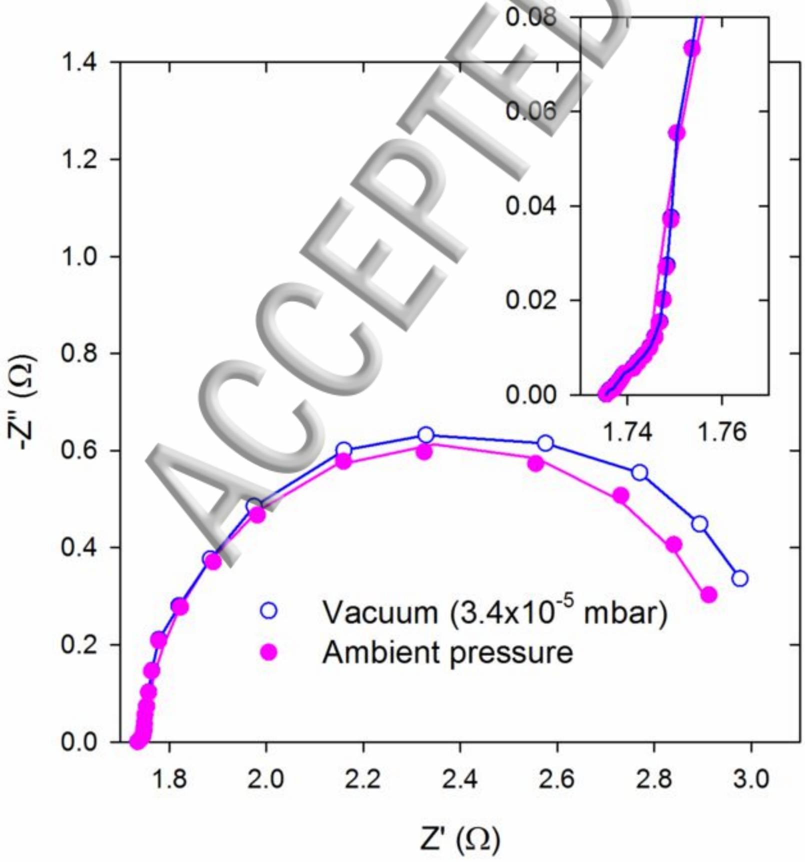

(a)
Thermoelement
R_{Ω}
Z_{WCT}
Z_{Wa}
$Z_{WCT,C}$
R_{conv}
C_{conv}
Ceramic contact
(b)
Thermoelement
R_{Ω}
Z_{WCT}
Z_{Wa}
R_{conv}
Ceramic contact



(a)
Z_{Wa}
$Z_{Wa}//R_{conv}$
Z_{WCT}
-Z'' (Ω)
Z' (Ω)
(b)
h=0 WK-1m-2
h=25 WK-1m-2
-Z'' (Ω)
Z' (Ω)



-Z'' (Ω)
Z' (Ω)
Vacuum (3.4x10^-5 mbar)
Ambient pressure
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.8
2.0
2.2
2.4
2.6
2.8
3.0
0.00
0.02
0.04
0.06
0.08
1.74
1.76