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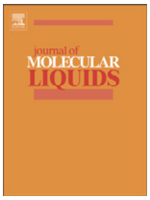

On evaluation of electric conductivity by mean of non equilibrium thermodynamic approach with internal variables. An application to human erythrocyte suspension for metabolic characterizations

Francesco Farsaci [a], Silvana Ficarra [b], Annamaria Russo [b], Antonio Galtieri [b], Ester Tellone [b],*

[a] IPCF-C.N.R., Via Ferdinando Stagno d'Alcontres 37, 98158 Faro Superiore, Messina, Italy
[b] Department of Chemical, Biological, Pharmaceutical and Environmental Sciences, University of Messina, Viale Ferdinando Stagno d'Alcontres 31, 98166 Messina, Italy

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ABSTRACT

In this paper we will approach a new method to obtain electrical conductivity by means of dielectric measurements. After a remark on non-equilibrium thermodynamics with internal variables formulated by Kluitenberg, we introduce complex conductivity and the relationship with the complex dielectric constant. Taking into account the dielectric model by us introduced we determine the real and imaginary part of conductivity as function of the frequency of perturbation. Also we determine phenomenological and state coefficients that lead to the determination of the two components in which is splitted the polarization, and to the entropy production due to electrical conductivity. These results are applied to an human erythrocyte suspension for metabolic deductions.

1. Introduction

Dielectric (and magnetic) properties of materials can be investigated by examining the interaction of an electromagnetic field with matter.

This interaction is generally governed by Maxwell's equations [1,2], to which must be added a sufficient number of equations, called constitutive equations (phenomenological and state equations), that specify some characteristic of the material in object. Many model have been formulated for this purpose but, if one consider isotropic media in the linear approximation, for the description of some material's electrodynamics properties can be considered the following equations

$$\underline{D} = \varepsilon \underline{E} \quad \underline{J} = \sigma \underline{E} \quad \underline{B} = \mu \underline{H} \tag{1}$$

where ε, σ, μ are complex dielectric constant (also called dielectric permittivity), complex conductivity and complex magnetic permittivity respectively, and the other terms of well known meaning.

In this paper we are interested only to dielectric relaxation phenomena and conductivity, and therefore complex magnetic permittivity will be neglected so to consider only the complex dielectric constant and the complex conductivity.

Indeed, complex permittivity can be written as

$$\varepsilon = \varepsilon' - i\varepsilon''$$

where ε' and ε'' are the real and imaginary parts respectively. These two quantities are the result of a dielectric measure.

While complex conductivity can be written as

$$\sigma = \sigma' + i\sigma''$$

Since we will investigate thermodynamics aspects it is useful to introduce dielectric complex modulus

$$\Gamma = \Gamma_1 + i\Gamma_2$$

because this quantity appear in all thermodynamic coefficient of the non equilibrium thermodynamic model which we will consider. The real Γ_1 and imaginary Γ_2 part of Γ are related to ε' and ε'' by the equations:

$$\Gamma_1 = \frac{\varepsilon' - 1}{(\varepsilon' - 1)^2 + (\varepsilon'')^2} \quad \Gamma_2 = \frac{\varepsilon''}{(\varepsilon' - 1)^2 + (\varepsilon'')^2} \tag{2}$$

So we can consider indifferently ε or Γ since they are related by Eq. (2).

Abbreviations: RBCs, red blood cells; WBCs, white blood cells; CEP, conductivity entropy production.

* Corresponding author.
E-mail address: etellone@unime.it (E. Tellone).

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In some previous papers [3,4,5,6,7,8] thermodynamic considerations and suitable approximations allow to obtain the phenomenological $L^{(0,0)}$ and $L^{(1,1)}$ and states $a^{(0,0)}$ and $a^{(1,1)}$ coefficients (when the medium is perturbed by an harmonic electric field) as function of Γ_1, Γ_2(experimentally measurable as function of ω) and of the frequency of perturbation ω. Moreover we have proposed [9] a model which express the function Γ_1, Γ_2 as function of ω for low and high frequencies. Since this model, based on Kluitenberg's theory, gives results best then those obtained by using Debye's model [9], this suggests us to evaluate the complex conductivity as function of the frequency (low frequency $\omega\tau \ll 1$) by taking into account the model proposed by us. The ability to evaluate the conductivity (phenomena which do not occur in a perfect dielectric material) only by means of dielectric measurements is very important because it gives a first information on the structure and thermodynamic behavior of the material concerned. For instance, the electrical conduction within biological materials takes place by means of the movement of the ions in each particular tissue type and any type of pathology leads to alteration of tissue functionality as well as to changes of the ionic content and mobility. Then, through the electric monitoring you can highlight any structural or histological abnormality because accompanied by specific electrical behavior. By a theoretical point of view this can also be done considering the blood as a component mixture [25].

Apply all this information for the study of the biological material may provide exciting new insights to better understand the physiological characteristics of the tissue or cell, considering the body as a composite volume conductor which comprises tissues with differing electrical properties.

In this context, it becomes important to emphasize that the dielectric measurement can be performed in vivo, then all the information on the conductivity can be obtained without the need for additional measures.

In this work we have tried to deepen the existing knowledge on the impact of dielectric microwave on the erythrocytes (data processed by Bao et al.) [10]. Also because, it has to be stressed that despite the several studies on electric fields, many aspects of dielectric properties of blood are still unclear. Besides, the precise knowledge of the electric properties of blood has received renewed interest also in the light of the latest data about electromagnetic pollution. In this perspective, the electric parameters of blood may be a prerequisite for fixing limiting values for the absorption of electromagnetic fields by biological tissues.

In the human body, the blood is a highly functional circulating tissue, composed of fluid plasma and cells: the most abundant cell type are red blood cells (RBCs), then there are white blood cells (WBCs) and reminders are platelets. Blood delivers oxygen to the vital parts, it transports nutrients, vitamins and metabolites, it is involved in the CO_2 elimination, and it is important for the body defense. Furthermore, recently studies point RBCs as model of study to predict the antiproliferative and neuroprotective effects of some molecules [11,12,13]. The present work will focus on the study of the impedance spectroscopy of RBCs because of their abundance and easy availability, are a valid experimental model to elucidate electric and dielectric information about their membranes and cytoplasm. This information will be helpful in understanding the structure and function of these cells, and their interaction with their environment. So for a more complete analysis of the structure and evolution of these tissue it is very important to approach it by mean of the non equilibrium thermodynamic theory evaluating internal variables that appear in this theory.

2. Material and methods

In every physical study the *experimental approach* is fundamental because it is the first interaction with the medium and it furnishes a quantitative and qualitative vision of the phenomena object of study. These information can be utilized to formulate models which are in agreement with experimental data. Obviously for the formulation of these models it is necessary identify the variables which describe the phenomena. Unfortunately, the number of variables that describe a biological system is very large, so it is essential to reduce this number to formulate a concrete model. Obviously this means replace the real system with an ideal one description of which is limited to the chosen variables. But, as a consequence of the complexity of biological phenomena, it is very difficult to identify the variables giving the best - or at least a sufficiently good - description. Every model will be associated to a particular choice of variables so to conceive the *theoretical approach*. By a dielectric point of view well known models are based on the introduction of combination in series or in parallel of capacitance and conductance. These electrical models, in some cases, describe well the real biologic elements and their function [2,24]; for example, it is well known that some aspects of the cell membrane are well described by a capacitance element [21,24].

We will remark that most of the classical models (related to combination in series or in parallel of capacitance and conductance) are always formulated for fit experimental data and, if they are not in agreement with experiments, they are mathematically modified to this aim.

In this work we don't formulate any model to fit data, but we will use some results, by us obtained in the framework of thermodynamic irreversible processes occurring inside the blood, to obtain the complex conductivity only by means of dielectric measurements.

We are conscious of the difficulties to adapt the non equilibrium thermodynamic theory (which is based also on a model of inert matter) to the very complex phenomena that occur in the blood. Nevertheless this new approach can result very important because it provides, by a thermodynamic point of view, new and more detailed information on some processes which occur inside the medium. The characterization of some physical entities (the more important of which is the entropy production) can be used to formulate a diagnosis and to study the evolution of some pathologies. In particular this new approach can be used to deepen the differences between physiological and pathological tissue.

Thus the problem is the applicability of the non equilibrium thermodynamic to the phenomena which occur inside system under study: the blood. In other words, the blood model that we consider is such to satisfy the basic axiom of the non equilibrium thermodynamic?

Our approach is based on the assumption (supported by experiments [22]) that in biological tissue hidden electrical phenomena occur to which correspond internal degree of freedom which must be taken into account for a more detailed description and ~~for~~ prediction.

So we consider the blood as a conducting fluid in which the three major particles are suspended (RBCs, WBCs, micro-particles) and distributed in an homogeneous way [22,26,27].

This allows us to consider the blood as a continuum medium which obeys the continuum mechanics indefinite equations and Maxwell's equation in the matter with a mass density ρ which varies as function of the blood's elements under consideration [23]. By considering the blood as a incompressible fluid, it is possible to prove that the Lagrangian's derivative $\frac{d\rho}{dt}$ of the mass density will result zero. In other word it can be proved that the mass density is almost constant for each fluid element during the motion. This is justified if we consider the mass density of the three major particles of the blood (as RBCs, WBCs, micro-particles).

Thus we assume that the mass density ρ is constant. Such an assumption is also in agreement with the basic axiom on local and instantaneous equilibrium [28]: *for sufficiently small deviation from equilibrium, a system can be divided into tiny (physical) volume elements, each of which can be regarded as a small homogeneous equilibrium system.*

Moreover the length and time scale [29] of these subsystems are infinitesimally small from a macroscopic point of view, but from molecular point of view they are still large, then the subsystem contains enough molecules and the average taken on the number of molecules has deterministic significance.