AN ALTERNATIVE APPROXIMATION FOR THE ELECTRON THERMAL CONDUCTIVITY OF F-REGION OF THE IONOSPHERIC PLASMA

ABSTRACT
In this study, an alternative approximation for the electron thermal conductivity of F-region of the ionospheric plasma is reported. The isotropic (independent of direction) electron thermal conductivity is compared with the anisotropic (dependent of direction) electron thermal conductivity. It is evaluated that while the classical thermal electron conductivity (isotropic) changes with electron temperature, the electron thermal conductivity having tensor form depends on many parameters in the ionospheric F-region such as electron temperature, electrical conductivity, collisions frequency and electron density. Moreover, the magnitude of the anisotropic thermal conductivity, in general, decreases with altitude in F-region of ionosphere for every seasonal.

Keywords: Electrical Conductivity, F-Region of Ionosphere, The Electron Thermal Conductivity.

İYONOSFERIN F-BÖLGESİİNİN ELEKTRON TERMAL İLETKENLİĞİNE ALTERNATİF BİR YAKAŞIM

ÖZET

Anahtar Kelimeler: Elektriksel İletkenlik, İyonosferin F-Bölgesi, Elektron Termal İletkenliği
1. INTRODUCTION (GİRİŞ)

Ionosphere physics may be regarded as a branch of aeronomy, the science of upper atmosphere. Ionosphere consists of different parts with respect to electron concentration and temperature [1 and 2]. A region refers to a part of the atmosphere (such as F-region, which starts at 150 km) and a layer refers to the ionized plasma within that region (such as F1 and F2). F1 layer, which lies between 150-200 km height, is the region with the biggest ionization and F2 layer has the biggest electron density in ionosphere [1 and 3]. The F-region has been defined as the part of the ionosphere above 150 km, although in many ways a looser definition, based on physical regime, might be preferred to a strict in terms of altitude. The main property of this region consists of the free electrons. The F region has the highest electron density in ionosphere. In general, changes of F-region electron density require changes in ionizing radiation, loss mechanism and/or transport process. The present paper deals with the electron thermal conductivity (having tensor form) of ionosphere F-region, mainly which lies at 150-400 km [1, 2, 3 and 4]. Electrical conductivity is a central concept in space science [5]. It determines how driving forces, such as electric fields and thermosphere winds, couple to plasma motions and the resulting electric currents. The tensor electrical conductivity, \( \sigma \), finds application in all areas of ionospheric electrodynamics and at all altitudes [1 and 4]. Naturally, expressions for \( \sigma \) appear in many classic textbooks. An expression for the electron thermal conductivity for a weakly ionised gas, taking into account electron-neutral collisions, was first given by Banks [6]. Banks used Chapman-Cowling mean free path theory, replacing the constant electron-neutral scattering cross section by an average momentum transfer cross section, and multiplying the results by the Spitzer-Harm factor \( \varepsilon = 0.149 \), originally obtained for a fully ionised gas, to take into account the thermoelectric effect [2, 4, 6 and 7]. The evaluation of the electron-neutral thermal conductivity, including the thermal factor \( \varepsilon \), however, involves a knowledge of the velocity dependent collisions cross section. The different expressions obtained by Dalgarno et al. (1967), Bank, Walker and Rees (1968) for electron-neutral thermal conductivity are apparently due to the different dependence of collisions cross section on velocity they consider [7].

Unfortunately, the relationship between electrical conductivity and electron thermal conductivity hasn't been explained for ionospheric plasma up to now but there is relationship in solid state. In solid state, this relationship is explained by Wiederman-Franz law. This law is valid at high temperature especially for electron [8]. Then it may be possible to use this equation for the ionospheric F-region. Our goal in this study is to use the Wiederman-Franz law in ionospheric plasma. The results obtained have been compared to classical electron thermal conductivity results.

2. RESEARCH SIGNIFICATION (ARAŞTIRMANIN ÖNEMI)

The present study intends to serve as a guide for researchers who make theoretical studies in ionospheric F-region. It will also constitute a background for experimental researchers.

3. THERMAL AND ELECTRICAL CONDUCTIVITY TENSOR (TERMAL VE ELKETIRIKSEL İLETENLİK TENSÖRÜ)

The force acting on the electron in plasma is given as follow. The effect of ions can be neglected at the high frequency approximation.

\[
\frac{d\mathbf{V}_e}{dt} = -e(\mathbf{E} + \mathbf{V}_e \times \mathbf{B}) - m_e \mathbf{v}_e \mathbf{V}_e
\]  

(1)
where \( v_e = v_{ei} + v_{en} \) in which \( v_{ei} = N_e \left[ 59+4.18 \log \left( \frac{T_e}{N_e} \right) \right] x 10^{-6} T_e^{3/2} \) and \( v_{en} = 5.4x10^{-16} N_n T_n^{1/2} \) are the electron-ion and the electron-neutral collision frequencies, respectively \([2 \text{ and } 9]\). The velocity and the fields are assumed to vary as \( e^{i(kx-\omega t)} \). The standard notation of magnetoionic theory is used.

The electron current density \( \mathbf{J} = -eN_e \mathbf{v}_e \) is given by,

\[
\mathbf{J} = \sigma_0 \mathbf{E} + \frac{e}{m_e(v_e - i\omega)} \mathbf{J} \times \mathbf{B}
\]  

(2)

where \( \sigma_0 = \frac{e^2 N_e}{m_e (v_e - i\omega)} \) is the longitudinal conductivity \([5]\). It is assumed that the z-axis of the coordinate system with its origin located on the ground is vertical upwards. The x-axis and y-axis are geographic eastward and northward in the northern hemisphere, respectively. The geomagnetic field is assumed as.

\[
\mathbf{B} = B_x \mathbf{a}_x
\]  

(3)

In a cartesian coordinates system, the solution of the eq.(2) can be written as,

\[
\mathbf{J} = \sigma \cdot \mathbf{E}
\]  

(4)

with

\[
\sigma = \begin{bmatrix}
\sigma_1 & -\sigma_2 & 0 \\
\sigma_2 & \sigma_1 & 0 \\
0 & 0 & \sigma_0
\end{bmatrix}
\]  

(5)

In here, all of the conductivities have an imaginary as well as real part. The real part is what we usually associate with conductivity. It is reciprocal of resistivity and is thus associated with energy dissipation. The imaginary part is associated with the dielectric properties of medium and is a purely alternating current parameter (inverse of reactance) \([4]\), the conductivities can be written as follow.

\[
\sigma_0 = \frac{e^2 N_e}{m_e} \left[ \frac{v_e}{v_e^2 + \omega^2} + \frac{\omega}{v_e^2 + \omega^2} \right]
\]  

(6)

\[
\sigma_1 = \frac{e^2 N_e}{m_e} \left[ \frac{v_e^2 + 2 \omega^2}{v_e^2 - \omega^2 + \omega_{ce}^2} + 4 \omega^2 v_e^2 \frac{v_e^2}{v_e^2 - \omega^2 + \omega_{ce}^2} + 4 \omega v_e^2 \right]
\]  

(7)

\[
\sigma_2 = -\frac{e^2 N_e}{m_e} \left[ \frac{2 \omega \omega_{ce} v_e}{v_e^2 - \omega^2 + \omega_{ce}^2} + 4 \omega^2 v_e^2 \frac{v_e^2}{v_e^2 - \omega^2 + \omega_{ce}^2} + 4 \omega v_e^2 \right]
\]  

(8)

where \( \omega_{ce} = \frac{-eB}{m_e} \) is electron cyclotron frequency.

As classical, electron thermal conductivity equation for ionospheric plasma is given as follow \([4]\).

\[
\kappa = 7.7 \times 10^5 T_e^{2.5} \text{ eV cm}^{-1} \text{s}^{-1} \text{K}^{-1}
\]  

(9)

Equation 9 is one dimensional depending only on the electron temperature in the ionospheric plasma. The electrical conductivity in ionospheric plasma is a tensor, and it related to plasma parameters. The ionospheric plasma is a good conductor \([4 \text{ and } 5]\), so it is possible to use that the Wiederman-Franz law could be used for the ionospheric plasma. This law is given by,
According to Equation 10, it can be said that if the electrical conductivity is a tensor, then the electron thermal conductivity must also be a tensor in the ionospheric plasma. This shows that the electron thermal conductivity depends on direction in the ionospheric plasma [7]. The tensor form of Equation 10 can be written as follows:

\[
\kappa = \begin{pmatrix}
\kappa_1 & -\kappa_2 & 0 \\
-\kappa_2 & \kappa_1 & 0 \\
0 & 0 & \kappa_0
\end{pmatrix}
\]  

Equation 11 has a complex structure because the electrical conductivity is complex. That is, the electron thermal conductivity tensor indicates the behavior that electron electric conductivity tensor exhibit in ionospheric plasma from a mathematical point of view.

4. NUMERICAL ANALYSIS (SAYISAL ANALİZLER)

The real parts of the electron thermal conductivity in the F-region of the ionosphere have been evaluated from Equation 11 for geographic coordinates 39°E, 40°N. The used plasma parameters have been obtained by using International Reference Ionosphere (IRI) as seasonal at 12.00 LT in 1998. Besides, the wave frequency is taken equal to plasma frequency for every altitude.

5. CONCLUSIONS (SONUÇLAR)

Values of classical electron thermal conductivity calculated for one dimension that only depends on the electron temperature are compared the values of electron thermal conductivity which have tensor form depending on electrical conductivity. The calculations were done as seasonal. According to Equation 9, the classical thermal conductivity doesn’t depend on any direction. It depends on the electron temperature. So, the trend of the change of the classical electron thermal conductivity with altitude is similar to the change of electron temperature for the selected months (21 March, 21 June and 21 December). But, in presence of magnetic field, the magnitude and direction of the electron thermal conductivity become different (Equation 11). Due to this, the electron thermal conductivity depends on many parameters such as electrical conductivity, magnetic field, collisions frequency and electron temperature in F-region. So, the electron thermal conductivity is less than the magnitude of the classical thermal electron conductivity (Figure 3, 4, 5). According to figures (3), (4) and (5), the change of the electron thermal conductivity with altitude \(K_0, K_1, K_2\) follows the change of electrical conductivity rather than electron temperature.

The real part of the electron thermal conductivity \(K_1\) changes non-linearly with altitude but it has different magnitudes for each season (Figure 4). The variation of the real part of electron thermal conductivity with altitude of \(K_0\) is shown in Figure 3. As can be seen in this figure, the real part of \(K_0\) decreases with altitude and has a minimum value between about 150-200 km. The real part of the electron thermal conductivity \(K_0\) is the most interesting. While \(K_0\) and \(K_1\) generally decrease with altitude, \(K_2\) indicates a different change with altitude. For example, \(K_2\) has maximum values about 150 km and has minimum about 280 km. At this altitude for June \(K_2\) has again a maximum value.

Consequently, it is concluded that while the classical electron conductivity changes with electron temperature, the electron thermal...
conductivity having tensor form depends on many parameters in the F-region such as electron temperature, electrical conductivity, collisions frequency and electron density. Furthermore, the magnitude of the electron thermal conductivity depending on direction decreases with altitude, when the classical thermal electron conductivity is compared. It is possible to say that the trend of anisotropic electron thermal conductivity is different from isotropic thermal conductivity in F-region as seasonal.

Figure 1. Electron temperature profile in the ionospheric F-region (Şekil 1. İyonosferin F-bölgesindeki elektron sıcaklığının yükseklikle değişimi)

Figure 2. Profile of the classical electron thermal conductivity (Şekil 2. Klasik elektron termal iletkenliğinin yükseklikle değişimi)
Figure 3. $K_0$ profile
(Şekil 3. $K_0$'ın yükseklikle değişimi)

Figure 4. $K_1$ profile
(Şekil 4. $K_1$'in yükseklikle değişimi)
Figure 5. K₂ profile
(Şekil 5. K₂’nin yükseklikle değişimi)

List of Symbols

- $m_e$: Electron mass
- $J$: The current density
- $K$: Electron thermal conductivity
- $V_e$: Electron velocity
- $N_e$: Electron density
- $v_e$: Electron collisions frequency
- $t$: Time
- $\sigma$: Electrical conductivity
- $v_{ei}$: Electron-ion collisions frequency
- $q_e$: Electron charge
- $\omega_{pe}$: Plasma frequency
- $v_{em}$: Electron-ion collisions frequency
- $E$: Electric field
- $\omega_{ce}$: Electron cyclotron frequency
- $N_n$: Neutral density
- $B_0$: Earth’s magnetic field
- $T_e$: Electron temperature
- $\omega$: Wave frequency
- $k_b$: Boltzmann constant

REFERENCES (KAYNAKLAR)