Measurement of the density and the composition of the upper atmosphere by the Electron-Ion trap sensor

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Abstract - This article explains the design of the electron-ion trap sensor for measuring the density and the composition of the upper atmosphere. The simulation of the electric field between the trap electrodes and the charged particles motion in it is carried out. The calculation of the maximum energy and speed of the particles below which the trap holds all charged particles, even in the case of the most unfavorable direction of their speed-along the gap between the electrodes. It is shown that this critical energy does not depend on the mass of the particle, and the probability of charged particles passage with an energy more than the critical energy through the trap is estimated [1].

Keywords: numerical analysis, vacuum gauge converter, ionization, mathematical model, experiment.

I. INTRODUCTION

The high concentration of charged particles in the ionosphere (ions, free electrons and protons) is the main problem that prevents the use of the artificial vacuum ionization sensors to measure the air density in the ionosphere. The ionization coefficient of neutral particles is so small in ion-electron sensor cold cathode, reaching the active area of ionization of the sensor from ambient air a substantial fraction of the ions, the concentration of which in the ionosphere is a few percent of the number of neutral particles, can alter the readings on the vacuum gauge dozens of times. To prevent this, before entering the active zone of the Converter an electron-ion trap must be installed then the ionization sensor readings will be correct, because the sensor ion current will be determined only by the concentration of neutral atoms and molecules, and gamma radiation, from which the trap does not protect and the intensity of which at these heights is more than at the earth's surface [1].

The trap of charged particles is beneficial to increase the reliability of the vacuum sensor readings and to determine the concentration of negative particles (mainly electrons) and positive particles: ions and protons and determination of the of neutral particles concentration. [2,3].
This Sensor is a vacuum gauge Sensor equipped with an electrostatic trap of charged particles. The trap should intercept all charged particles included in the ionosphere, not allow them to enter the active area of the sensor and totally pass neutral atoms and molecules.

The design of such a charged particle trap connected to a vacuum Sensor shown in Figure1.

![Figure 1- Charged particle trap design: three electrode[right], four electrode [left.]](image)

The trap involves some electrodes as a hollow truncated cone connected with a high DC source voltage. Cathodes attract positive charged particles and anodes attract negative charged particles. Measuring channels are used to measure electrical currents that make it easy to measure the concentration of positive and negative particles.

The top end of the trap is open to the air. Charged units falling into the interelectrode space of traps, are deflected by strong electric fields to the electrodes in which the negative particles are attracted to the anodes, positive particles are attracted to the cathodes). The neutral particles will fall into the working zone of the sensor. This confirms that its readings will be correct in proportion to the neutral atoms and molecules concentration in the atmosphere.

**The mathematical model**

The charged particle trap finding is done by the use of an analytical method and by the use of standard electric field stimulation program. Since high exactness of such a model is not required, so we will use the analytical one. Its errors will be determined by the electric field edge curvatures. The errors will be so small because the gaps between the electrodes are smaller than the height of them. [5,6]

To find the electric field in the space between electrodes, we will use the formula for the coaxial cylindrical capacitor electric field: [1].

$$E = \frac{U}{r \ln \frac{R_1}{R_2}}$$

$U$ = the capacitor plates voltage,
$r =$ current radius;
$(R_1)$ and $(R_2)$ are the inner and outer electrodes radii.

In the planned trap design, the gaps between adjacent electrodes decreased when the height is decreased which increases the electric field because the particles will enter deeper into the trap.

To calculate the field in this design, you can replace the conical surfaces by cylindrical shape ones with gradually decreasing diameters, as shown in Figure (2), left. In this case, the equation (1) is for each step of such surfaces. It is
easy to go from it to the continuous function \( E(\ h) \); if you set the linear functions \( R_l (\ h) \) \& \( R_u (\ h) \), where \( (\ h) \) is the current height of the cones [1]:

\[
E(\ h) = \frac{U}{r \ln \frac{R_u(\ h)}{R_l(\ h)}}
\]

(1)

The height of the trap is divided to 10 sections, and calculations will be done for the radii corresponding to the middle of the sections. The formula to find these cones radii at an arbitrary height \( h \) can be gained from the geometric construction that is shown in figure. (2)(right).

Regarding the design shown in (figure 2) right, we can find the current radii of the trap cone as follows [8]:

\[
R(\ h) = R_l + \frac{R_u - R_l}{H} \cdot h
\]

(2)

\( R(\ h) \) : is the cone radius at a height \( (\ h) \);

\( R_u \) is the radius of the cone at the upper end;

\( R_l \) is the radius of the cone at the lower end;

\( H \) is the total height of the truncated cone.

For a trap of four-electrode, the electrodes dimensions are shown in Tab. (1), { Assuming the thickness of the electrodes is (0.1 mm)}.

| Number of cones | The upper | The lower |
|-----------------|-----------|-----------|
| \( D_u [\text{mm}] \) | 19.2      | 10.1      |
| \( D_l [\text{mm}] \) | 18.82     | 9.81      |

| Number of cones | 1 | 2 | 3 | 4 |
|-----------------|---|---|---|---|
| \( D_u [\text{mm}] \) | 19.2 | 15.1 | 11 | 7 |
| \( D_l [\text{mm}] \) | 18.82 | 14.81 | 10.82 | - |

Let's assume all cones height \( H \) is (40mm) then divide it by height to (10) sections, and the current radii must be found for the middle of these sections. Then we can approximate conical cylindrical surfaces for each section and by the use of the expression (1) to estimate the electric field of each section. the electric voltage value is the Same as for a vacuum sensor which equals (1000 Volt). (Table 2) & (Fig. 3) show the results of finding the electric field for one of the electrodes pairs.

Table 2. Finding the electric field for the first pair of electrodes
Regarding charged particles falling into the interelectrode space, when they fall along the interelectrode gap then there is the critical case. In other cases, the particles collide to the electrodes and they are either neutralized if the electrode is oppositely charged, or repel it if they are with the same charge and go to the opposite electrode to be neutralized. Therefore, the calculation of the limit energies of charged particles of the critical case when their initial velocity is directed to the gap between the electrodes is shown below:

| h, [MM] | R₁(h), [MM] | R₂(h), [MM] | R₉av(h), [MM] | E₁, B/[MM] | E₉, B/[MM] | E₉av, B/[MM] |
|---------|-------------|-------------|---------------|------------|------------|-------------|
| 38      | 7.35        | 9.89        | 8.62          | 478        | 600        | 539         |
| 36      | 6.91        | 8.8         | 7.855         | 493        | 630        | 561         |
| 32      | 6.58        | 8.3         | 7.44          | 506        | 640        | 483         |
| 24      | 6           | 7.9         | 6.95          | 545        | 680        | 612.5       |
| 20      | 5.9         | 7.4         | 6.65          | 570        | 660        | 615         |
| 18      | 5.8         | 7           | 6.4           | 550        | 708        | 629         |
| 14      | 5           | 6.90        | 5.95          | 560        | 734        | 647         |
| 10      | 4.9         | 6           | 5.45          | 570        | 761        | 665.5       |
| 6       | 4.22        | 5.575       | 4.8975        | 590        | 794        | 692         |
| 2       | 3.71        | 5.130       | 4.42          | 600        | 830        | 715         |

Once moving in a transverse electric field, a charged particle is affected by a force that deflects it in a transverse direction. However, the electric field is uniform, the charged particle is moving with a uniform acceleration, and in such a situation, the field will increase as the particle sinks into the trap and as it reaches the internal electrode [9]. Although high exactness is not required, we suppose a uniform field and equal to the corresponding mid-gap between electrodes at half of the height of the trap. In such cases, the particle will move along the (R) axis with a uniform acceleration:

\[
r = \frac{1}{2} m q E t^2
\]

(3)

Supposing that at this time the particle velocity along the (z) axis is constant and equals (V), we can calculate the current trap height \((H-h) = VT\), where the particle approaches the opposite electrode [8].
Passing from the particle velocity to its energy, we obtain:

\[ E_p = \frac{mV^2}{2}, \quad V = \sqrt{\frac{2E_p}{m}} \]  \hspace{1cm} (4)

When \( h_T = 0 \), we get the maximum kinetic energy of the particles that are captured by the trap, when their velocity direction is along the gap between the trap electrodes. \[9\]:

The mass of the particle will no longer appear but just its charge. So, for the electrons and ions with one charge, the energy at which they will be trapped is equal. This conclusion is so important because it allows us to find the energy threshold for charged particles. Replacing in equation (10):

\[ H = 40 \text{mm}, \quad q = e = 1.6 \times 10^{-19}, \quad d_{av} = 1.65 \text{mm}, \quad E = 620 \text{volt/mm} \]

we get:

\[ E_{p,\text{max}} = \frac{H^2 q E}{4d_{av}} = 2.4 \times 10^{-14} = 150 \text{ KeV} \]

This equation is approximate, because there will be an increase in the electrical field strength as the particle reaches the opposite charge electrode and goes deeper into the trap. The real value of critical energy of the particles captured by the trap is higher than the estimated because \( E \) depends on \( r \) and \( h \).

The most important is considering the unfavorable state of particle velocity direction in relation to trap position. Actually, the velocity direction of the particle in relation to the trap can be regarded random, because the nanosatellites position (where the sensor will be placed) are not stabilized in relation to the earth surface, and the particles move randomly, though, the effects of the magnetic field of Earth on charged particles within the ionosphere, making them move in cyclotron orbits along the magnetic field lines. So the probability of the direction of the particle initial velocity along the gap between the electrodes can be calculated as the ratio of the solid angle \( \theta \), where the particle won't collide with the electrodes of the trap, to solid angle \( 2\pi \) in absence of the field. Regarding the trap geometry, we can estimate this angle is approximately about \( 1^0 \) for a trap of four electrodes and \( 1.5^0 \) for the three electrodes trap.

So, although we set the solid angle that a particle will enter the trap \( 120^0 \) degrees rather than \( 180^0 \) degree, one can estimate the probability of increasing the speed of the particle as (0.8%) regarding the trap of the four electrodes and (1.25%) regarding the trap of the three electrodes. So the probability of \( 99\% \), the trap will pick up any energy charged particles, and 1% remaining of the particles, the energy of the picked particles will be set to \( 0.15 \text{ MeV} \). So, one can say that this trap will neutralize all charged particles. The concentration of charged particles in the ionosphere is about \( 50 \) to \( 1000 \) times less than the neutral particles concentration.

II. CONCLUSIONS

We can conclude the following:

1. The ionosphere characteristics such as (density; ionization degree; composition; temperature and the radius of the rotation of the cyclotron in the Earth’s magnetic field) are very variable and are not dependent only on height, but on the day time, year time; latitude; and solar action and other factors, the effect of these properties is not widely studied. (4)
due to the difficulty of the directly measuring at such heights and the lack of instruments that are suitable to be installed on the micro and nanosatellites, This confirms the importance of developing such instruments.

2. The existing industrial instrument list (devices to measure ionization and mass spectrometry) can’t be used for these purposes because of the high rate of ionization and the scarcity of strong in the upper layers of the atmosphere. direct measuring is so difficult at the height of 150 to 500 km, where the most complex operations of the interaction processes of the atmosphere with solar radiation occurs.

3. We consider the possibility of designing a sensor to measure the upper atmosphere density and the composition, permitting measuring the neutral and charged particles concentration separately and it can be installed on nanosatellite. This sensor includes an inversed magnetron vacuum sensor, which permits the measurement of the neutral particles concentration and the (electron-ion) trap, which do not allow the passage of the charged particles to the active region of the vacuum, which maintains the exactness of its reading.

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