ROCKET-BORNE EXPERIMENT FOR THE MEASUREMENT OF THE VARIATION IN ELECTRIC CONDUCTIVITY WITH ALTITUDE (GEKKO EXPERIMENT - REXUS14)

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ABSTRACT

This paper deals with description of a rocket-borne experiment which is designed to carry out measurement of ion mobility by using Gerdien condensers. The development was made by a university student group at Budapest University of Technology and Economics within the REXUS/BEXUS programme. The physical background including the Gerdien condenser principle and the measurement method is described and technological aspects and feasibility of the experiment are also discussed. The paper provides a brief description of the actual capability of the experiment and a short review of the failure experienced at the flight onboard REXUS14. Further improvements regarding accuracy, reliability are also described.

1. INTRODUCTION

REXUS experiments are flown on spin stabilized sounding rockets, typical apogee of which is at about 90km (Fig.1) [1], [2]. Rockets are launched from ESRANGE Space Center, North Sweden. The REXUS platform allows carrying out measurements in the middle atmosphere. The middle atmosphere is a less known part of the atmosphere because it is hardly accessible by measurements. Thus, the launch site is located at high latitude, in the polar cap where galactic cosmic rays participate in greater degree in ionization of the atmosphere. The polar cap is a special location from the point of view of ionisation processes, taking into account the direct connection partly to the tail of the magnetosphere, partly to the interplanetary space.

The main objectives of the experiment are measurement of atmospheric ion density and composition with altitude and study of the altitude dependence of electric conductivity by recording mobility spectra of positive and negative ions. Required vertical resolution is at least one recorded mobility spectra in every 5 km in the altitude range from 22 km to 75 km.

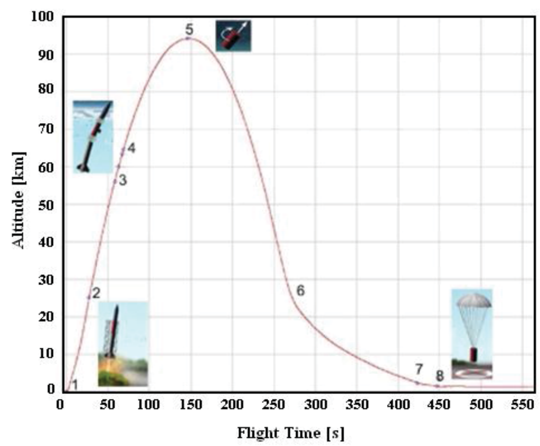

Figure 1. REXUS Flight profile[1]

2. PHYSICAL BACKGROUND

The Gerdien condenser is a cylindrical shaped condenser which has an inner and an outer electrode. A schematic of the equipment is shown in Fig.2.

The condensers are placed on the outer side of the rocket to ensure direct airflow between the two electrodes. Depending on the polarity of the applied bias voltage on the condenser, the positively or negatively charged ions will be deflected towards the inner electrode. When they hit the cathode the generated current is proportional to the ion density and also the mobility of the different ion groups [4]. In order to measure the positive and negative ions at the same time, two Gerdien condensers were placed on the opposite sides of the rocket.

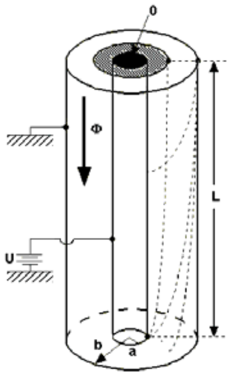

Figure 2. Gerdien condenser, working principle [3]

The requirements for the measuring device include the estimated currents and the bias voltages to be applied in different altitudes. Eq. 1 shows the expression of the measured current.

$$I = \sum_i \frac{2n_i e\pi\mu_i L}{\ln(b/a)} V \qquad (1)$$

where e is the elementary charge, n_i is the ith ion density, V is the applied voltage, L is the length of the condenser, b and a are the radius of the outer and the inner electrodes, and μ_i is the mobility of the ith ion.

An ideal voltage-current characteristic for one ion group is shown in Fig. 3.

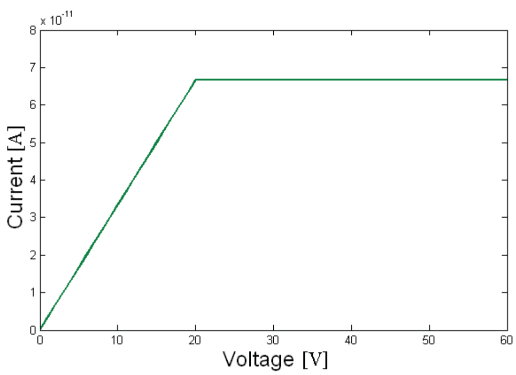

Figure 3. Ideal voltage-current characteristic

Under a critical voltage the current has a linear relationship with the applied voltage and the saturation current is measured when all of the ions from the specific ion group are captured. The slope of the curve is related to the mobility and the saturation current is related to the ion density. Section 5 contains a brief description of the data analysis.

It is known from previous studies that the main ions in the middle atmosphere are the proton hydrates, atomic oxygen, nitrogen, hydrated oxygen molecules, etc. In order to estimate the expected currents, the mobilities of these different ion groups were calculated according to Eq. 2.

$$\mu = \frac{e}{nM\nu_{in}} \qquad (2)$$

where M is the molecule weight and ν_{in} is the collision frequency between the ions and the neutral molecules.

The collision frequency is estimated from Eq. 3.

$$\nu_{in} = N_A \sigma_{in} \sqrt{\frac{8k_B T}{m_{in}\pi}} \qquad (3)$$

where N_A is the Avogadro number, k_B is the Boltzman constant, T is the temperatures in Kelvin and m_{in} is the effective mass of the ions and the neutral molecules.

The estimated currents are in the range of 10^{-12} to 10^{-9} [A]. In order to calculate the required bias voltages the ideal trajectory of the ions were examined taking into consideration their estimated mobilities. The critical mobility (i.e. the minimum mobility which allows for an ion to be captured at the applied voltage) is calculated from Eq. 4.

$$\mu_c = \frac{(b^2 - a^3)\ln(b/a)\Phi}{2LV} \qquad (4)$$

where φ is the speed of the airflow in the condenser (note that it is not equal to the velocity of the rocket).

The required bias voltage can also be expressed from Eq. 4. Taking into consideration the average mobility of the ion groups the applied voltages shall be between 0 and 60 [V].

Another crucial requirement of the measurement is the altitude range where the measurement can be performed. If the mean free paths of the ions are greater than the distance between the inner and the outer electrode, the air cannot be considered as a continuum. Therefore, the defined altitude range of the measurement is between 20 and 85 km.

3. UNCERTAINTIES

Due to the special conditions of the measurement (e.g. supersonic rocket flight, low measured currents) the distortions that may affect the measurement had to be taken into account. These distortions were separated into environmental and measuring device uncertainties. As it is very hard or impossible to examine all of the circumstances that occur during the flight, Monte-Carlo simulations were carried out to determine the uncertainties and also the Likelihood function of the measurement.

The first examined distortion was the photoemission which is significant in the higher altitudes. The second is the ion loss due to the turbulence caused by the supersonic pipe flow [5]. This is a very crucial factor because not only the inner flow in the pipe but the shockwaves can cause such losses as well. The third is the electric field perturbation caused by the separation of the positive and the negative ions in the condenser. The generated electric field is calculated from Eq. 5 by solving the Poisson equation for two ion groups.

$$E(r) = \frac{V_0}{r\ln(b/a)} - \frac{N^+ e}{2\varepsilon_0}\left(r - b^2 - \frac{a^2}{2r\ln(b/a)}\right) \tag{5}$$

where V_0 is the applied voltage, r is the position, b is the radius of the outer electrode, a is the radius of the inner electrode, e is the elementary charge, and N^+ is the density of the positively charged ions.

For this reason, besides the currents the voltages are measured as well, which also has an uncertainty but it is easier to handle. The distortions of the measurement device are separated into those related to the current measurement and those related to the voltage measurement. Each circuit has a bias error, a temperature drift and the current measurement is corrupted by a stochastic noise as well, following normal distribution. This can be determined by using hypothesis testing. The deterministic noises can be compensated easily after the measurement. The results of the Monte-Carlo simulations showed that the Likelihood function is the probability density function of a normal distribution.

After determining the uncertainty of the measured current it is necessary to determine the uncertainties of all expressed quantities, e.g. mobility, density.

4. DATA EVALUATION

The evaluation consists of five separated steps. The first is to find the breakpoints in the measured characteristics. The second is to express the ion density from Eq. 6.

$$n = \frac{I_{sat}}{vAe} \tag{6}$$

where A is the aperture of the condenser, I_{sat} is the saturation current, and v is the velocity. The third step is to determine the slope of the assumed ideal characteristic from Eq. 7.

$$G_n = \left.\frac{dI}{dV}\right|_{Vn} - \left.\frac{dI}{dV}\right|_{Vn-1} \tag{7}$$

where n means the n^{th} breakpoint, and G_n is the slope in the n^{th} breakpoint. From the slope, the mobility was determined from Eq.8.

$$\mu_i = \frac{G_i \ln(b/a)}{2\pi n_i eL} \tag{8}$$

where μ_i is the i^{th} ion mobility, and n_i is the i^{th} ion density. The last step is to express the uncertainties. As large amount of data was expected, an evaluation algorithm was created to simplify the evaluation process by performing the evaluation steps almost automatically. To demonstrate the data analysis, a simulated measurement is shown in Fig. 4 with one sweep from 0 [V] to 60 [V] and with two ion groups whose parameters are summarized in Tab. 1.

	μ [m²/Vs]	n [m⁻³]
Ion1	$1.3*10^{-2}$	$7*10^{9}$
Ion2	$6.2*10^{-3}$	$8.8*10^{9}$

Table 1. Simulation parameters

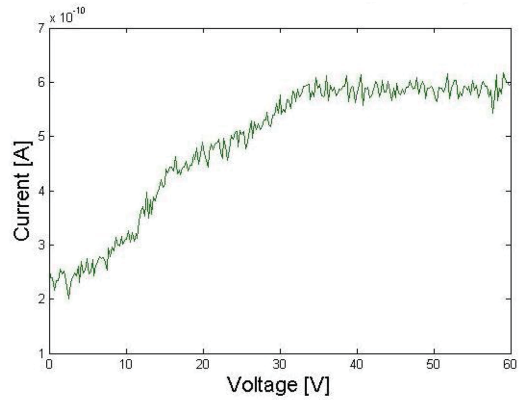

Figure 4. Simulation results, 2 ion present

A simple searching algorithm was used which calculates the first and the second derivatives after smoothing the curve. In the first derivative it searches for decreasing parts and separates them into different intervals. Between these intervals it examines the second derivatives and searches for null transitions. Each null transition means a breakpoint. The results are shown in Tab. 2.

	μ [m²/Vs]	Δ μ [m²/Vs]	n [m⁻³]	Δ n [m⁻³]
Ion1	$1.32*10^{-2}$	$3.94*10^{-5}$	$6.38*10^{9}$	$6.35*10^{8}$
Ion2	$6.2*10^{-3}$	$3*10^{-4}$	$8.79*10^{9}$	$6*10^{8}$

Table 2. Data evaluation algorithm results

5. SUPERSONIC PIPE FLOW PROPERTIES

It is well known that at supersonic speeds the flow in a pipe behaves very differently than at subsonic speeds. The main difference is that the flow cannot be considered as an incompressible flow. Therefore, it was of key relevance to determine the temperature and the airflow velocity in the condenser. At supersonic flights the effects of the shockwaves shall be taken into account. This means that some parameters (e.g. temperature, density, flow speed) will have abrupt changes in their values [6]. These changes will happen in a very short length, approximately in few times the mean free path. Eq. 9 shows the rate of the temperature change.

$$\frac{T_2}{T_1} = \frac{[2\gamma M_1^2 - (\gamma - 1)][2 + (\gamma - 1)M_1^2]}{(\gamma + 1)^2 M_1^2} \qquad (9)$$

where M is the Mach number of the undisturbed flow (velocity of the rocket) and γ is the adiabatic coefficient. According to this calculation the air temperature in the condenser can reach about 600°C. Another significant consequence of the shockwaves is that the airflow in the condenser is compressible. This condition is described by the entropy law of thermodynamics.

6. DESIGN

The REXUS experiments are located in separated modules and electronic interface including power and communication lines are provided by the service module (Fig. 5.).

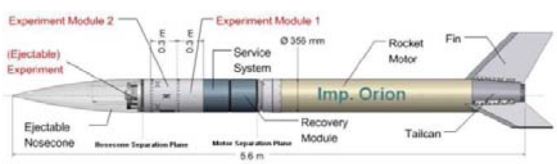

Figure 5. A standard REXUS configuration [2]

The Gekko experiment is located in a 300mm height module of the rocket under the nosecone and consists of two Gerdien condensers mounted on the surface of the rocket and an electronic box placed inside the experiment module (Fig. 6).

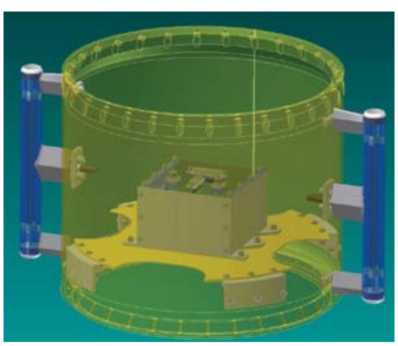

Figure 6. Gekko experiment setup

6.1. Mechanical design

From the aspect of mechanics, the critical issues have been raised by the condensers placed on the skin of the rocket. Since condensers have to withstand high mechanical loads due to vibrations and thermal load from the friction, it is an essential requirement to analyse and simulate the behavior of the condensers during flight.

Once it is proved that the condensers are able to operate safely, another main aspect was the analysis of the airflow inside the condensers. The airflow velocity in the condenser tubes has much influence on the bias voltage to apply, thus the measurement limits and precision are also affected by the airflow velocity simulation.

The only solution for the simulation of structural strength and airflow characteristics was the Finite Element Method simulation. Therefore, several simulations have been carried out to determine the natural frequencies of the condensers and after that to ensure that the strength is sufficient even if resonance is present. Obviously, it is preferable to set the natural frequencies much higher than the expected frequencies during the flight.

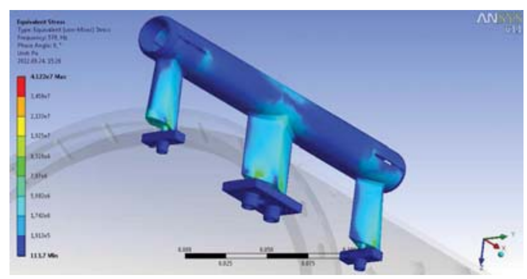

Figure 7. The results of a vibration simulation

The other main point of focus was on the aforementioned airflow analysis. When the condensers pass through the atmosphere, the air at the inlets of the condensers suffers high loads and therefore the airflow velocity drops. According to the simulation results, the velocity of the airflow inside the condensers is approximately 350 - 400 m/s which is much slower than the velocity of the rocket itself (1200 m/s). The bias voltage therefore had to be halved compared to the first plans.

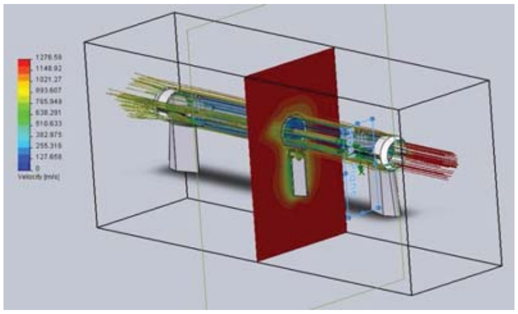

Figure 8. The trajectories of the airflow inside and around the condensers

After the production of the condensers, vibration tests had been carried out on the condensers to get more accurate results than from simulation. However, a wind tunnel test would have been desirable but there was no available supersonic wind tunnel to perform the test.

6.2. Electrical design

The main functions of the Gekko electronics are the current measurement, bias voltage adjustment, measurement control, data acquisition and communication. The electronics are built up on three PCBs: Power Supply Unit, On-Board Data Handler and Amplifier board. The PCBs are connected with a motherboard (Fig. 9).

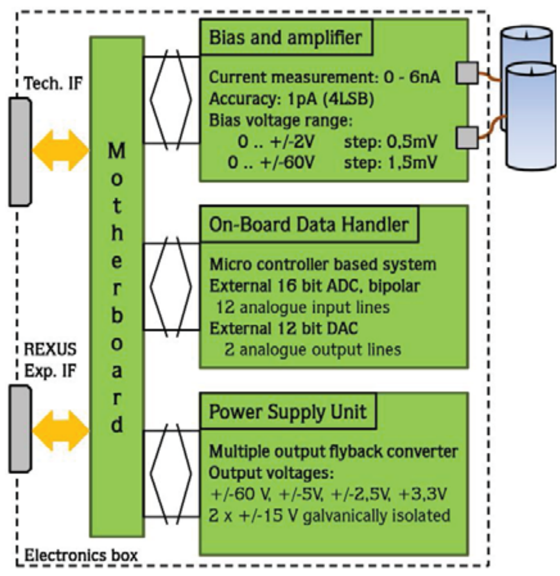

Figure 9. Gekko electronics, block scheme

The current of the central electrodes shall be measured in the range of 1pA to 6nA while the electrodes are biased in the range of 0..60V and 0..-60V. This low level current is measured by a precision amplifier applying compensating current measurement method (Fig. 10).

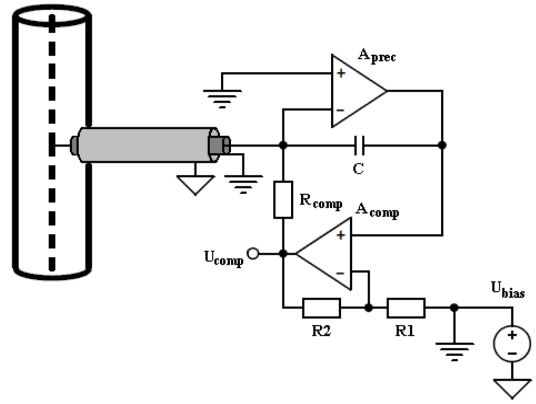

Figure 10. Current measurement method

The condenser is biased by shifting the ground level of the precision amplifier and the compensating amplifier as well. When a balanced state is reached the electrode potential is equal to the bias voltage and its current is compensated through the resistor R_{comp} by the compensating amplifier. The current of the condenser is calculated as follows: $I_{cond} = - U_{comp} / R_{comp}$.

The input bias current of the precision amplifier is compensated too, thus modifying the measurement. To reduce the measurement error the leakage current of the C capacitor and the connection of the electrode, including the PCB trace and the cabling, are also considered. The Gerdien condensers are connected by triaxial cables of which the inner shield layer is connected to the bias voltage generator thus guarding the inner conductor (Fig. 10).

The amplifier was tested with a reference current generator. The transfer characteristics of the two amplifiers are shown on Fig. 11 and 12.

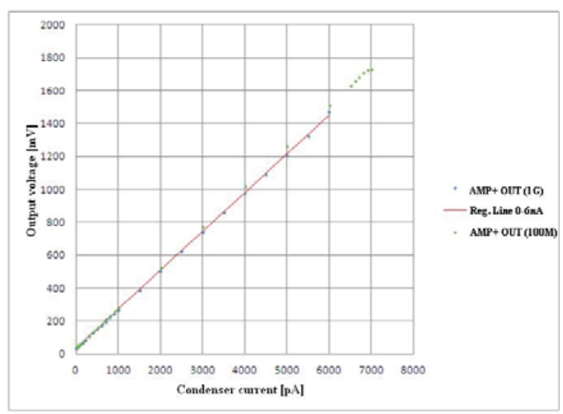

Figure 11. Positive amplifier, transfer characteristic

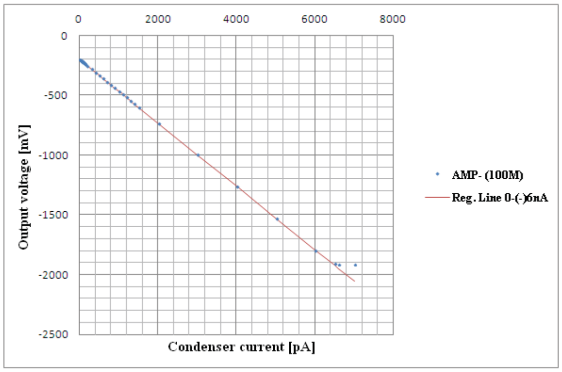

Figure 12. Negative amplifier, transfer characteristic

Fig. 11 and Fig. 12 show the regression line that was fitted to the test points. The transfer parameters of the amplifiers are presented in Tab. 3.

	slope [mV/pA]	offset [mV] (T=20°C)
positive	0,235	36
negative	-0,265	-201

Table 3. Amplifier parameters

Fig. 13 shows the complete electronics box after assembly:

Figure 13. Gekko electronics box, top cover open

7. FLIGHT RESULTS

The Gekko experiment was flown on board REXUS14 on the 7th of May 2013. The experiment was powered at T-600s (before Lift-Off) and the functional test was performed successfully at T-300s. After Lift-Off the communication with the Gekko experiment was lost.

After payload recovery several failures were identified. The ground control system reported overload on the power line of the Gekko experiment at T+1,5s. Due to a short circuit the power consumption of the experiment exceeded 20A and the power protection unit cut off the experiment.

The post flight analysis showed that the short circuit was the consequence of the static acceleration and maybe some resonance. The PSU PCB (Fig.14) bent down to an unexpected extent and some pins touched the box (Fig. 15) thus shorting the BUS 28V to the structure.

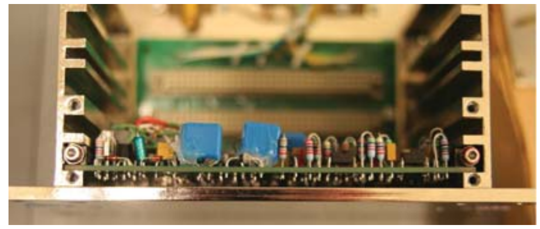

Figure 14. PSU PCB in the electronics box

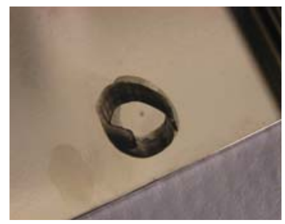

Figure 15. Blackened point in the surface

At the post flight recovery it was found out that the plastic insulation rings of the condensers were melted (Fig. 16) which was probably the consequence of the shock waves. Also the soldering thin in the cable was melted and the airflow carried the melted thin into the module (Fig. 17).

Figure 16. Melted plastic insulation ring

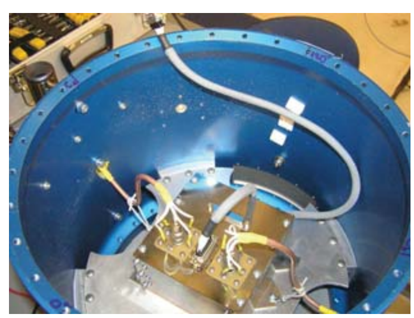

Figure 17. Melted thin on the surface of the module

8. CONCLUSION

Due to the failures presented in section 7 the scientific objectives of the Gekko experiment were not fulfilled. However, the experiment was partly successful as important experiences were gained both during the development and from the flight results. The most probable explanation for the unexpectedly high temperature that the condensers were exposed of are the shock waves. The Gekko experiment also served with important data about pipe flow properties in supersonic flights. Detailed analysis of the video recordings made by the cameras of other REXUS teams during the flight are to be carried out to extend our knowledge about the properties of the pipe flow. After detailed analysis the mechanical design will be reconsidered and the experiment is planned to be flown again to complete the scientific objectives.

9. REFERENCES

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