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Atmospheric density probe for VLEO applications

Taishi Kato, Momoka Shimoi, Shoma Taira, Yoshinori Nakayama*, Takashi Ozawa, Yusuke Yamashita***, Takumi Abe****, Kumiko Yokota, Masahito Tagawa**

Kobe University, Rikko-dai 1-1, Nada, Kobe 657-8501 Japan
**National Defense Academy of Japan, Harumizu 1-10-20, Yokosuka, 239-8686 Japan*
***Japan Aerospace Exploration Agency, Jindaiji-Higashimachi 7-44-1, Chofu, 182-8522 Japan*
****Department of Aeronautics and Astronautics, The University of Tokyo, 3-1-1, Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan*
*****Institute of Space and Astronautical Science, Yoshino-dai 3-1-1, Sagamihara, 252-5210 Japan*

Corresponding authors: Taishi Kato (205t320t@stu.kobe-u.ac.jp)
Masahito Tagawa (tagawa@mech.kobe-u.ac.jp)

1. Introduction

Due to increased demands of high-resolution Earth observation, a satellite orbiting altitudes lower than 300 km, which called very low Earth orbit (VLEO) or sub-LEO, is started considering. Compensation of atmospheric drag is mandatory for such VLEO satellites. It has been widely recognized that the atmospheric drag of satellites (F_d) are influenced by the atmospheric drag coefficient of satellite (C_d) and mass density of the orbit (ρ) by the fundamental relation (1).

$$F_d = \frac{1}{2}\rho V^2 C_D A_{ref} \qquad (1)$$

where A_{ref} is the cross-sectional area of satellite, and V is the orbital velocity. A_{ref} and V are evaluated precisely with the satellite design and GPS data, however, C_d is inaccurate due to the lack of method of experimental ground testing. Thus, C_d is often computed by the direct simulation Monte Carlo (DSMC) method, however, molecular scattering event at satellite surface is too much complicated to simulate in DSMC accurately. Therefore, there remains two uncertain parameters in equation (1), ρ and C_d. Because F_d is evaluated by on-board accelerometer or GPS data during satellite operation, ρ can be evaluated based on the C_d value even though it is not very accurate. In contrast, ρ is obtained by the atmospheric model predictions. Various empirical atmospheric models have been used to predict the atmospheric density such as MSIS [1,2], JB [3] or DTM [4] etc. Among these models, NRLMSISE-00 atmosphere model, which is the latest version of the MSIS-90 model [1], has been widely used [2]. However, the problem of atmospheric models including NRLMSISE-00 is its accuracy. Accuracy of these atmospheric models have been evaluated by some sounding rocket experiments [5] or free fall of spheres [6], and it was reported that the atmospheric density predicted by MSIS overestimates more than 40 % in some conditions in upper atmosphere [5,6].

Low accuracy of the atmospheric models including NRLMSISE-00 are mainly attributed to the lack of observation data at low altitudes. Because the neutral atmosphere is difficult to observe by remote sensing, an instrument to directly measure the atmospheric density needs to be launched. Some sounding rocket experiments gave an absolute density of atmosphere, but provides the data only at the limited moment and location. In contrast, global observation of the atmospheric density was performed by SLATS also showed the disagreement of atmospheric density of MSIS predictions and that evaluated form satellite drag (Figure.1). However, high-resolution accelerometer is high-cost, and GPS analysis provides only low resolution data.

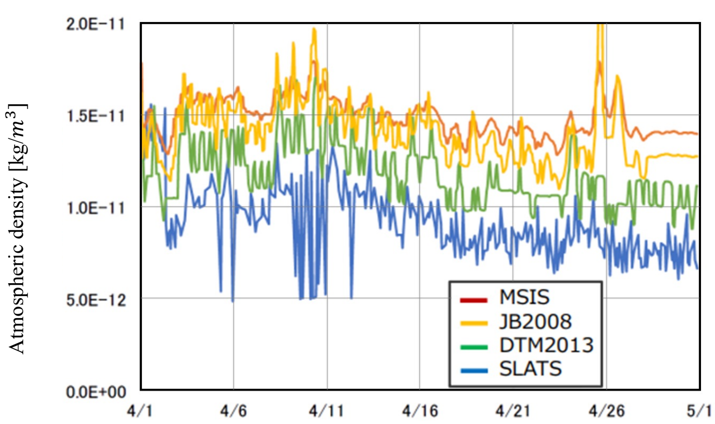

Figure1 Comparison of atmospheric number density between SLATS data and atmospheric models [7]

2. The dynamic pressure gauge

The dynamic pressure gauge designed in this study is shown in Figure 2 which is called Momoka Probe. The Momoka probe is based on the design reported by Patterson to measure the density of free molecule flow and by Clemmons for streak mission [8-10]. The Momoka probe is made of SUS304 and has a spherical shape with the outer diameter of 100 mm. The spherical sphere is used as an accommodation chamber which thermalize the incoming molecules with relative velocity of 7.5 km/s. The thermalized molecular density is detected by MG-2F miniature ionization gauge (Canon-Anelva Corp.). The temperature of accommodation chamber is measured by Pt sensor.

The analytical study was given by Patterson to measure the molecular flow density outside the probe from the pressure inside the accommodation chamber. According to the Patterson's analysis equation (2),(3) is hold in the equilibrium condition. Where P_{in} is the pressure measured with a indent flow at 0 degree (normal incidence) to the aperture, P_{in}' is the pressure measured with a indent flow at 180 degree (the aperture locates backside of the probe), $P_{\pi/2}$ is that with 90 degree (aperture locates parallel to the flow), and S is the ratio of flow velocity and thermal velocity which is given in equation (4). Where V is components of mass velocity and α is angle of attack. On the velocity component parallel to the orbital velocity, we obtain the equation (5) from equations (2) and (3). From the equations above, we obtain the equation (6) which gives the pressure of outside of the probe. Equation (6) indicates that the pressure of the outside of the probe is calculated from the pressure measured at three different directions.

$$\frac{P_{in}}{P_{\pi/2}} = 1/exp(S^2) + S\sqrt{\pi}(1 + erf(S)) \quad (2)$$

$$\frac{P_{in}'}{P_{\pi/2}} = 1/exp(S^2) - S\sqrt{\pi}(1 - erf(S)) \quad (3)$$

$$S = \frac{V\cos(\pi\alpha/180)}{\sqrt{2kT/m}} \quad (4)$$

$$S = \frac{P_{in} - P_{in}'}{2\sqrt{\pi}P_{\pi/2}} \quad (5)$$

$$P_{out} = \frac{P_{in}}{exp\{-S^2\} + \sqrt{\pi}S\left[1 + \sqrt{1 + erf(S)}\right]} \quad (6)$$

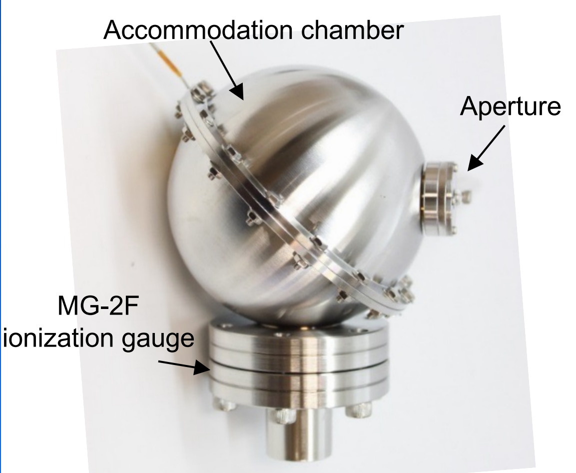

Figure 2. photograph of Momoka probe

3. Rarefied gas experiment

The orbital velocity of VLEO satellite is 7.5 km/s, which is difficult to reproduce in a ground-based facility. Even though a laser-detonation system can produce molecular beam pulse in this velocity range, it is not a continuous flow and a thermal equilibrium condition, which is required for holding equations (2) – (6). Therefore, the laser-detonation pulsed hyperthermal beam source was modified to continuous thermal beam source.

Figure 3 shows the schematic drawing of the modified system. It consists of three vacuum chambers, source, reaction and time-of-flight (TOF) chambers. In order to obtain continuous thermal beam, the pulsed supersonic vale (PSV) for laser-detonation system is replaced to the variable leak valve (VLV) with an auxiliary accommodation chamber which is inserted in Figure 3.

The Momoka probe is hanged from the rotatable stage in the reaction chamber. A 3mm skimmer was inserted between source and reaction chambers such that 3mm molecular beam was entered to the probe. Pressures inside the probe was measured by MG-2F ion gauge attached to the probe, whereas that outside the probe was measured by another MG-2F ion gauge attached to the reaction chamber wall (out of the beam axis). The pressure inside the probe was measured at three different probe orientations and P_{in} , P_{in}' , $P_{\pi/2}$, and the pressure outside the probe was calculated by equation (6). The analytical pressure obtained from equation (6) was compared with the pressure directed measured by the MG-2F gauge placed the reaction chamber.

The experiment was performed in the conditions shown in Table 1, and the results are listed in Table 2 where P_{amb} is pressure outside the probe actually measured, and P_{out} is pressure outside the probe calculated by eq. (6). It is clearly indicated that the analytical pressure calculated by equation (6) gives the value close to the pressure directly measured within the error of 20%.

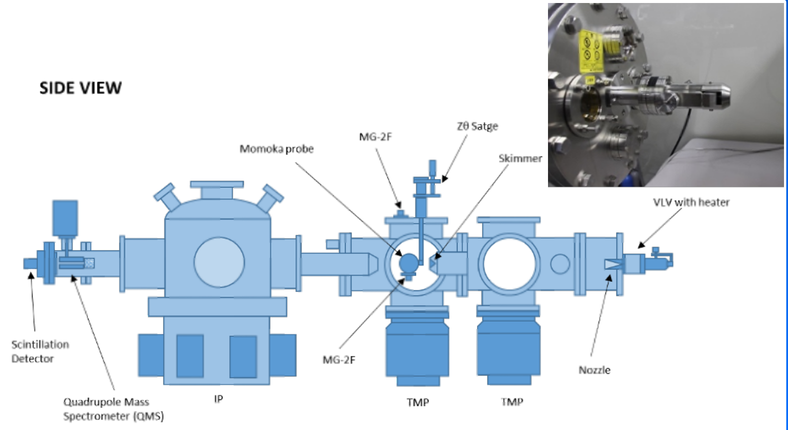

Figure 3 The schematic drawing of the apparatus. The inserted photograph shows the variable leak valve with an auxiliary accommodation chamber.

Table 1 Experimental conditions of the rarefied gas experiment.

Particle species	N_2
Velocity (m/s)	517
Temperature (K)	300
Number density (/m^3)	2.25E+14
Wall temperature (K)	330

Table 2 Results of the rarefied gas experiment. The analytical results using equation (6), pressure measured by ion gauge, and the error are listed.

P_{amb} (Pa)	P_{out} (Pa)	Error (%)
1.30E-05	1.04E-05	-20
1.79E-05	1.45E-05	-19
2.36E-05	1.88E-05	-20
3.19E-05	2.54E-05	-20
4.18E-05	3.34E-05	-20
5.80E-05	4.61E-05	-21

4. DSMC simulations

The Effect of the implementation configuration of Momoka probe on the satellite is investigated by the DSMC. The computational code was developed in the group. Figure 6 shows the implementation model for DSMC calculation. Cubic body of the satellite is assumed and the Momoka probe locates on the side surface of the satellite (Figure 4(a)). The pressure without the accommodation chamber is also calculated as a comparison purpose (Figure 4(b)). The simulation conditions for the VLEO environment are shown in Table 3. This is based on data taken from the NRLMSIS-00 model on January 1st, 2020 at an altitude of 268 km. The results are compared in Figure 5. Interactions between molecules are not considered in this simulation due to the large mean free path of the condition. The wall temperature is settled at 300 K and the reflection conditions are diffuse reflection.

The results are compared in Figure 5. The solid line shows the pressure in Momoka probe and dashed line shows the pressure at 50mm from the satellite surface without the accommodation chamber. It is indicated that the pressure inside Momoka probe indicates two orders higher than that without the accommodation chamber. Relative changes of pressure due to angle of attack (AoA) with/without the accommodation chamber are also inserted in Figure 7. The pressure without accommodation chamber increases rapidly with positive AoA. This is due to the scattering of molecules at satellite surfaces. In contrast, the pressure inside Momoka probe is almost constant against the change of AoA from -10 to +10 degree. This is owing to the insensitive AoA characteristics and accommodation capability of Momoka probe. From the DSMC calculation results, it is concluded that Momoka probe is insensitive to the satellite attitude at positive AoA. The molecular density is accommodated in the chamber which provide to large ion current, i.e., measurement with high SN ratio signal is provided. Thus, it is concluded that Momoka probe has many advantages as a total density probe in VLEO.

Table 3 Simulation conditions for the VLEO environment used in DSMC calculation

Species	N_2, AO, O_2
Flow velocity, (m/s)	7744
Gas temperature, (K)	576
Number density, ($/m^3$)	4.21E+14
Wall temperature, (K)	300

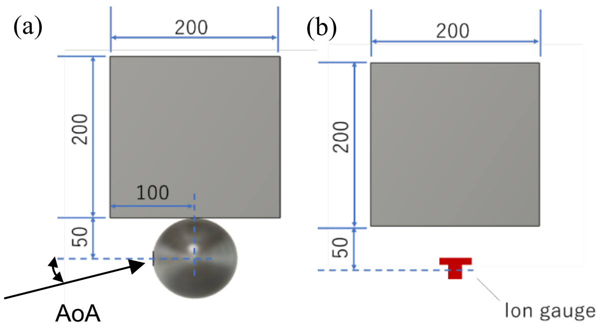

Figure 4 Implementation models of Momoka probe to a satellite for DSMC calculation. (a) Momoka probe, (b) Bare ionization gauge without accommodation chamber

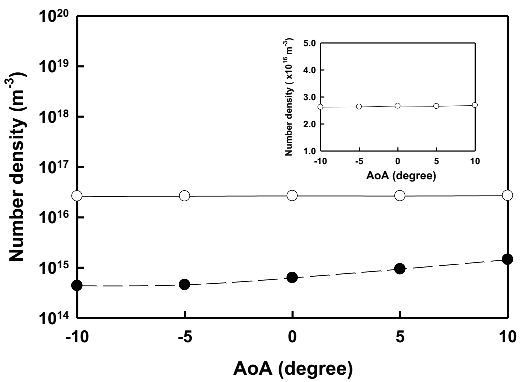

Figure 5 Pressures computed by DSMC in VLEO conditions as a function with AoA. Solid line: pressure inside Momoka probe, dashed line: pressure at 50mm from the satellite surface without accommodation chamber. The pressures in Momoka probe are enlarged by linear scale in the insertions.

5. Conclusions

A dynamic pressure gauge with accommodation spherical chamber, Momoka probe, was designed and tested for VLEO applications. It was designed based on the design reported by Patterson and Clemmons. The experimental results using continuous thermal N2 beam suggested that the analytical method proposed by Patterson is applicable to Momoka probe, however, it needs to measure pressures at three different orientations, which is difficult in orbit. It was also analyzed by DSMC that Momoka probe is insensitive to the flow directions and accommodates the molecules at two orders higher density inside the probe. These properties are advantageous for the measurement of total mass density in VLEO environment, and long-term observation of total atmospheric density in VLEO provides many scientific data as well as engineering data related to air breathing ion engine (ABIE).

Acknowledgments

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