Development of a Low Pressure Self-propelled Vapor Supply Subsystem for Electric Propulsion

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The aim of this paper is to develop a low vapor pressure self-propelled supply installation to fit the flow rate request of electric propulsion system for micro-satellite. This system was designed on the premise that the same liquid propellant can be used to the electric and chemical propulsion systems in the same time. However, the liquid propellant should be vaporized as vapor state before injecting to thruster. Therefore, one vaporizing tank is included in the system and will be one of most important component in this study. In designing stage, a theoretic model was derived to provide a criterion of vaporizing tank geometry. The vapor flow rate was limited by needle valves and estimated by orifice flow meter equation. To evaluate the performance of supply system, two calibration methods was used to estimate the flow rate by measuring the flow coefficient of orifice. The results showed the supply subsystem could be operated with steam flow rate range 20 to 85 μg/s with error less than 10%.

Nomenclature

A	=	cross section area of tank
C_d	=	discharge coefficient
C_v	=	flow coefficient of orifice
D	=	diffusion constant
ΔP	=	pressure difference between upstream and downstream
Δt	=	time step
M	=	atomic weight
m_{tank}	=	vapor or gas weight in the tank
$\dot{m}$	=	mass flow rate
n	=	number of iteration times
P	=	pressure of vapor or gas
P_{final}	=	final pressure condition
P_s	=	saturated vapor pressure

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P_t	=	pressure condition at a certain time
P_0	=	initial pressure condition
Q_g	=	flow rate of vapor or gas
R	=	ideal gas constant
$S.G.$	=	specific gravity of species
S_0, S_1	=	cross section area of duct
T	=	temperature
t	=	time
V_{vapor}	=	vapor velocity
z	=	height

I. Introduction

The developments of micro-satellite are noticed due to lower cost of launch to orbit. It is defined by global mass less than 100 kg that should be smaller and lighter than current ones. To reach this purpose, lightening and downsizing subsystems – especially propulsion and power, are necessary. The propulsion systems must be with high specific impulse that may reduce fuel cost in attitude control for long term missions. On the other hand, high thrust propulsion systems have the merits to reduce the time period in orbit transformations. So far, the technologies of many electric propulsion systems were developed for the former requirement, but in developing with heavy high power systems for the latter. However, high thrust chemical propulsions are faced with hard fuel weight penalty due to the characteristics of poor specific impulse. Therefore, a micro-satellite with both electric and chemical propulsion systems may be more suitable for multi-purpose of attitude and orbit control than an individual one.

A current electric and chemical propulsion system includes two or more individual propellant supply subsystems that may occupy relatively large volume and weight. And furthermore, the flexibilities of propellant utilization are limited due to that different propellants are served to each propulsion with poor allocations respectively. To apply to the micro-satellite, the complexity of propulsion systems should be simplified. In this study a concept of electric and chemical propulsion system integration is suggested. Fig. 1 shows one kind of monopropellant served by a common main supply installation that may simplify and lighten the system machinery substantially. Using monopropellant, such as hydrogen peroxide, nitrous oxide, or hydrazine, has benefit in remnant fuel management. However the supply subsystem should be variable with large range of flow rate, for example, the scales of flow rate for the chemical and the electric propulsion are g/s and μg/s to mg/s respectively.

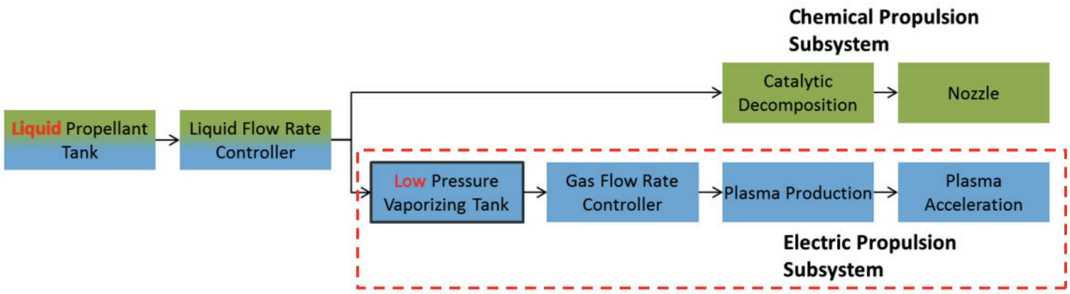

Figure 1. Electric and chemical propulsion systems with vapor supply installation

In the past, Lichon and Sankovic[1] presented a 600 s mission-average specific impulse hydrazine arcjet. The propellants used are nitrogen, hydrogen, and ammonia which are the catalytic decomposition products of N_2H_4 which stored in liquid state in common. Zube et al.[2] demonstrated an on-orbit performance of a 2 kW hydrazine arcjet system. The typical specific impulses for hydrazine arcjets are from 400 to nearly 600 s. In recent years, high-test peroxide (HTP) has attracted renewed attention as a safer and environmentally friendly green monopropellant and become a potential alternative to the hazardous hydrazine propellant. Although the specific impulse of HTP is smaller than that of hydrazine, the advantages of easier and safer handling of hydrogen peroxide, resulting in cost and time savings in system testing and development, are worthwhile tradeoffs. In this study, water substituted for hydrogen peroxide to be used for test due to its chemical stability and similar properties. Water is also one kind of products in hydrogen peroxide decomposition reaction. In the other hand, they have the same chemical species H and O that the properties of plasma may be similar. For these reasons, water could be a suitable specimen for system test especially in hydrogen peroxide experimental imitation. Kakami et al.[3] developed an ink-type injector with flow rate 2.7 to 38 μg per mass shot. The reliable injection system is very suitable for pulsed plasma thruster. However a system can be operated continuously is still desired.

The aim of this study is to develop a low vapor pressure self-propelled supply installation (as shown in Fig. 1 with dash line) to fit the flow rate request of electric propulsion system.

II. Vapor Supply Subsystem Design

The vapor supply subsystem is shown in Fig. 2 with dash line. Liquid water was injected to vaporizing tank which had been evacuated as vacuum. Liquid water vaporized until vapor pressure equaled to saturated vapor pressure. Commonly, heating is necessary to promote the process to reach higher pressure, produce large amount of vapor for injecting to installations in the downstream especially for experiments in atmosphere. However there are disadvantages of energy consumption and difficulties in keeping warm. In the experimental tests and applications of electric propulsions, the ambient pressure is always vacuum, and the requirements of mass flow rate usually very small that heating may not be available. The liquid propellant supply subsystem with steam flow rate 10 to 100 μg/s was focused in this study. Lower vapor pressure can fill the bill easier with an ordinary size of orifice. In addition, lowering saturated vapor pressure by cooling has benefit to against condensing in a warmer downstream ducts and installations. In this study, there was another tank in downstream as temporary vapor storage. That also had benefit to ensure no liquid exist by controlling vapor pressure much lower than saturated vapor pressure. For example, the temperature and saturated vapor pressure of water were 10 ºC and 1193 Pa in vaporizing tank, and 21 ºC and 2439 Pa in temporary storage ones. The vapor pressure of temporary vapor storage tank was controlled around 500 Pa to fit above-mentioned purpose.

Both vapor pressure of temporary vapor storage tank and flow rate were controlled by flow controlling sets including a solenoid valve and a needle valve. The solenoid valve (J262G90VM, made by ASCO Japan Co. Ltd.) can control flow open and cut off with settling time less than 10 ms even in high vacuum condition ($1.3\times10^{-1} \sim 1.3\times10^{-4}$ Pa). The needle valve, which was set in the downstream of temporary vapor storage tank, was used to limit the flow rate as a cross-section adjustable orifice. The flow rate in needle valve can be essentially estimated by

$$Q_g = 41.7\, C_v \frac{\Delta P}{\sqrt{S.G.\cdot T}}\ [sccm] \tag{1}$$

This equation applies to the cases which are with more than two times in pressure difference or vacuum condition in the downstream side. The pressure was about 500 Pa in the temporary vapor storage tank (upstream) and less than 10 Pa in thruster (downstream). For the aim of steam flow rate 10 to 100 μg/s (0.8 ~ 8 sccm), the flow coefficient C_v was $7.7\times10^{-4} \sim 7.7\times10^{-3}$ with above pressure conditions. The needle valve (SuperNEEDLE, made by FRONTO Co., Ltd.) was used to test with wild C_v tuning range.

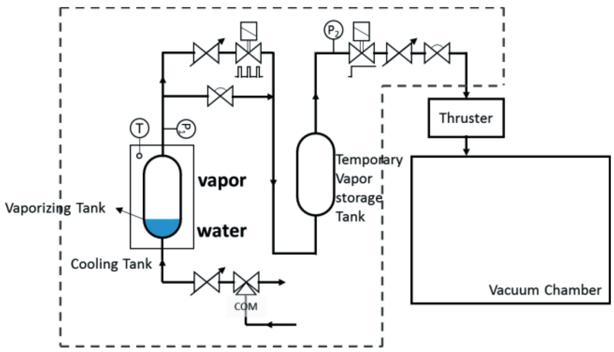

Figure 2. Vapor supply subsystem for liquid propellant

III. Theory Derivation of Vaporing Tank Design

Before designing supply subsystem especially the geometry of vaporing tank, the analyzing of vaporization is needed. A 1-D theory model with diffusion procedure was suggested to estimate the vapor pressure, which urges flow rate.

A. Pressure Gradient in the Tank

Considering an isothermal tank with cylinder shape (see Fig. 3), there was no variations in radial direction but just with a few liquid in the bottom that the tank space can be seen as a 1-D structure. To simplify the model, no condensing phenomenon and forced convection existed; therefore the surface area of liquid would be a constant and the same to the cross section area *A* of the tank. The vaporizing process would started when vapor pressure was less than saturated vapor pressure that caused pressure unbalanced and diffusion. In diffusion model, the vapor velocity could be expressed by Fick's first law.

$$V_{vapor} = -D\frac{M}{RT}\frac{dP}{dz} \tag{2}$$

where the diffusion constant D could be estimated by empirical formula as follows for water.

$$D = 0.241\left(\frac{T}{288}\right)^{1.75}\left(\frac{1.013\times10^{5}}{P}\right)\ [cm^2/s] \tag{3}$$

If there was an exit (but ignored the effect of exit shape) in the wall of tank, the tank would be an open system with vapor leakage. Vaporization and diffusion would never stop until liquid propellant depleted. If the process was a steady state, the production of vapor by vaporization must be equal to the mass consumption $\dot{m}$ from exit. That means the variation of vapor mass in tank was 0.

$$\frac{d}{dt}m_{tank} = V_{vapor}A - \dot{m} = 0 \tag{4}$$

The vapor pressure with height z in tank could be solved by Eq. (2) to (4) with saturated vapor pressure P_s on the liquid water surface ($z = 0$).

$$P(z) = P_s\,exp\left(-\frac{\dot{m}}{2.627\times10^{-6}\,T^{0.75}}\frac{z}{A}\right)\ [Pa] \tag{5}$$

It could be rewrite by its dimension less forms as

$$\overline{P}(z) \equiv \frac{P(z)}{P_s} = exp\left(-\frac{\dot{m}}{2.627\times10^{-6}\,T^{0.75}}\frac{z}{A}\right) \tag{6}$$

where the vapor pressure in exit with height z depends on saturated vapor pressure P_s (which can express as the function of tank temperature), mass flow rate $\dot{m}$ [g/s] , and the parameters of tank geometry (where the unit of height z and cross section area A is cm and cm^2 respectively).

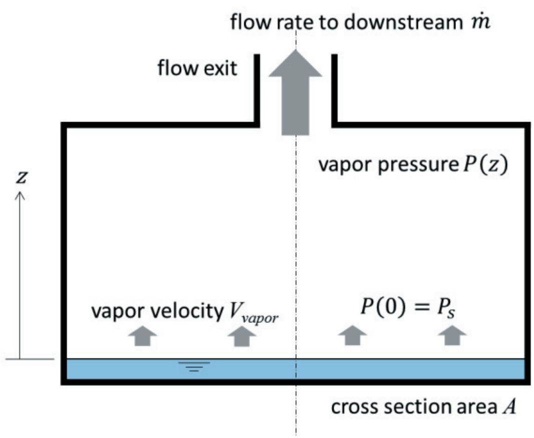

Figure 3. 1-D theory model

B. Criteria of Tank Geometry Design

Consider the case of mass flow rate limited by orifice; the mass flow rate can be defined as

$$\dot{m} = C_d\frac{S_0}{\sqrt{1-\left(\frac{S_0}{S_1}\right)^2}}\sqrt{2(P_{upstream}-P_{downstream})\rho} \tag{6}$$

If $P_{upstream}$ is much larger than $P_{downstream}$, the difference of pressure between upstream and downstream can be simplified by $P_{upstream}$ only. Rewrite the Eq. (5) by Eq. (6), we can get

$$\dot{m} = C_1\,exp\left(-\frac{\dot{m}}{C_2A}z\right) \tag{7}$$

$$C_1 = C_d \frac{S_0}{\sqrt{1-\left(\frac{S_0}{S_1}\right)^2}} \sqrt{\frac{2M}{RT}} P_s \quad (8)$$

$$C_2 = 2.627 \times 10^{-6} T^{0.75} \quad (9)$$

Where C_d, S_0, S_1 are the design factors of orifice and ducts which may be considered as constants. Then P_s is the function of T and is also seen as constant. First-order derivative with respect to z was served to solve Eq. (7) and the solution can be presented as follows.

$$\frac{1}{\dot{m}} = \frac{1}{C_2}\frac{z}{A} + \frac{1}{C_1} \quad (10)$$

or

$$\frac{z}{A} = C_2\left(\frac{1}{\dot{m}} - \frac{1}{C_1}\right) \quad (11)$$

In a larger flow rate system, the cross section area of tank A must be larger for producing and providing enough vapors, and the height z (position of duct) should be as much as possible near the liquid surface. Conversely, the tank might be "slim" for a lower flow rate system. However the geometry of tank must be confined by the limits of satellite space and mass. In this study, a tank with inner height 155 mm and inner diameter 85.1 mm was chose to produce enough amount of vapor. The product of vaporization was about 560 μg/s, which was much more than the objective of flow rate 10 to 100 μg/s, and that was easy to get balance of mass payment with a well flow orifice, which limited the flow rate. Sometimes the pressure gradient also has to be considered by Eq. (5). The theoretic results are shown in Fig. 4. The pressure was 99% to 86% of saturated vapor pressure with flow rate 10 to 100 μg/s and the tank size in this study. However, the result would become less than 30% if the mass flow rate more than 1 mg/s. In a large flow rate conditions, heating to increase pressure or designing a new tank with large bottom geometry is needed.

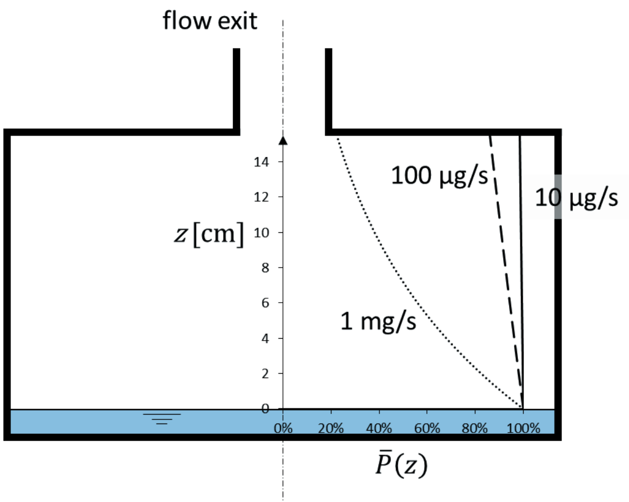

Figure 4. Pressure gradient with different mass flow rate conditions

IV. Flow Rate Calibration

To verify the reliability of liquid propellant supply subsystem in this study, three methods may be applied. Firstly measuring consumptions of propellant weight with other conditions in constant was a directly and easily method. However the calibration tests in this study with the mass flow rate requirement 10 to 100 μg/s should cost a lot of time until sufficient variation of weight can be observed (0.864 to 8.64 g/day). Therefore, other two ways following the orifice flow meter equation (Eq. (1)) had been suggested – constant pressure method and pressure drop method -- to measure the flow coefficient C_v of needle valve (or orifice). Argon flow with an accurate flow meter was applied to substitute for liquid propellant in both two methods to make sure the test results was exactly.

A. Constant Pressure Method

In the constant pressure method, the orifice cross section of the needle valve was adjusted to keep gas pressure of temporary vapor storage tank in a certain range. As the pressure approaching a constant value, variety of gas mass in the tank was 0 that means ejection should equal to injection. Then the flow coefficient C_v of needle valve can be calculated by Eq. (1) with current flow rate. For liquid propellant case, the specific gravity of argon (1.38) may be replaced by steam (0.625), and vapor flow rate can be estimated with the known conditions such as flow coefficient, tank pressure and flow temperature. The method may cost dozens of minutes for one calibration data that had much shorten the process than the weight variation measuring method.

Fig. 6 shows the experimental results by using constant pressure method with argon as the test gas. The pressure conditions in temporary vapor storage tank and thruster were 500 Pa and less than 10 Pa respectively. The flow coefficient C_v could be estimated by Eq. (1). Then the flow rate of steam case could be calculated by the same equation. From the results, the flow coefficient was in the range between 1.05×10^{-3} and 4.45×10^{-3} that corresponded to steam flow rate 20 to 85 μg/s.

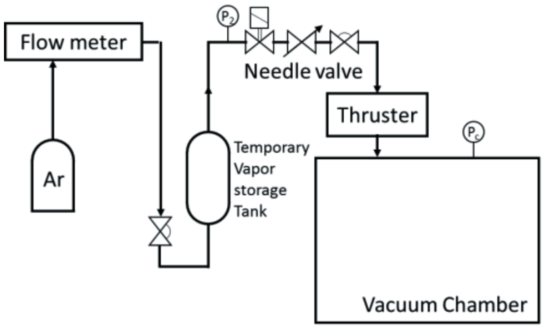

Figure 5. Calibration system for constant pressure method

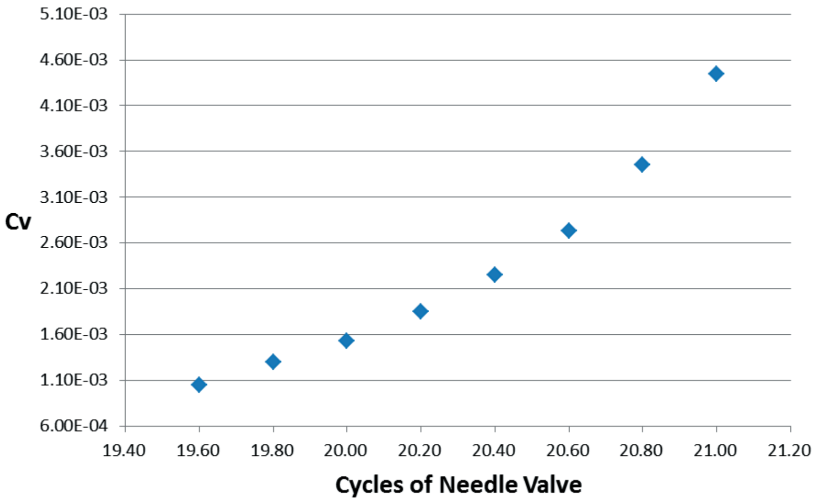

Figure 6. Experimental result of flow coefficient by constant pressure method

B. Pressure Drop Method

Figure 7 and 8 shows the experimental system and simulation model used to estimate flow coefficient of needle valve respectively. Firstly, temporary vapor storage tank was with initial pressure P_0 (or initial vapor mass m_0). As opening the solenoid valve, the pressure would drop and be a time dependent parameter due to propellant consumption. Flow rate also depended on time and the instantaneous flow rate could be calculated by Eq. (1) with current pressure. This process would continue until pressure approaching 0. A numerical model was suggested to simulate the time-varying pressure drop and estimate the flow coefficient and further calculate flow rate with any known pressure data.

In the model, the real variation of pressure during an infinitesimal time (Δt < 10 ms) can be approached by the model. After one iteration cycle (Δt), the calculated pressure value would be used to calculate a new instantaneous flow rate and then a new variation of pressure occur in the next

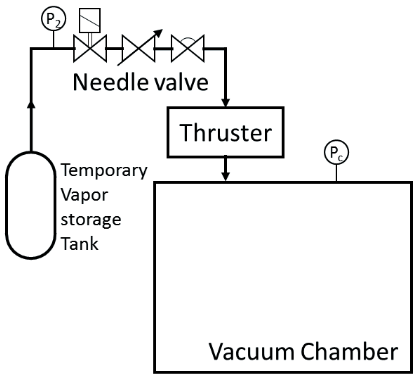

Figure 7. Calibration system for pressure drop method

cycle. Finally, a sufficient pressure variation (from P_0 to P_{final}) could be observed during a period of time ($n \cdot \Delta t$). Fig. (9) shows the varieties of cost time until the same set point of pressure with different flow coefficient but the same initial pressure condition. The time cost in a larger flow coefficient case should be less than in a smaller one because of larger initial flow rate. That means flow coefficient or flow rate can be easily estimated just by comparing the time cost from experimental data to it from simulation. The experimental calibration tests just cost several seconds to several minutes for one calibration data that much shorten the time of flow rate calibration.

The result is shown in Fig. 10. The experiment and simulation started form pressure 500 Pa. As the pressure lower down to 300 Pa the experimental profile (line in bold) would be recorded and compare to the simulation data (dash line) and then estimate the flow coefficient. The comparing result shows a different tendency in higher (> 400 Pa) and lower (< 400 Pa) pressure regions that caused the difficulties in calculating flow coefficient. However we still can find any two dash lines surrounding the experimental line. For example, the bold line in the left was surrounded by simulation results of flow coefficient 2.2×10^{-3} and 2.6×10^{-3}. At the least, a vague value of flow coefficient could be approached with error less than 10%. In another hand, the test results of constant pressure method could give us a criterion to evaluate the accuracy of simulation result. The difference of flow coefficient between these two methods is about 2 to 10%.

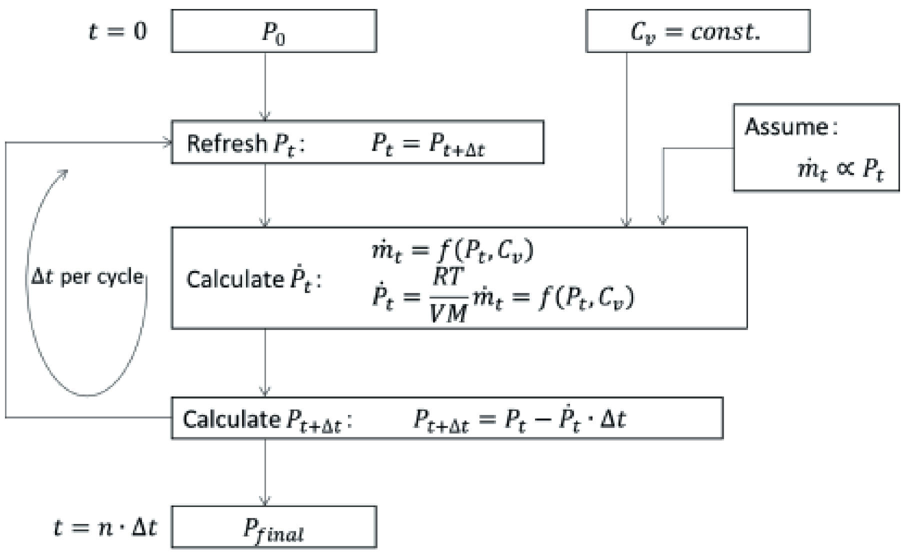

Figure 8. Flow chart of simulation model

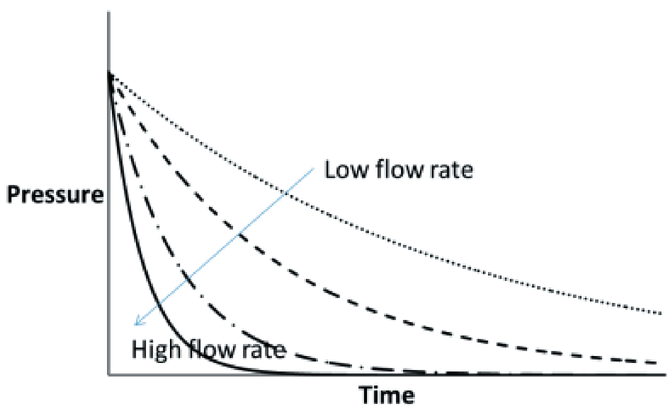

Figure 9. Varieties of pressure drop velocity with different flow coefficient

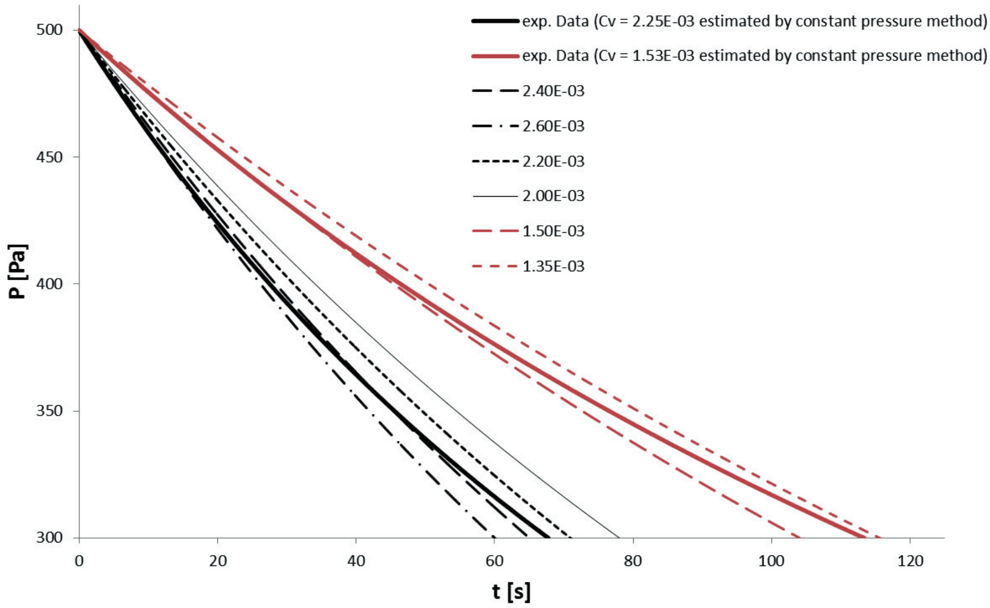

Figure 10. Simulation and Experimental result of flow coefficient by pressure drop method

V. Conclusion

In this study, a concept of multi-purpose propulsion system coupled by chemical and electrical thrusters with the same liquid propellant supply subsystem was suggested. To apply to electrical propulsions on micro-satellite, the requirement of propellant mass flow rate was 10 to 100 μg/s. One theoretical model was suggested to help us design the propellant supply subsystem. To evaluate its performance, two calibration methods was been used to estimate the flow rate by measuring the flow coefficient of orifice. The results showed the supply subsystem could be operated with flow rate range 20 to 85μg/s with error less than 10%..

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