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微小重力環境での燃焼および惑星居住への適用の可能性

Combustion Under Microgravity Environment and Its Applicability for Planetary Habitation

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1. Introduction

Human planetary habitation must contribute to make a sustainable society, find space resources, develop new materials by utilizing unique environment of space, and so on. Toward it, we need broad knowledge associated with physical, chemical, and biological sciences, that is, we need to address this theme as a crosscutting issue. As the topic presented in the report, I deal with energy usages, especially the utilization of the combustion under micro- and low-gravity environment. In terms of the utilization of the microgravity environment to clarify the combustion science, it has the great advantage for a numerical validation with low computing cost, because natural convection can be suppressed, and thus, for instance of fuel droplet, the combustion system becomes spherically symmetry. Since the first microgravity combustion experiment of fuel droplet using drop-tower conducted by Kumagai and Isoda[1)], many researches have been being conducted for isolated droplet[2)], droplet pair[3)], droplet array[4,5)], and 2D droplet lattice[6)] as a fundamental combustion science. As the important piece of research on the combustion associated with the planetary habitation, fire safety issue has been being addressed. FLARE project which is the recent campaign for the fire safety is ongoing by Fujita et al[7)]. In summary, the knowledge of the combustion under microgravity is very beneficial, however, there are few researches on it as the practical and active use for the planetary habitation such as energy generation. In the case of the moon, utilization of hydrogen is discussed because the existence of ice in the polar region is revealed[8)]. The atmosphere of Mars which has the highest habitability in the solar system planet consists of carbon dioxide (CO_2). Since the CO_2 includes the oxygen, utilization of CO_2 as the oxidizer of the propulsion system is expected. To make effective use these resources, deep understanding of the combustion under microgravity is necessary. In this report, the difference in the combustion phenomena under normal, low, and microgravity environment is introduced and the potential of the use of combustion associated with the planetary habitation is discussed.

2. Engine vs. Fuel Cell

To generate energy, we have several options; solar panels, fuel cells and engines. The solar panel has a great advantage in terms of the utilization of the sun light that is not permanently exhausted. However, it is inferior to other energy sources in efficiency and energy density. Figure 1 shows the relationship between the operation temperature and theoretical efficiency of Carnot cycle on behalf of engine, and fuel cell on behalf of the facility which does not utilize combustion. In both cases, they are calculated with the initial temperature, that is the lowest temperature in these systems, of 300 K. For fuel cell, fuel is hydrogen and the chemical equilibrium components are not considered. Fuel cell shows a high efficiency in the lower temperature side, meanwhile, Carnot cycle does in the higher temperature range. Since the chemical reaction release the energy as temperature increases, the power output increases with the high temperature operation. Therefore, engine is superior to the fuel cell in the power generation with high efficiency, that can be achieved by the high temperature operation. For energy generation at the limited space, or propulsion use, the engine exerts the potential.

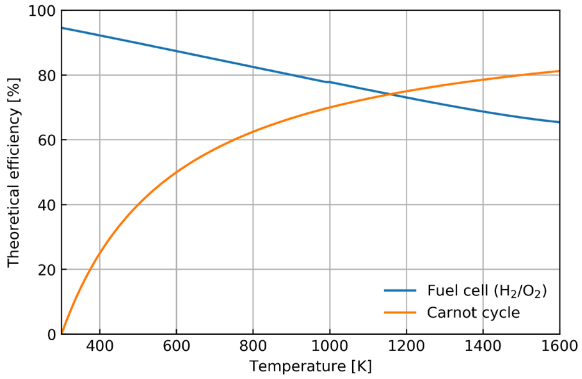

Fig. 1 Temperature dependance on the theoretical efficiencies of Carnot cycle and fuel cell

3. Gravity Effect on the Combustion

Gravity-induced natural convection affects combustion accompanied with phase change such as liquid and solid fuel. For example, liquid rocket utilizes the liquid hydrogen. For the Mars vehicle, ducted rocket whose fuel is some metal particles was proposed[9]. Because the solid metal particle such as aluminum also change their phase during combustion, they show the same physical and chemical processes to the liquid fuels.

Figure 2 shows the difference example of the temperature distributions in 1 G and 0 G conditions acquired by the numerical calculation. The ambient temperature and pressure are 600 K and 1 atm respectively. The upper row of figure is 1 G condition and the lower one is 0 G condition. The center figures surrounded by square correspond with the ignition delay time defined as the period from heat up timing to the time when the time derivative of the temperature history is maximized. As shown in the figure, temperature rise caused by the spontaneous ignition starts from the bottom of the droplet under 1 G condition. The hydrocarbon fuel, especially higher *n*-alkane, shows the two-stage ignition. Two stage ignition consists of the chain branching reaction under low temperature, and thermal explosion activated by high temperature. From our study, it is confirmed that this temperature rise is caused by the cool flame subsequent the chain branching reaction. Fuel is heavier than air and falls to the bottom. As a result, the fuel concentration becomes high in the bottom region and ignition occurs from the bottom. Afterward, hot burned gas moves upward by the natural convection. Meanwhile, the ignition occurs evenly around the droplet under 0 G condition.

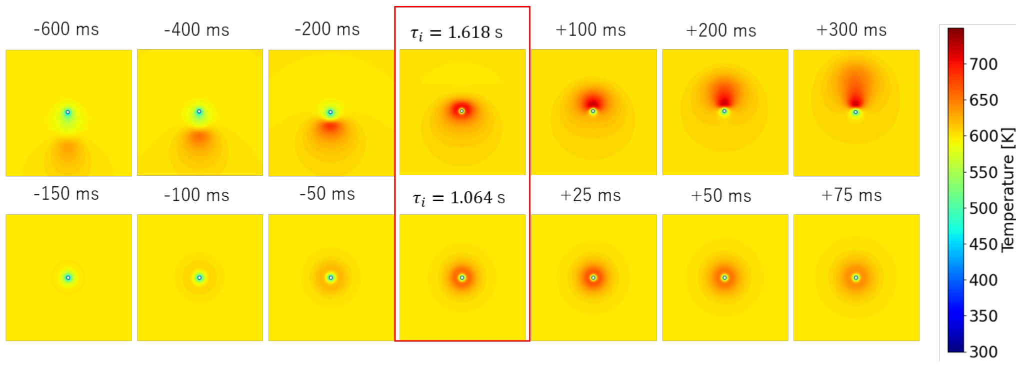

Fig. 2 Temperature distribution histories under 1 G (upper) and 0 G (lower) conditions.
(ambient temperature: 600 K, ambient pressure: 0.1013 MPa)

To evaluate the impact of the gravity effect on the combustion time of these fuels, Grashof number is generally employed. Grashof number is the ratio of buoyancy and viscosity, and it can be expressed by the following formula in the case of the droplet or metal particle combustion system with its initial diameter of d_i,

$$Gr = \frac{g\rho^2 d_i^3}{\mu^2}\left(\frac{T_f - T_a}{T_m}\right) \tag{1}$$

where g is the gravitational acceleration, ρ and μ are the average density and the viscosity calculated by the mean temperature T_m of flame temperature T_f and ambient temperature T_a. Figure 3 shows the gravity dependence on the Grashof number with various initial droplet diameters. Temperature of 2300 K for T_f and 300 K for T_a are employed, that is the same condition as the Sato's work[10]. The symbols of circle, triangle, and square are the Grashof number on the earth, Mars, and Moon respectively. Heat transfer driven by the natural convection gets high with high Grashof number. Therefore, as decrease in the Grashof number due to low- or microgravity, the burning rate constant k_0 generally gets lower than that of normal gravity, k. Okajima et al. revealed the relation of $(k/k_0 - 1) \propto Gr^{0.52}$ around $Gr \sim 1$[11], and Sato et al. did that of $(k/k_0 - 1) \propto Gr^{0.25}$ around $Gr \gg 1$[10]. Actual spray combustion system of liquid fuel, the spray consists of fine droplets whose diameters of 10^0 to 10^1 µm order. Therefore, there are few effects of the gravity on the combustion of these fine droplets even if under normal gravity. So, if the combustion characteristics of these fine droplet can be clarified, the knowledge can be applied to the combustion design under microgravity environment. However, since both spatial and time resolution cannot be secured, we cannot help using a large droplet. This is the reason why the droplet combustion is being researched under microgravity environment. Grashof number is not only affected by gravity but also density, that is, ambient pressure. As shown in the right figure, Grashof number of 10 MPa, which actual combustor pressure reaches, is 10^4 greater than that of atmospheric pressure.

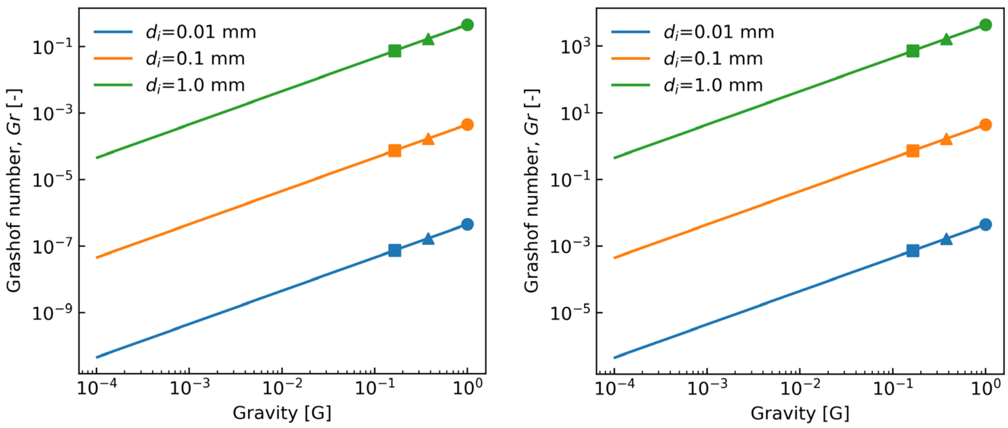

Fig. 3 Gravity dependance on the Grashof number with different initial droplet diameters (left: 0.1013 MPa, right: 10 MPa)

As another effect of the gravity on the combustion phenomena, Tanabe reported that the natural convection affects the induction time of the *n*-dodecane droplet[12]. During the chain branching reaction, the concentration of the intermediate agent produced in the reaction process controls the reaction speed. Since the natural convection yields the dissipation of these agents, ignition delay time gets behinds to the time without convection.

As shown in the Fig. 4, the difference of the simulated temperature history under 1G and 0G conditions is introduced. This calculation corresponds with that of the result seen in Fig. 2. The temperature is the maximum temperature in the calculation domain. In the case of the 0 G condition, temperature rise is steep, and the subsequent temperature oscillation was found. Similar behavior was found around 1.6 s of 1 G case, however the ignition location transition as surrounding of the droplet yields this behavior, and the ignition location after the first temperature peak was different with before the first peak as seen in Fig. 2. So, this behavior can be distinguished with the oscillation. Meanwhile, although the temperature rise timing of 1 G condition is earlier than that of the 0 G condition, temperature rise is gradual, and the ignition delay time becomes longer than that of 0 G condition. It is thought that the agent dissipates by the natural convection and the chain branching reaction becomes slower. In terms of the oscillation, even if the oscillation occurs out of the simulated time range of the 1 G condition, the behavior definitely shows difference so far. For the fundamental combustion researches, we have been obtaining the knowledge on the combustion difference under the microgravity environment mentioned above, which can contribute the combustion design in the low and microgravity environment.

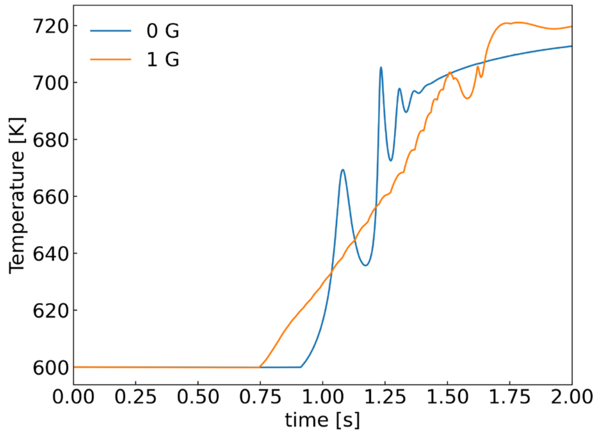

Fig. 4 Temperature histories of an isolated droplet under 1 G and 0 G conditions (ambient temperature: 600 K, ambient pressure: 0.1013 MPa)

4. Summery

For the planetary habitation, although the combustion is inferior to the fuel cell in efficiency under low temperature operation, to use the combustion phenomena has some potential to gain the energy for the power generation in the limited space, and for propulsion system. For the spray combustion, the combustion time and ignition timing depends on the gravity due to the natural convection. The combustion phenomena have been being clarified under microgravity environment because these effect can be minimized and the combustion system becomes simple without convection. The knowledge is very useful for the combustion design in the low and microgravity environment.

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References

1) S. Kumagai and H. Isoda: Proc. Combust. Inst., **5** (1955) 129.
2) M. Tanabe, M. Kono, J. Sato, J. Koenig, C. Eigenbrod, F. Dinkelacker and H. J. Rath: Combust. Sci. Technol., **108** (1995) 103.
3) O. Moriue, Y. Nishiyama, Y. Yamaguchi, H. Hashimoto and E. Murase: Proc. Combust. Inst., **34** (2013) 1585.
4) M. Mikami, H. Oyagi, N. Kojima, Y. Wakashima, M. Kikuchi and S. Yoda: Combust. Flame **146** (2006) 391.
5) M. Saito, Y. Ohno, H. Kato, Y. Suganuma, M. Mikami, M. Kikuchi, Y. Inatomi, T. Ishikawa, O. Moriue, H. Nomura and M. Tanabe: Intl. J. Microgravity Sci. Appl., **36** (2019) 360205.
6) M. Mikami, M. Kikuchi, Y. Kan, T. Seo, H. Nomura, Y. Suganuma, O. Moriue and D. L. Dietrich: Intl. J. Microgravity Sci. Appl., **33** (2016) 330208.
7) O. Fujita: Intl. J. Microgravity Sci. Appl., **32** (2015) 320402.
8) S. Li, P. G. Lucey, R. E. Milliken, P. O. Hayne, E. Fisher, J. Williams, D. M. Hurley and R. C. Elphic: Proc. National Academy of Sci. U. S. A., **115** (2018) 8907.
9) M. Ushijima, H. Hara, A. Muramatsu and T. Kuwahara: Proc. 46th AIAA/ASME/SAE/ASEE Joint Prop. Conference and Exhibit, AIAA (2010) 2010-6999.
10) J. Sato, M. Tsue, M. Niwa and M. Kono: Combust. Flame, **82** (1990) 142.
11) S. Okajima and S. Kumagai: Proc. Combust. Inst., **19** (1982) 1021.
12) M. Tanabe, M. Kono, J. Sato, J. Koenig, C. Eigenbrod and H. J. Rath: Proc. Combust. Inst., **25** (1994) 455.