Scale Modeling of Space Fire

Yuji NAKAMURA¹, Kaoru WAKATSUKI² and Aki HOSOGAI³

¹ Graduate School of Engineering, Hokkaido University, Sapporo 060-8628, Japan
² National Research Institute of Fire and Disaster, Tokyo 182-8508, Japan
³ Aerospace Research and Development Directorate, Japan Aerospace Exploration Agency, Tsukuba 305-8505, Japan

(Received 12 January 2013; received in revised form 12 April 2013; accepted 20 April 2013)

Abstract
This paper presents a novel ground-based methodology to investigate an important characteristic of fire in space. Based on the concept of scale modeling - Grashof-number (Gr) similarity -; the transport process found in small-scale fire in low-pressure (on earth) should be similar to that in space. Our similarity approach has successfully achieved to form the nearly-spherical shape of flame over the small rod-shaped combustibles (e.g., electric cable) by adopting the low pressure. Important finding is that the flame spread rate becomes faster in low-pressure than that in the normal-pressure and this is exactly the same with what found in low gravity experiment. This paper demonstrates the advantage of the scale modeling to predict the extraordinary fire in a simple way.

Key words
Scale Modeling, Low-gravity, Low-pressure, Space Fire, Flame Spread

1. Introduction

1.1 Background: current strategy for fire safety in space
Fire in space (e.g., space stations, other planets) must be prevented with our best knowledge in order to conduct a manned space mission safely. There are a number of critical fire-safety regulations for materials used in space habitats, however, the test to evaluate whether the material could pass the regulation or not is generally performed on earth, not in space. Nowadays variety of fundamental research outcomes are available to conclude that materials exposed in microgravity are more flammable as compared in normal gravity [e.g., 1]. Considering this fact, the regulation test must be carefully designed to evaluate properly the fire safeness in space.

Fig.1 shows the test method proposed by NASA for the electric cables (wires) used in space (NASA NHB8060.1C) [2]. Generally a polymer, which is highly flammable, is used for the insulator because of its high-quality of electric insulation resistance. Therefore the flammability of cable shall be examined in order to evaluate whether it is satisfactory for use in space. The procedure of the test is as follows; first a specimen is placed in straight with angle of 15 degree from vertical and is ignited at the bottom edge with prescribed ignition power. After the successful ignition, a flame spreads along the cable to upward (or may not spread if the insulator shows satisfactory fire retardancy). If the flame does not spread more than 6 inch (about 0.15 m) by this method, the cable is “passed” and officially approved to use in space.

Recall that this test is performed on earth, we easily expect that the buoyancy affects the combustion behavior extensively. In this configuration, flame should cover the unburned cable during the spread event to promote the preheating to it. Since the flame spread behavior is mainly controlled by the heat transfer to the unburned fuel, the flame shape depending on gravity should affect the subsequent combustion behavior. Moreover, the flame shape becomes “non-symmetric” along the wire which is hardly expected in space. Additionally, it is well-known that diffusion dominates the transport processes in space (under microgravity), resulting that the heat would be accumulated at the fire area. Obviously, no such situation is expected on earth: generally transported by buoyancy-driven flow to promote the heating to the other area. Considering altogether, we should wonder what kind of potential fire scenario this test can cover up; namely, it is question whether this test can properly evaluate the material safeness subjected to the fire in space. To overcome this difficulty, we need to develop new methodology to evaluate the flammability of the material used in space satisfactory with concrete scientific background to ensure that the test can cover up the fire in space. This is motivation in the present work.

1.2 Objective and aim of this study
In order to fulfill the safety requirement in space, it is inevitable to understand the fire behavior itself under various gravity conditions (less than normal-g): how the transport process is affected by buoyancy and how the fire
character is modified because of it. For this purpose, most popular way is to utilize so called microgravity environment. There are several facilities to achieve gravity-suppressed condition; namely, the orbital maneuvering object (like International Space Station: ISS), parabolic flight, and drop tower. Unfortunately, none of them is handy and easy to adopt; rather, they are quite costly and time-consuming for preparation. Moreover, these facilities commonly have “inherent” limitations to perform the test, such as the small test volume [e.g. 3], the less-number of test chance etc. In this sense, applying these microgravity environment to perform the material flammability test, which required high-reproducibility (large number of test is necessary) and large chamber volume is preferable, does not sound realistic and practical. Thus, once we have other methodology which can reproduce/simulate the various-gravity phenomena under normal gravity, it should be more very beneficial in practical point of view. The objective of the present work is to propose such novel methodology based on scale modeling concept.

2. Scale Modeling

2.1 What is “scale modeling”? [4-5]
Scale modeling stands for an investigation approach to find the scaling law applicable to the specific phenomena. What to be scaled (modeled) is called “prototype” and the scaled one is called “scale model”. Scaling law gives the relation between prototype and scale-model. Scale modeling is useful to examine the fundamental physics lied on the phenomena. In other word, once the governed physics for the specific phenomena are known, the scaling law can provide us the methodology how to reproduce the phenomena in a different environment.

2.2 How to simulate the low-gravity fire?
One example of microgravity fire test is shown in Fig.2 [6]. Direct picture of spreading flame and illustration for modeling purpose are both shown here. In this image, flame spreads toward right direction over the thin cellulosic sheet subjected by slow air-blowing, 2.0 cm/s, from opposite direction of flame spreading. Flame moving speed (often called “flame spread rate”) is an order of several millimeter per second.

Now, let us consider the main factors to govern the transport. Due to the slow-flowing condition, inertia force given by the external flow is weak and nearly equivalent to the viscous (diffusion) force. Naturally, it is expected to form thicker boundary layer over the combustible surface and flame is moving inside the boundary layer. Not only the viscous force, the flame is subjected to the residual gravity (so long as it is not perfectly zero) so that buoyancy force can play a role a bit on the transport process. Now we know that there are three important forces (inertia, viscous force, buoyancy) to govern the transport processes to the interested phenomena here.

Then, let us introduce non-dimensional numbers by taking ratio of these forces and notice that the following non-dimensional groups are key parameters to govern the transport process here; such as Reynolds number \( (Re = \text{inertia/viscous}) \) and Grashof number \( (Gr = \text{buoyancy/viscous}) \). By using these non-dimensional groups to characterize the feature of microgravity fire, it should be “low-Re and (very) low-Gr”. Eventually, our target in this study is to achieve this combination (low-Re and low-Gr) without reduction of gravity. By the way, since Schmidt number \( (Sc) \) is close to unity for most of gas species, low-Re can be replaced to low-Pe \( (Pe: \text{Peclet number}) \).

![Assumption: flame is thin enough (far from extinction)](image)

Fig.2 Spreading flame over thin sheet (STS85); referred by Ref. 6. (Top: direct pic. Bottom: illustration for modeling purpose)

To make it simpler, let us consider the case without external flow. Under this condition, the representative flow is buoyancy-driven flow so that inertia force is replaced by buoyancy force (inertia = buoyancy; namely Froude number is unity). Then \( Re \) becomes the ratio of buoyancy and viscous forces and this is physically the same as Grashof number. Namely, under such condition, only Grashof number \( (Gr) \) is remained as key parameter to determine the overall transport process. In other word, if we could achieve sufficiently small \( Gr \) without managing gravity, it directly means that we could simulate the micro (or low-) gravity fire on earth. Actually we can show that it is possible. Let us look into \( Gr \) in following:

\[
Gr = \frac{L^3 \beta \Delta T \rho}{\mu^3} = L^1 \Gamma \rho
\]  

(1)

Here, \( \rho \) is density \([\text{kg/m}^3] \), \( G \) is gravity acceleration \([\text{m/s}^2] \), \( \beta \) is coefficient of volume expansion \([-] \), \( \Delta T \) is temperature difference between flame and ambient \([\text{K}] \), \( L \) is representative length scale \([\text{m}] \), and \( \mu \) is coefficient of viscosity \([\text{Pa s}] \). Taking into account the equation of state,
density is linearly correlated to the pressure ($\rho \sim P$). Eventually, dependency of $L$, $P$, $G$ on $Gr$ can be expressed as $L^3 G^2 P^2$, as shown in Eq.(1). Readily, it is understood that an applying small scale with low-pressure can achieve low-$Gr$ without managing gravity. Therefore, small scale experiment (small-$L$ is applied) in low-pressure vessel (low-$P$ is applied) expects to deliver the same dynamics found in microgravity fire. One thing should be noticed that the total pressure cannot be so small to have fire since the fire is diffusion flame and minimum oxygen partial pressure is required to sustain the flame. Therefore, the smaller length scale is inevitable to achieve satisfactory low-$Gr$ at normal gravity environment. By the way, it is good to know from Eq.(1) that smaller $L$ is more effective to achieve low-$Gr$ since it has cubic dependency ($L^3$), whereas square dependency in pressure ($P^2$). In the next, let us see how this methodology works. It should be noted that the combustion combination of Eq. (1) and assumption of $Sc \sim 1$ makes the following relation:

$$\frac{\rho^2 G \beta T L^3}{\mu^2} \sim \frac{G \beta T L^3}{D^2}$$

simply, kinematic viscosity ($\mu/\rho$) is replaced by the mass diffusivity, $D$. As is known, mass diffusivity has inverse relation to pressure so that this quantity is also scaled by $L^3 G^2 P^2$. In this sense, aforementioned strategy is not affected. However, it should be mentioned that above discussion is valid only when other quantities rather than $L$, $P$, $G$ (such as $\mu$, $\beta$, $\Delta T$) are the same for both prototype and scale model. If one use different solid fuel to burn, or different ambient diluent is applied in scale model, perfect scaling is not fulfilled. It is interesting to consider all possibilities for variety choice of scale models to simulate the better simulator of low-gravity fire; it would be more future work. In the following, the discussion is only limited to the case when the same material and same gas component are used for both prototype and scale model.

3. Verification and Discussions

3.1 Experimental system

To verify the proposed methodology based on $Gr$-similarity as stated above, the simple test was designed and performed. To fulfill small-$L$ as required, a thin rod-shape specimen (thin polymer coated over the metal wire) was selected as the representative test sample. This sample has been often used as the model fire test of the electric cable [7]-[11]. Fig.3 shows the schematic illustration of our experimental apparatus. Detail descriptions can be found in elsewhere [9-11], so that only brief description has been made here. Test was performed inside a combustion chamber connected to vacuum pump to control the internal pressure in a sub-atmospheric range ($< 101$ kPa). Ambient gas was filled by the dried air (79% of nitrogen mixed with 21% of oxygen) at the subscribed pressure prior to the test. Sample was placed horizontally via holders in the chamber and was ignited by coil heater located at right-edge as shown in the figure. Once the ignition had been successfully achieved, flame spread steadily toward the other end (left edge in the figure). Spreading event was recorded by a digital video camera through the glass window and instantaneous flame shape so as to the spread rate was obtained. During the test, whole gas line was closed so that the chamber was completely isolated. Effect of chamber volume had been carefully checked in our previous works [e.g. 12] and it was ensured that the present chamber was sufficiently large to discuss about the overall flame spreading behavior. Coated polymer; combustible in the present test, was polyethylene (PE). Outer diameter of the sample was 0.8 mm (O.D.) and the thickness of coated PE was 0.15 mm. For convenient purpose to have stable flame formation, nickel-chrome alloy (NiCr) was selected as inner metal core. Due to the limited volume of combustible, the flame height was about a few tens millimeter under the standard condition (normal gravity and atmospheric pressure). In this way, we had achieved small-$L$ (namely, low-$Gr$) which was inevitable to simulate the microgravity fire on earth.

Fig.3 Schematics of experimental apparatus [10]

It should be noted that the flame spread of cable-like sample tended to show quasi-steady behavior [e.g., 11-13]. Steadiness of the flame motion had been controlled by selecting the proper combination of test conditions and we chose such combination in this study.

3.2 Flame shapes in sub-atmospheric pressure

Fig.4 shows instantaneous images of flame formed in a various pressures. Upper and lower figures show the direct picture and backlight image (to visualize the shape of molten PE), respectively. Once the thin coated PE was heated, the PE was melted at relatively low temperature to form molten PE and gasified at relatively high-temperature ($\sim 800$ K). Thus formation of molten PE had been always observed and flame had been formed surrounded by it, likely droplet combustion. Fig.4 also clearly shows that the flame shape (i.e., its height and width) is dramatically changed by the imposed pressure. Flame became tear-drop shape at the normal pressure ($\sim 100$ kPa) due to the effect of buoyancy-driven flow. Low-density gas produced by combustion moved upward driven by buoyancy force, resulting that flow patterns became conical shape (ambient gas gathers toward
the axis). However, as the pressure decreases to 1/3 (~30 kPa), no such deformation was observed. Rather, the flame became nearly spherical shape, suggesting that radial diffusion transport should be dominant. This was quite similar to what we have observed in microgravity, implying that imposing low-pressure is effective to simulate the microgravity fire.

Our previous study had shown that overall flow patterns in low pressure also became somewhat conical shape showing the clear presence of buoyancy-driven flow [14]. Although the buoyancy flow is present, flame shape in low pressure looks insensitive by that. This is because that the diffusion transport is dominant in the flame scale. In other word, within the flame scale (<10 mm), relative importance of buoyancy force becomes “relatively” smaller than diffusion (viscous) force. Small soot particle appeared in the top of flame shows an evidence for the presence of buoyancy flow.

The flame color was quite different depending on the imposed pressure; lower pressure gives less luminous. In this sense, flame strength got weaker and radiation heat transfer from luminous flame should have been negligible as the pressure decreased.

Fig. 4 shows the response of the flame scale (height and width) against the imposed total pressure. From this figure, it is understood that the flame height decreases whereas the flame width increases as the total pressure decreases. The change of flame width by the change of pressure shows almost linear relationship, while that of the flame height shows non-linear. When the pressure was reduced to one-third (1/3), the flame width increased roughly 20%. Aspect ratio became unity around at 40 kPa (=0.04 MPa), suggesting that the spreading flame becomes nearly spherical shape [10]. Overall, this observation fact ensures that the flame shape in microgravity is successfully simulated by applying low pressure (in small-scale test), namely, Gr-similarity works well to represent the flame shape in different gravity conditions. Since the flame shape in steady-process can be considered as “static” character, we can say that the static similarity is fulfilled according to Gr-similarity approach.

One thing cannot be simulated the microgravity situation via Gr-similarity approach is the shape of molten PE formed inside the flame. Under the presence of gravity, PE always formed underneath of the core wire and the shape is not likely sphere, whereas the no such trend is found under microgravity test (not shown, but it is obvious since there is no gravity drag). Thus, if the shape of molten PE is very sensitive to the interested phenomena, Gr-similarity approach does not work. Although, most of the combustion problems are generally insensitive of combustion characteristics, this point should be addressed for further study.

### 3.3 Flame spread rate in sub-atmospheric pressure

Once the ignition was successfully done at the right edge, flame appeared over the wire and the flame moved slowly toward the left (unburned side). Flame motion was nearly steady so that the flame spread rate had been determined as system eigenvalue. Since the flame dynamics (namely, flame spread rate) is very important to characterize the fire character, it is worthwhile to investigate whether low-P flame spread shows similar behavior under low-G fire. In other word, we should check not only the static similarity but also the dynamic similarity should be addressed to ensure that Gr-similarity approach is useful in terms of simulating the space fire satisfactorily.
Fig. 6 shows the change of flame spread rate as a function of imposed pressure (note that the pressure is normalized by standard pressure, $P_0 = 101$ kPa, in this figure). Although there are several plots in this figure showing the effect of confinement [12]; let us focus on the top one, indicating the “open (~ sufficient chamber volume case)” condition. It is clearly understood that the flame spread rate increases almost linearly as the pressure decreases. Lower than 25 kPa (i.e., $P/P_0 < 0.25$) of total pressure, flame suddenly lost the stability to lead extinction; thus no spread data was available.

It is valuable to emphasize that the flame spread rate becomes higher in low-pressure, even though the flame luminous is weak and close to extinction as pointed out previously. In order to explain this strange behavior, let us look back the response of flame shape (width) in the low pressure. As indicated in Figs. 5 and 6, we should notice the similarity in the response of both flame width and the flame spread rate against the pressure. According to Fig. 6, the flame spread rate increases roughly 14 % when the pressure decreases to one-third (1/3); interestingly this is somewhat similar to the increment of flame width (20 %) as described. Thus, it can be naturally considered that flame width should play an important role on determination of flame spread rate under the condition studied here. Actually this similarity is acceptable from physical point of view. As flame gets wider, longer region of unburned fuel should be heated by the flame and it enhances the melting so as to gasification of unburned PE. Consequently, flame can easily move forward to show the faster spread rate.

Now let us consider the flame shape and flame spread found in microgravity experiment. The spreading flame in microgravity subjected to the slow-flow was somewhat oval shape to have wider flame area along the wire (see embedded pic in Fig. 6 [e.g. 8, 15]). More importantly, the spread rate in microgravity was found to be faster than that in normal gravity [e.g., 15]; the increase was around 20 % as compared to the one in normal gravity. Notably, this increase is found to be quite similar to what is observed in low-pressure case as shown in Fig. 6 (say, ~30 kPa). The reason of this similarity should be referred by the similarity in transport process. Looking back to the previous discussion made in Sec. 2.2, $Gr$ is a key dimensionless group to govern the transport process in considered system. Due to this fundamental and scientific background, the similarity of flame shape and its motion found in both microgravity and low-pressure should be ensured. Throughout the test, it has been concluded that the utilization of low-pressure fire test can be potentially used to evaluate the flammability of the material used in space on earth, without depending on costly microgravity environment. This methodology has potential to apply to fulfill JAXA’s space utilization scenarios by 2020 [16]; establishment the new regulation to test the fire safeness for materials used in space.

3.4 Future work

If $Gr$ is the only non-dimensional group to ensure the similarity of transport processes in microgravity, we can simply estimate the condition to be applied to simulate the target low-gravity fire on the earth. To simulate the phenomena in low-gravity, simply we choose the proper combination of $L$ and $P$ to be identical $Gr$. For example, use 1/2 scale of prototype and apply 1/3 of pressure in closed chamber on earth (namely, $L'=1/2, P'=1/3, G'=G_0$, whereas * stands for the quantities of scale model, whereas without * stands for the quantities of prototype), simulated gravity should be $(1/2)^3(1/3)^2 = 1.4x10^{-2} G_0$. If the scale is further smaller to 1/4 of prototype, we would simulate one-order smaller gravity field ($(1/4)^3(1/3)^2 = 1.7x10^{-3} G_0$). If the scale is 1/10 of prototype, it would become further smaller ($(1/10)^3(1/3)^2 = 1.1x10^{-4} G_0$), which is hardly achievable via parabolic flight and nearly equivalent to the drop tower. To verify whether low-pressure can really simulate the low-gravity cases, the low-gravity experiment should be performed. This is actually our future plan.

It is true that $Gr$-similarity approach works well as described, however, this works only effective when the flame status is fully governed by transport process. In other word, this approach may not work to reproduce either ignition or extinction in space on earth, where not only transport but also chemical processes play a role. If one wish to reproduce such phenomena, consideration of one more dimensionless group is inevitable to express the similarity in chemical process; potentially Damkohler number $(Da)$.

4. Concluding Remarks

In this paper, an attempt had been made to reproduce the fire in space on earth by taking advantage of scale modeling concept. Based on Grashof number $(Gr)$ similarity in transport process, applying the combination of small-scale and low-pressure can reproduce the exactly same characteristics in flame shape (static character) so as to flame spread rate (dynamic character). This is because that the flame shape and its behavior are governed by transport process. Further study is underway to expand this methodology to reproduce ignition and extinction in space on earth, at which the chemical process plays a role.

Acknowledgement

This work has been supported by JSPS (Grants-in-aid for Young Scientists: #21681022). We specially thank to Professor Kozo Saito at University of Kentucky to his sincere guidance and fruitful discussion on scale modeling. Discussions with Prof. Fujita at Hokkaido University are also greatly appreciated.

References

[2] NASA office of safety and mission quality, Flammability, odor, offgassing and compatibility requirements and test procedures for materials in
environments that support combustion, NHB8060.1C, (1991)


