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Application of Computed Tomography to Microgravity Combustion

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***Abstract*:** This paper describes applications of computed tomography (CT) to combustion phenomena under microgravity conditions. Infrared Thermography (IT) has been considered as a promising method for two-dimensional measurement of flames. We have applied IT to CT for a butane flame under microgravity conditions. The method joining spectroscopy to CT for diffusion flame of hydrogen has also been carried out. Intensity of chemical luminescence, which is originated from combustion-chemical reaction in the flame, can be measured by scanning a spectrometer with collimator. The effectiveness of the CT applications to microgravity combustion has been confirmed from two method.

***Keywords*:** computed tomography, diffusion flame, infrared thermography, microgravity combustion, spectroscopy.

1. Introduction

Microgravity combustion science, originated by Dr. S. Kumagai in the 1950s (Kumagai, 1957), is one of the very original space-related science fields established in Japan. Under microgravity conditions, combustion phenomena are dominated by diffusion, and thermal convection (i.e., buoyant flow that greatly influences combustion at normal gravity) has little effect on combustion. This fact significantly simplifies and facilitates the understanding of combustion phenomena. Therefore, investigation of microgravity combustion is a key to solving such complicated phenomena. This paper describes an advanced investigation on the visualization for combustion phenomena under microgravity conditions with computed tomography (CT) from the previous report (Shimizu et al., 1996). Infrared Thermography (IT) has been considered as a promising method for two-dimensional measurement of flames, because the high temperature measurement performance and spatial resolution have been improved substantially. Since the flame can be assumed ideally axisymmetric, the spatial distribution of radiation intensity is obtained using only a series of scanned data. Hence, the research joining IT to CT for diffusion flame of butane has been performed to realize a three-dimensional temperature measurement of flame under microgravity conditions, which is essential to the research of this flame combustion. Additionally, the method joining spectroscopy to CT for diffusion flame of hydrogen has been carried out. Intensity of chemical luminescence which is originated from combustion-chemical reaction in the flame, can be measured by scanning a spectrometer with collimator. Thus a two-dimensional luminescence (OH radical) distribution can be obtained. The effectiveness of the applications of CT to microgravity combustion has been confirmed.

2. Method Joining IT to CT

2.1 Experimental Set-up

The experiments using butane as a fuel under microgravity conditions were performed at Micro-Gravity Laboratory (MGLab.) in Gifu prefecture, Japan. Specifications of facilities of MGLab. are depicted in Table 1.

A schematic diagram of set up for IT-CT is shown as in Fig. 1. A temperature distribution of butane flame from the side of view was taken by an infrared thermography camera (Nippon Avionics Co., Ltd., TVS-8000), and simultaneously a B-type thermocouple (Rh30Pt70-Rh6Pt94) was used for temporal distribution measurement of flame temperature according as flame expands by diffusion.

Table1. Facility specifications of MGLab.

Drop method	Capsule free drop in vacuum
Braking method	Friction damper, Bellows braking
Vertical shaft	150 m (freedrop zone 100 m, braking zone 50 m)
Accuracy of vacuume	4 Pa
Duration of microgravity	4.5 sec
Braking deceleration	about 10G

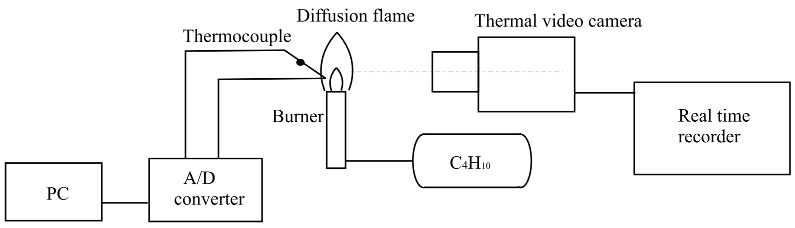

Fig. 1. Schematic diagram of set up for IT-CT.

2.2 Results and Discussion

As a preliminary result, Figures 2 and 3 show the side view images of a diffusion flame by the IT camera under normal and microgravity conditions, respectively. The figures present the two-dimensional distributions of flame temperature. The range of measurement was limited at 426.5 to 940.0˚C due to the restriction of device. The flame shown in Fig. 2 elongates its shape in vertical direction due to thermal convection. On the other hand, the flame shown in Fig. 3 presents almost spherical form because of dominating diffusion under microgravity conditions and almost no convection.

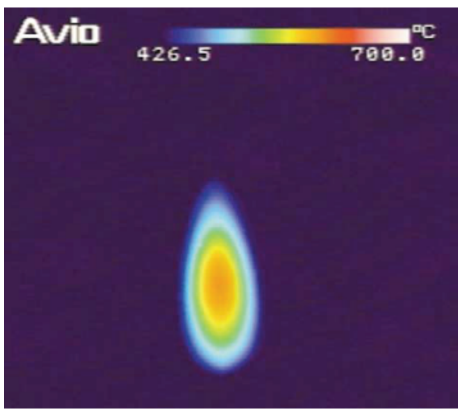

Fig. 2. Flame under normal gravity.

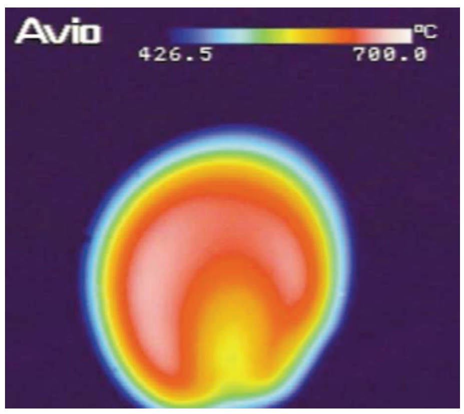

Fig. 3. Flame under microgravity.

Temporal variation of flame temperature which was measured by thermocouple under microgravity conditions and output of gravity sensor were shown as in Fig. 4, where axis of abscissa expresses time and adjusts the time of the beginning of microgravity conditions to zero. Ignition was performed before the capsule would fall down, and the flame would be expanded naturally under microgravity conditions (i.e., the diffusion is dominated with very weak thermal convection). The temperature distribution inside the flame has a highest point at outer side in the flame. Hence, the measured temperature of expanding flame has a peak (as the highest temperature zone passes through the measuring point of thermocouple) and then converges to the certain lower temperature at the inside flame, as the flame expands spatially at the beginning of microgravity experiment.

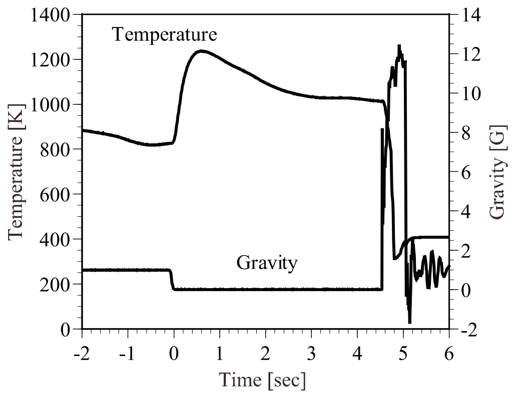

Fig. 4. Temporal variation of temperature of the flame and gravity.

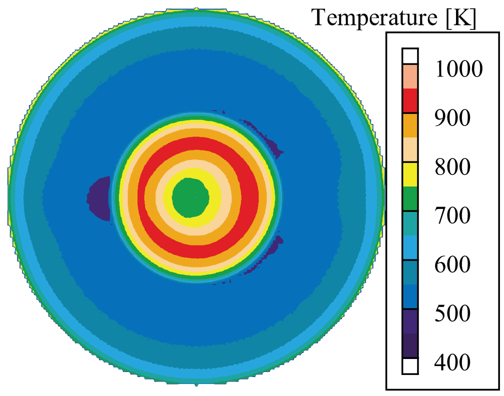

Fig. 5. Tomogram of the flame under microgravity.

The image in Fig. 3 shows the temperature distribution image of the infrared thermal camera. It is assumed that the radiation intensity received by the camera sensor is spatially integrated value in depth (there exist no gases that show absorptivity). The radiation intensity is generally proportional to the fourth power of temperature. Then, a series of temperature data was picked up from the IT camera image data, where the elements of the series were raised fourth power. It is assumed that the flame is axisymmetrical on vertical axis, and CT reconstruction for the radiation intensity was carried out with the series of the data and then returned CT reconstruction to temperature distribution (the fourth root of radiation intensity). The adopted CT reconstruction method (algorithm) is the filtered back-projection method, where the filter function used in the convolution (Shepp and Logan, 1974). Hence, Figure 5 shows the temperature tomogram in horizontal cross section of the flame shown in Fig. 3. The obtained image in Fig. 5 is seemed to be not axisymmetrical exactly. The correct center of CT reconstruction by the data series is supposed to exist between the nearest and the second nearest data pixel to the defined center in Fig. 5.

In Fig. 5, a ring-like artifact at the verge of the circular CT image region exists because the base values in the intensity distribution data are not zero. In such case, we can shift the data series to appropriate base values so as to obtain CT image without the artifact at the verge (Kak et al., 1977). In our CT calculations, however, the radiation intensity is derived from the fourth power of temperature, so the intensity should not become below zero. Though we tried to carry out CT reconstruction with the shifted data series as mentioned above, the errors occurred where the radiation intensity data became below zero. Therefore, we performed the CT reconstruction without the shifting operations and the result is shown here. The temperature distribution inside the flame is the lowest at the center and higher at outer side in the flame. As the position of temperature measuring point (thermocouple) in Fig. 4 is not clarified strictly at the temperature distribution of the flame section (IT image) in Fig. 3, the highest temperature in Fig. 4 is not strictly in agreement with that in Fig. 5. Since the heat transfers from the joining point of thermocouple through the supporting wire, and the flame turbulence which is caused by thermocouple itself are generated, it is difficult to measure flame temperature by thermocouple correctly.

In this experiment, the flame flared out when the gravity conditions change from normal to microgravity. Figure 6 shows the IT camera image at that time and the flame deforms partly from spherical shape and is extended to the left. It is observed that the data series of section (A-A′) of the angle of about 52 degrees to the horizontal surface is axisymmetrical with respect to the center of this data series. Therefore, CT reconstruction for (A-A′) was also attempted. In this case, since the symmetry of data was not good enough, the data series was folded one side data from the center to the contrary side in order to keep the axisymmetry distribution. As a result of performing the above-mentioned processing for CT reconstruction, the image was obtained as shown in Fig. 7. The similar result is obtained as Fig. 5, where the temperature inside the flame is lowest at the center and higher at the outer side in the flame. Because two-dimensional distribution image was measured with the IT camera, CT reconstruction is available with the data series at arbitrary section which is locally axisymmetrical.

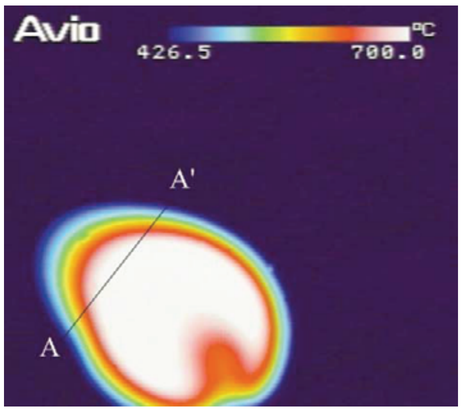

Fig. 6. Flame flares when gravity changes.

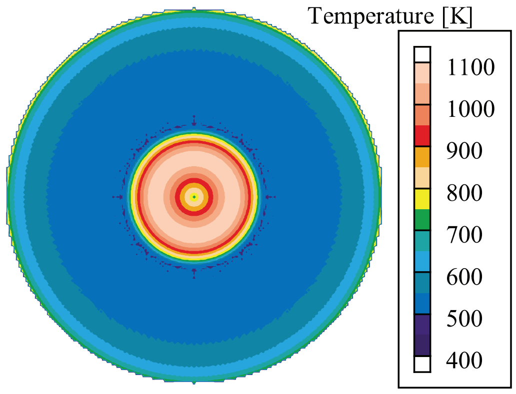

Fig. 7. Tomogram of section A-A´.

3. Method Joining Spectroscopy to CT

3.1 Experimental Set-up

Figure 8 shows a schematic diagram for the experiment joining spectroscopy to CT. The spectroscope (Ocean Optics., Inc., S-2000) with collimator could be traversed horizontally and a spatial distribution of the luminescence spectrum of OH radical was measured. Here, hydrogen was used as a fuel in order to limit the luminous-chemical substances generated by combustion to one kind. The only OH radical is produced in the combustion-chemical reaction of hydrogen. The luminescence that is originated from OH radical in combustion phenomena of hydrogen has been measured in many recent reports under normal gravity conditions. The experiment under the microgravity conditions using the facility of MGLab. could not be carried out, by avoiding some safety problems in the case of hydrogen combustion as hydrogen is much easier to be ignited than butane. In this work, the experiment could be carried out only under normal gravity conditions.

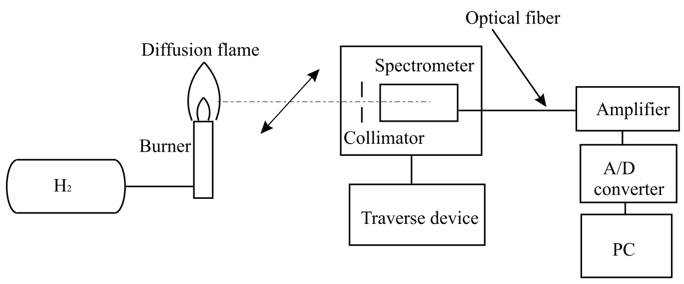

Fig. 8. Schematic diagram of the experiment for spectroscopy-CT.

3.2 Results and Discussion

Figure 9 shows the spectroscopic data of hydrogen diffusion flame. The obvious peak is observed at about 310.5 nm (theoretically, 306.3 nm for OH radical) in the figure. A series of the data at 310.5 nm was picked up by spatial scanning spectroscopy at the distance of 19 mm from burner nozzle. Since a symmetry of the data series was not good, the data series was folded one side data at the center to the contrary side in order to keep the axisymmetry distribution and CT reconstruction was performed, as shown in Fig. 10. The intensity distribution inside the flame becomes higher at the outer side in the flame, that is, a combustion-chemical reaction in outer zone of the flame is more active than inner and core part.

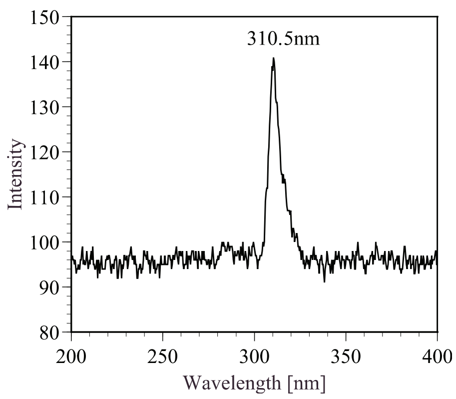

Fig. 9. OH radical luminescence.

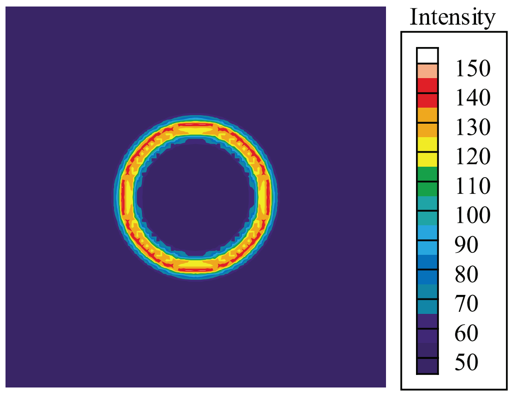

Fig. 10. Tomogram of section at 19 mm from burner nozzle.

4. Concluding Remarks

This paper has described an application of CT method to microgravity combustion. The flame under microgravity conditions is dominated by diffusion and very weakly influenced by thermal convection. CT reconstruction of the temperature distribution has been performed by the temperature data obtained from an infrared thermography camera. This method has the advantages of performing CT reconstruction with the data series at arbitrary section which is locally axisymmetrical, because two-dimensional distribution image can be measured with the IT camera. Additionally, the application joining spectroscopy to CT for diffusion flame has been conducted successfully under normal gravity conditions.

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