Diffusion Jet Flames in Low and High Gravity Fields

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Abstract

Behavior of diffusion flames under the low and high gravity was experimentally studied for the better understanding of the convective air inflow into the diffusion flame. Also how the gravity affects the stability and blow off of the flame was investigated. The gravity level was artificially controlled by using a drop tower and a spin tester in the range from \( G=0.02 \) to 15 where \( G=1 \) means the normal gravity on the earth. The laminar diffusion flame of butane was made on the tip of the small vertical pipe. The results showed that the length and the width of the flame were reduced with an increase of the gravity level. The oscillation and blow off of the flame were observed in the high gravity level. The blue flame region observed at the anchor portion of the diffusion flame became more intense with increasing gravity level. It can be explained that the phenomena of the natural convective air inflow is enhanced by the high gravity.

1. Introduction

A lot of combustion experiments under micro-gravity have been carried out to make clear the combustion phenomena because the influence of the natural convection became very weak in such gravity levels\(^1\)\(^{-3}\). To reduce the convective flow caused by the buoyancy, the less gravity has been required. From the comparison between micro- and normal gravity flames, the effect of the natural convection on the flame propagation and flame structure has been scientifically investigated in the previous works executed by other researchers\(^4\)\(^{-7}\).

The authors have investigated the gravity effect on the candle flame under high gravity up to \( G=10 \) by using a spin tester\(^8\). From this experiment, it was confirmed that the length and width of the candle flame decreased with an increase of gravity level. However, no studies have ever tried to investigate the gravity effect on the gas jet diffusion flame under the variously changed gravity level from \( G=0 \) to \( G=10 \).

In this paper, in order to make clear the effect of natural convection on the combustion phenomena in detail, it is necessary to obtain new experimental data measured under the wide range of the gravity level, because the magnitude of the natural convection depends on the gravity level through the buoyant effect. The purpose of this study is to provide the more information about the gravity effect on the combustion phenomena under the various gravity levels. To attain this purpose, a butane gas fueled diffusion jet flame was observed under low and high gravity conditions which were artificially produced by a drop tower and a spin tester, respectively.

2. Experimental Apparatus and Method

To generate various levels of low gravity, a drop tower was developed. The drop tower had an experimental shuttle (300 mm \( \times \) 300 mm \( \times \) 450 mm) and a counter shuttle. Each shuttle was connected with a rope through the pulleys as shown in Fig. 1. When the experimental shuttle started to fall from the top of the tower, the counter shuttle was pulled up from the bottom. Then the experimental shuttle was received the downward acceleration by the gravity force of its weight. Through the
connecting rope, it was also received upward acceleration by the weight of counter shuttle. Then the restricted fall caused by the combination of two acceleration forces was resulted on the shuttle. The effective falling height of the shuttle was around 9 m. The tower had 6 passing time sensors which detected the falling movement of the shuttle and the gravity level in the falling shuttle was calculated from the acceleration movement of it. At the falling period, variation of the gravity level was less than ±0.01.

By adjusting the weight of the counter shuttle, the gravity level was easily controlled in a range from \( G = 0.02 \) to 1. Where \( G \) is a dimensionless acceleration of the gravity defined by the following equation:

\[
G = \frac{g}{g_e},
\]

where, \( g_e \) is the acceleration of the gravity on the earth, \( g \) is an acceleration of the artificial gravity formed in the experimental shuttle which is in the falling state.

A spin tester shown in Fig. 2 was constructed and used to generate the centrifugal acceleration force which was applied to form the high gravity. A gondola type experimental chamber (it was called just “gondola” in the following part, and its size was 300 mm x 300 mm x 450 mm) and counter weight was set on the each end of a rotary arm of the spin tester. The radius of the arm was about 0.9 m. The multi-channel slip rings system was set on the center shaft of the arm. The control signal and combustion information such as video signals were transferred from the gondola to the outside of the spin tester through the slip rings. The gondola was swung out to the radial direction by the centrifugal force when the arm was started to rotate. The inclination of the gondola was increased with increasing the rotational speed of the arm. However the normal direction of the gondola was always kept to the resultant vector direction of the gravitational and centrifugal forces. The artificial gravity formed in the gondola was derived from:

\[
g^4 - 2ag^3 + bG_3 - 2aG + a^2 = 0,
\]

where, \( a \) and \( b \) are expressed as:
Here, $N$ is the rotating speed of the arm, $R_a$ is the radius from center shaft to the pin connection of the gondola, and $R_d$ is the length from the pin to the flame in the gondola. The maximum gravity level was about $G=20$ at the rotating speed of 160 rpm.

By the combination of these two experimental systems, behavior of the diffusion flame could be observed under various gravity levels in the range from $G=0.02$ to 15. The combustion equipment shown in Fig. 3 was commonly used for the both of low and high gravity experiments. It was mounted both in the shuttle of the drop tower and in the gondola of the spin tester, respectively. The equipment consists of a nozzle, a gas flow regulating system and a fuel tank. The gaseous butane was used as the fuel because of its easy handling. The flow rate was controlled by the needle valve and was monitored with a pressure gauge. The 2 mm, 4 mm and 6 mm diameter nozzles were prepared for the experiment. Fuel jet from the nozzle was laminar and the Reynolds number of the fuel flow through the nozzle was in a range from 160 to 900. The fuel was ignited at a few seconds before the start of drop experiment. In the case of high gravity experiment using the spin tester, fuel was ignited under normal gravity condition prior to the rotation. Behavior of the diffusion flame set on the nozzle tip was observed by using a CCD camera and recorded directly by a VTR system.

![Combustion equipment](image)

**Fig. 3** Combustion equipment.

### 3. Experimental Results and Discussion

#### 3.1 Flame Measurement at Low Gravity Field

The length $L_f$ and width $W_f$ of the flame were measured from the video image of the flame. Where, $L_f$ is a distance from the bottom of flame to the top of flame and $W_f$ is a maximum flame width measured in horizontal direction. The blue flame region was observed in the anchor portion of the flame. The distance between the nozzle tip and the end of blue flame was defined as the blue flame length $L_b$. It was also measured, because it was good indicator of the enhancement of the convective air inflow into the anchor portion of the flame. **Figure 4** shows the time histories of the flame length and other parameters through the drop experiment at $G=0.55$. Before the start of falling, the flame was stable. The flame length $L_f$ just after the start of falling had received the some disturbance, however it seemed to become stable before the shuttle reached to the bottom. The average flame length after it became stable, was longer than the length of that in the normal gravity. The flame width $W_f$ increased rapidly after the start of falling, but the change was small. The blue flame length $L_b$ was perturbed slightly but there was no significant change. **Figure 5** shows the results of the drop experiment at the small gravity of $G=0.55$.

![Time histories of drop experiment](image)

**Fig. 4** Time histories of drop experiment ($G=0.55$).
G=0.02. Data corresponding three runs of the drop experiment were over-plotted in the figure. After the start of falling, flame length was reduced rapidly from normal gravity state and was elongated gradually. At 0.5 seconds after starting, the flame length became longer than that at normal gravity. At 0.7 second after starting, flickering of flame was observed. However \( W_f \) was smoothly changed compared with the change of \( L_f \).

The reduction of the flame length observed just after the start of falling was considered as follows. The convective flow just balanced around the flame under normal gravity state and was changed instantly at the start of falling. The air inflow that should be balanced in the low gravity needed to some period of time to appear. It seemed that the flickering of the flame observed in the very low gravity as shown in Fig. 5 was the nature of the laminar gas jet diffusion flame. Since the flame length was too long at the low gravity conditions, it was difficult to make a stable diffusion jet flame in this falling shuttle. It needed a long period of time to stabilize the air inflow motion. Therefore, it may be necessary to use the higher drop tower for deciding the flame length at \( G=0.02 \) with high accuracy. In this report, we assumed that the mean length of flickering flame at the later stage of the falling period were equivalent to the length when the experimental gravity level was kept stationaly with long period.

3.2 Flame Measurement in High Gravity Field

In the high gravity experiments, the measurement of \( L_f, L_b \) and \( W_f \) were very easy, because the high gravity was stationary formed in the gondola of the spin tester. However another difficulty appeared in the spin tester experiment. Every moving substance in the centrifugal field had been suffered by the Coriolis' force. When the Coriolis’ force was stronger than the buoyancy force, the flame observed from the coordinate rotating with the spin tester was seemed to move toward the rotating direction. The classical dynamics of the Coriolis' force analyzed before the experimental study had shown that the Coriolis’ effect would appear slightly around \( G=2 \), and the flame would be inclined at that gravity level. However, at the higher gravity level than \( G=5 \), the buoyancy force caused by the high temperature flame would overcome the Coriolis’ force. According to the observation of the flame in the gondola, the inclined angle of the flame was maximum at the gravity level of \( G=2 \), and its effect on the flame length seemed to be negligible. Then in this report, the Coriolis’ force is ignored in the discussion.

4. Gravity Effect on the Flame Structure

Figure 6 shows the photographs of the flames under the various gravity levels. It is found that the flame structure depends strongly on the gravity level. The inclined flame observed at \( G=4 \) is the result of the Coriolis’ effect mentioned above. The flame became short and narrow with an increase of \( G \). These results mean that the buoyancy effect ap-
peared around the flame at the high gravity enhanced the air inflow motion, and then the flame surface area to burn the same amount of fuel was reduced. In other words, the burning rate in the diffusion flame was enhanced with an increase of the convective flow which was activated by the buoyancy effect. There was the blue flame region between the nozzle tip and luminous flame zone and its length could be measured from the photographs. The weak blue flame was observed in the low gravity. However the blue flame was expanded to the half of the flame length in the high gravity.

Figure 7 shows the gravity effect on the flame length. The flame length in this figure was normalized by the value at $G = 1$. The data of dimensionless $L_f$ does not depend on the flow rate of fuel. The solid symbols in the figure correspond to the data measured by the drop experiment and white symbols are the data from the spin tester experiment. It is found that the manner of gravity effect on the flame length was changed around $G = 2$. $L_f$ was reduced with an increase of $G$ in the condition of $G < 2$. In the condition of $G > 2$, however, the reduction of the flame length was very small. The flame extinction caused by the blow off was observed in the high gravity. The gravity effect on the flame width is summarized in Fig. 8. All the data of normalized $W_f$ are fitted on one straight line, even if the flow rates are different. The flame width is reduced in the constant tendency with an increase of $G$. From Figs. 7 and 8, it can be confirmed that the area of the flame surface is reduced with an increase of $G$.

Figure 9 shows the effect of gravity on the blue flame length $L_b$. $L_b$ increases with an increase of $G$. However the significant increase of blue flame length was observed in $G > 5$. The reason of this change can be explained as follows. A natural convection was promoted by an increase of $G$ and the air inflow into the flame was enhanced. In the anchor portion of
the diffusion flame, there was some quenching area between the nozzle tip and bottom of the flame. The air inflow through this quenching area was also enhanced by the natural convection produced by the buoyancy of flame. This air inflow enhanced a premixing of the air and fuel, and made the blue flame region in the anchor portion of the diffusion flame. It meant that the flame structure was changed from diffusion flame to partially premixed diffusion flame by the buoyancy effect corresponding to the high gravity.

5. Gravity Effect on the Flame Stability

Stability of the flames was investigated under the various gravity levels. Especially, the occurrence limits of the oscillation motion and the blow off were measured. $G$ was changed from 1 to 15 by the spin tester. The data were plotted on a map of Reynolds number vs. gravity as shown in Fig. 10. The Reynolds number of the flame is defined as:

$$Re = \frac{Vd}{v},$$  (4)

where $V$ is an issuing velocity of the fuel, $d$ is an inner diameter of nozzle and $v$ is a kinematic viscosity of the fuel.

It was found that the flame with high Reynolds number became unstable with an increase of the gravity level. In the unstable flame region, the flame oscillation which meant a periodic elongation of the flame was observed. The periodic oscillation of axially symmetrical elongation of the flame was very similar to the flickering motion of the laminar diffusion flame which had been reported in the previous works$^{9,10}$. In those works, the reason of this oscillation was explained by the shear flow type instability of laminar jet flow. However, there was no discussion about the buoyancy effect on the flame instability. The results reported here clearly shows the buoyancy effect on the shear flow type instability of the flame.

The buoyancy effect was promoted by an increase of $G$. Then the vertical velocity of the flame became high by the natural convection. The shear layer between the flame boundary and the surroundings became large, and the shear type instability appeared in high gravity. The blow off limit depended on burning velocity of fuel and also depended on the shear flow at the anchor portion of the flame. Here, an inequality of instability limit with taking into account the effect of $G$ can be derived from Fig. 10 for the limit of the appearance of unstable oscillating motion.

$$A_1 \cdot Re \cdot G^{0.9} \leq 1$$  (5)

And the blow off limit is expressed as follows.

$$A_2 \cdot Re \cdot G^{3.2} \leq 1,$$  (6)

where, coefficients are $A_1 = 10^{-3}$ and $A_2 = 1.87 \times 10^{-6}$, respectively.

6. Summary

The drop tower with counter shuttle and the spin tester were developed to investigate the combustion phenomena at low and high artificial gravity. The diffusion flame of butane gas jet issuing from a nozzle was studied at various gravity levels ranged from $G=0.02$ to 15 by using these experimental systems. The results for the butane flame are as follows.

1) The length and width of the flame decrease with an increase of the gravity level.

2) The blue flame region between the nozzle tip and luminous flame zone is expanded by an increase of gravity level.

3) The shear type instability of the diffusion flame is enhanced at high gravity.
4) The instability and blow off limit of the diffusion flame can be summarized as the functions of gravity.

References