過重力状態における燃料液滴の燃焼[英文]

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過重力状態における燃料液滴の燃焼

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COMBUSTION OF FUEL DROPLETS UNDER INCREASED-GRAVITY CONDITIONS

S.Okajima, K.Abe, S.Yamaguchi and M.Shimada

Abstract

The effect of natural convection on the burning characteristics of fuel droplets was investigated, using the experimental technique to realize the combustion of fuel droplets under the condition of acceleration of fall higher than the gravitational acceleration achieved in the combustion chamber that rose with a constant acceleration. The behavior of burning fuel droplets was photographed with a movie camera and analyzed to determine the true characteristics of fuel droplets burning under natural convection.

The evaporation constant of burning droplets increases with increasing acceleration of fall, but its value obtained under the condition of 1.6 x (gravity) is only about 13% larger than that under a normal-gravity condition. The flame around a burning droplet is not spherical but is distorted into an oval shape due to the influence of natural convection, and even at under the condition of 1.6 x (gravity) the upper and lower part of the flame are directly proportional to droplet diameter and square root of droplet diameter, respectively. These facts indicate that, even though the acceleration of fall exceeds the gravitational acceleration, the burning processes of fuel droplets are very similar to those under a normal-gravity condition.

1. Introduction

The gas flow affecting the combustion of fuel droplets is classified into natural and forced convection. Those two kinds of gas-flow effects frequently appear in combination, though they are essentially different from each other in nature. Under these circumstances it seems significant to investigate separately their individual effects on the combustion of fuel droplets. In the previous investigations,[1, 2] the authors conducted experiments to study the combustion of fuel droplets under the influence of decreased acceleration of fall, which was achieved by varying the acceleration of the falling combustion chamber, and examined the effect of natural convection on the fuel-droplet combustion. Especially, under a zero-acceleration or so-called zero-gravity condition, experiments on the combustion of moving droplets were carried out, and the influence of forced convection on their burning, not disturbed by natural convection, was studied.

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However, the authors' previous studies were not sufficient for revealing the whole area of the combustion of fuel droplets under natural or forced convection, because they were restricted to the case in which the relative velocity of a fuel droplet with respect to the surrounding gas was of the order of several centimeters per second. Thus, in order to obtain the more detailed understanding of the effect of the relative velocity on the burning fuel droplets, it is necessary to examine the combustion of fuel droplets at higher relative velocities under the condition where natural and forced convection do not coexist.

As the first stage of the study, the authors developed the experimental technique to achieve the fuel-droplet combustion under the condition of acceleration of fall higher than the gravitational acceleration, which was realized in the combustion chamber that ascended vertically with a constant acceleration. The behavior of such burning fuel droplets was observed by taking their direct photographs with a movie camera installed on the rising assembly, and the influence of acceleration, that is, natural convection, on the burning characteristics such as the evaporation constant and flame shape was examined in detail.

2. Experimental Apparatus and Procedure

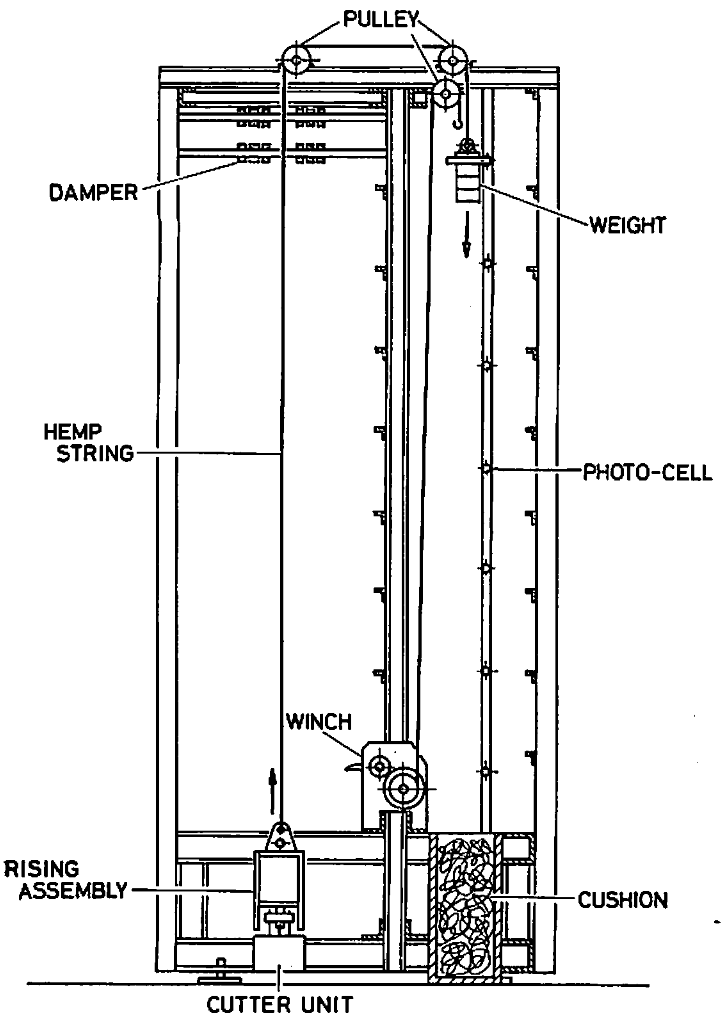


Fig. 1. Tower.

Full description of the experimental apparatus employed in this study is shown in Fig. 1. The rising assembly connected to a counter-weight by a hemp string through a pulley system is pulled up as it falls. The effective acceleration of fall α inside the combustion chamber is expressed as $2gM/(M + m)$ in the case of negligible drag and friction, and α can be varied in the range from g to 2g by changing the mass of the counter-weight M, where g and m are the gravitational acceleration and mass of the rising assembly, respectively.

The rising assembly (Fig. 2) measures 240 x 400 x 400 mm and weights 17 kg. This contains an optical system and a combustion chamber with an igniter and is held at a given position with a piece of polypropylene ribon string, which passes through the cutter unit fixed to the end of the stand, together with a piece

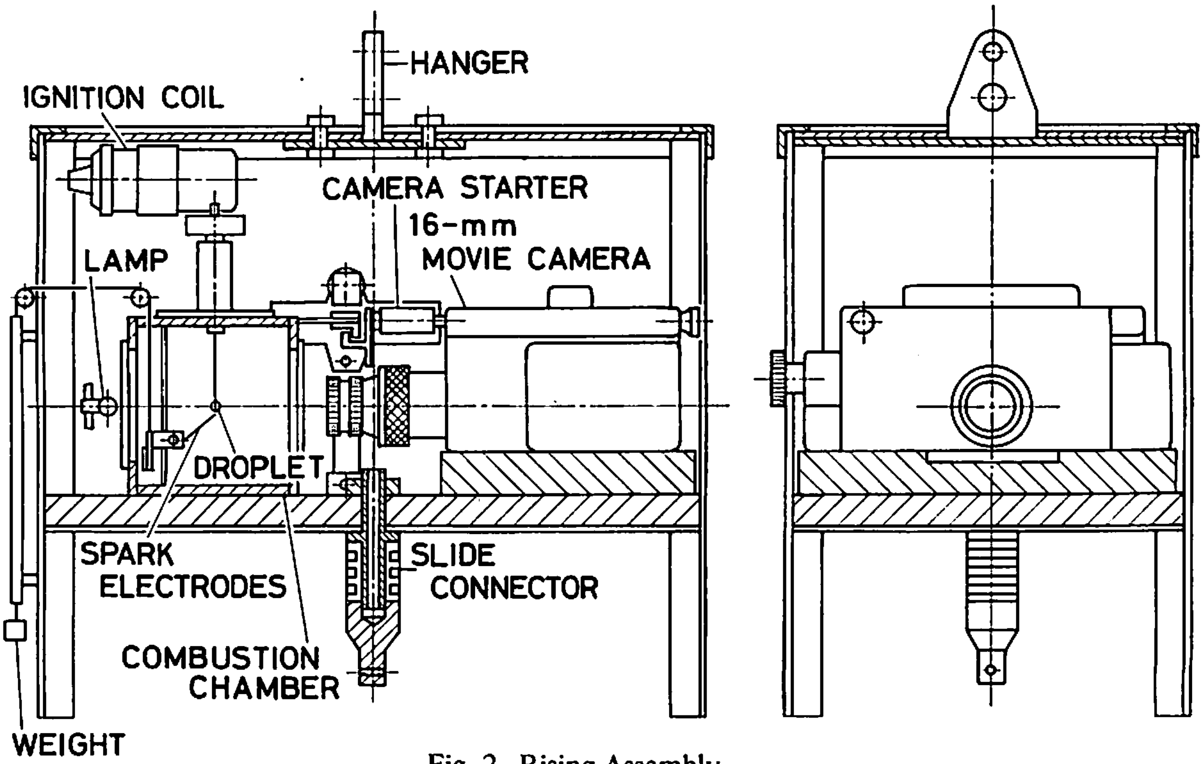


Fig. 2. Rising Assembly.

of a fine copper wire conducting the primary current of the ignition coil. The slide connecter, which is installed on the bottom of the rising assembly, has three separate electrodes, capable of leading three channels. The combustion chamber is a closed wooden box of 110 x 80 x 95 mm inner dimension and is fitted with a glass window to allow observation of the burning process. The optical system provides the lamp for silhouette of the burning droplet and a 16-mm movie camera equipped with a lens of 35 mm focal length, operating at a speed of 20 frames per second and a magnification of 0.71. The part of the igniter supporting the spark electrodes is constructed so as to move automatically about 15 mm away from the fuel droplet after ignition to prevent their interference with the flame during combustion process. The supporting fibre of the droplet is made from a silica with approximately 0.15 mm in diameter and 40 mm in long. Though the fuel droplet oscillates at the start of its rise, at the droplet sizes and α used this oscillation is damped before its burning process is initiated. As the height of rise is about 4 m, the combustion of fuel droplets is able to be observed for about 0.9 second even at $\alpha = 2g$. The upward motion of this assembly is stopped by damper and the shock of the fall of the counter-weight is absorbed by feather cushions. The practical value of α is determined from the distance of the fall of the counter-weight and from the time measured by means of CdS disposed vertically at 50 cm interval as shown in Fig. 1.

Figure 3 shows the diagram of control system. After introducing a fuel droplet into the rising assembly fixed on the stand, an experiment is performed in the following operational sequences,

1) Closing switch K_1 activates the electromagnet, which triggers the camera.

2) Clsoing switch K_2 establishes the primary current of the ignition coil.

3) By cutting the ribbon string and copper wire, the combustion chamber is pulled up with a constant acceleration and the primary current of the ignition coil is broken to produce a spark for ignition.

3. Experimental Results

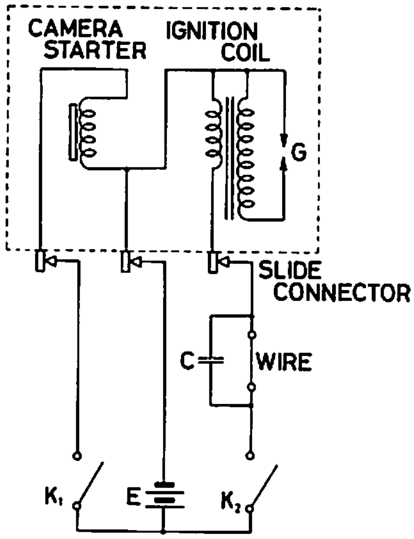
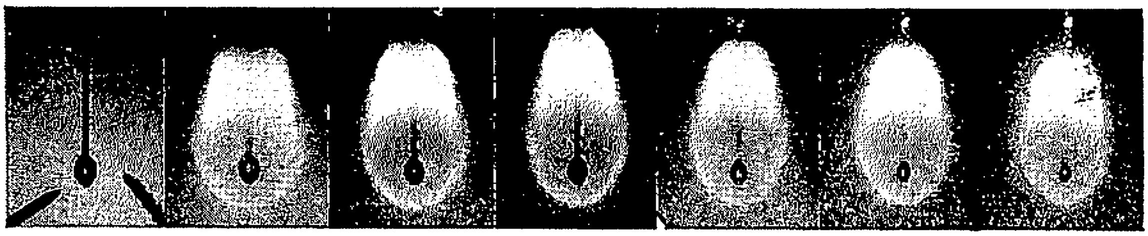
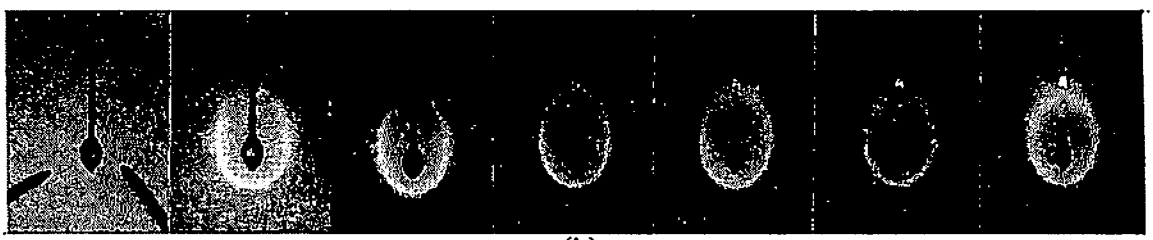


Fig. 3. Diagram of control system.

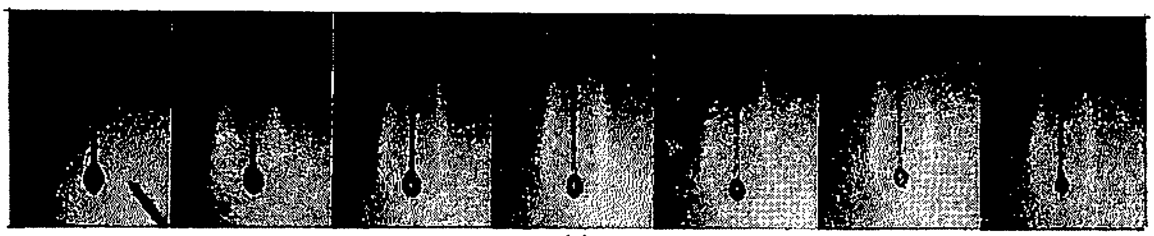
The experiments were made on n-heptane, ethyl alcohol, and benzene droplets, about 1.4 mm in initial diameter, suspended on a quartz fibre at room temperature and atmospheric pressure. Examples of direct photographs of fuel droplets burning under the condition of 1.6 x (gravity) are shown in Fig. 4. The first frame of each sequence gives the situation before the fuel droplet is ignited. The system for measurement of the burning fuel droplet is shown in Fig. 5, where H_1, H_2, and 2W are upper height, lower height, and diameter of flame on the horizontal section through the center of the droplet, respectively. In Fig. 6 are shown typical results for the fuel droplets burning under 1.6 x (gravity) condition in which the squared droplet diameter D^2 are plotted against time from ignition t, where since the fuel droplet is not strictly spherical due to the supporting fibre, 45° diameter was used as a resonable substitute. [3] As seen from this figure, the plot of D^2 against t gives precisely a linear relationship during combustion process as well as a normal-gravity condition, and it is possible to obtain the evaporation constant K as $-dD^2/dt$. The



(a)



(b)



(c)

Fig. 4. Direct photographs of burning droplets under the condition of 1.6 x (gravity).
(a) n-heptane, (b) ethyl alcohol, (c) benzene. Time interval, 0.10 sec.

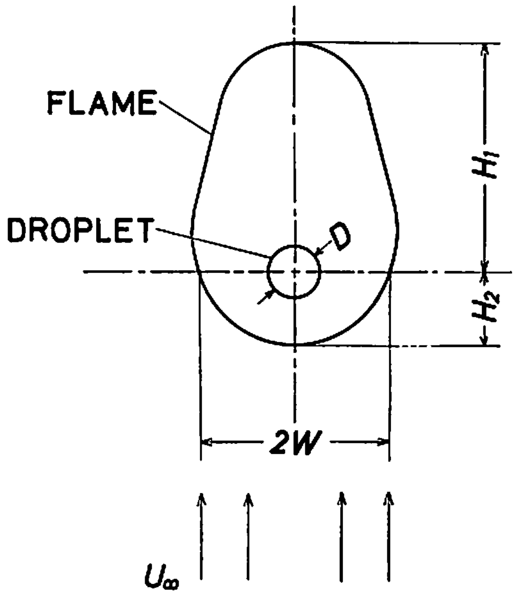


Fig. 5. Schematic presentation of burning droplet.

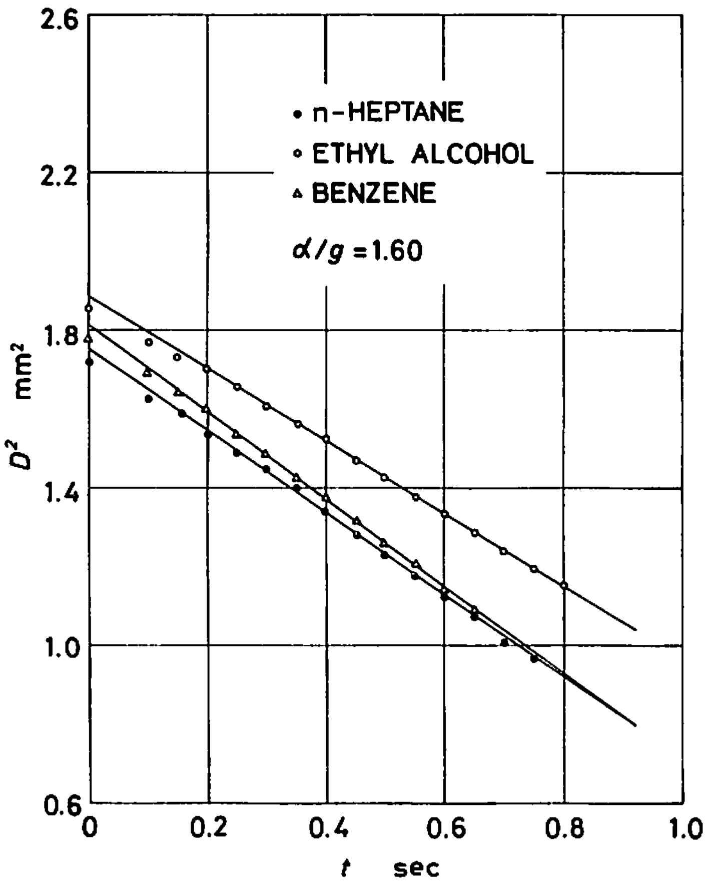


Fig. 6. Square of droplet diameter vs. time from ignition of burning droplets under the condition of 1.6 x (gravity).

values of the evaporation constant of n-heptane, ethyl alcohol, and benzene droplets obtained from this figure are 1.10, 0.90, and 1.20 mm^2/sec, respectively, and these values are only about 13% larger than those obtained under a normal-gravity condition.

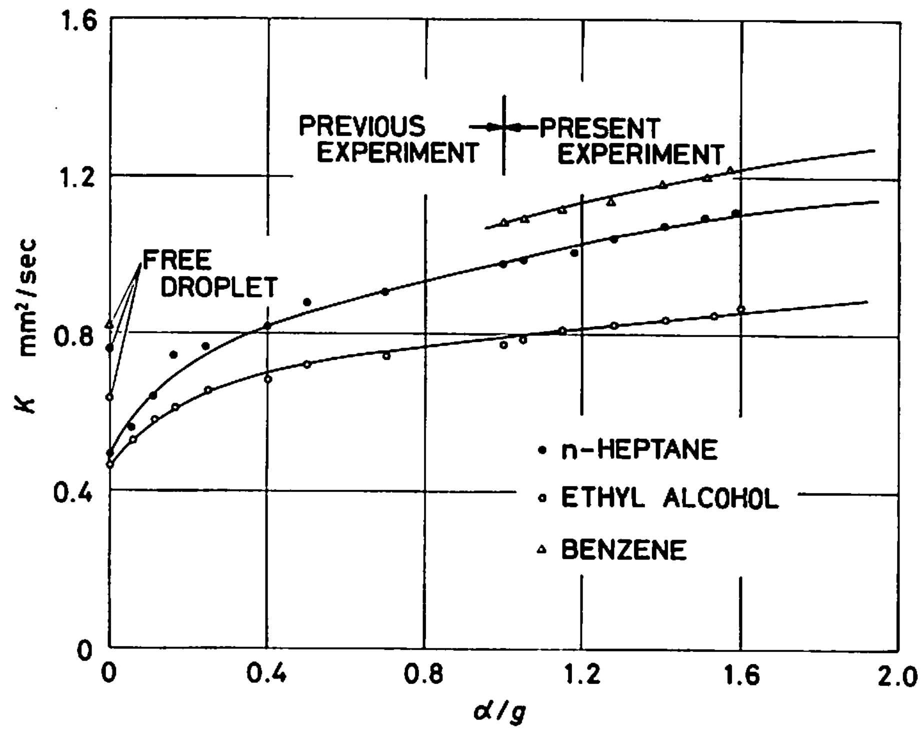


Fig. 7. Effect of acceleration of fall on evaporation constant of burning droplets.

Figure 7 shows the effect of acceleration of fall, that is, natural convection, on the evaporation constant of burning fuel droplets, where the results in ranging from 0 to g were obtained previously by Kumagai and Isoda. [1] From this figure it is found that, for all the fuels investigated, as the acceleration of fall increases, the evaporation constant increases also due to the promotion of natural convection. The values of the evaporation constant under a zero-gravity condition observed by Kumagai and Isoda are abnormally small as compared with those of the free fuel droplets obtained previously. [2, 3] This fact probably means that, at the values of K near $\alpha/g=0$, their experiment suffers from the flaw that a marked amount of the heat evoluted in the burning process may be lost through the metallic electrodes which are embedded in the flame.

Law and Williams [4] presented that the curve of K as a function of a/g for alkane droplets burning under natural convection can be expressed as

$$K = K_0 \ [1 + C(\alpha / g)^{0.52}]$$

where $C(\alpha/g)^{0.52}$ is a bouyancy factor, K_0 is the evaporation constant of the burning droplet under a zero-gravity condition and C is a constant which is to be determined empirically. Excellent agreement between the data shown in Fig. 7 and the above prediction was obtained for the three fuels studied in this work, except the low values of K near $\alpha/g=0$.

The flame around a burning droplet is not spherically symmetrical but is distorted into an oval shape owing to the effect of natural convection, of course, and in the case of benzene droplets carbon particles are produced considerably near the flame as a result of thermal decomposition of aromatic hydrocarbon vapor, as seen from Fig. 4(c), and due to this obstruction the upper height of this flame can not be measured from these photographs. Figures 8, 9, and

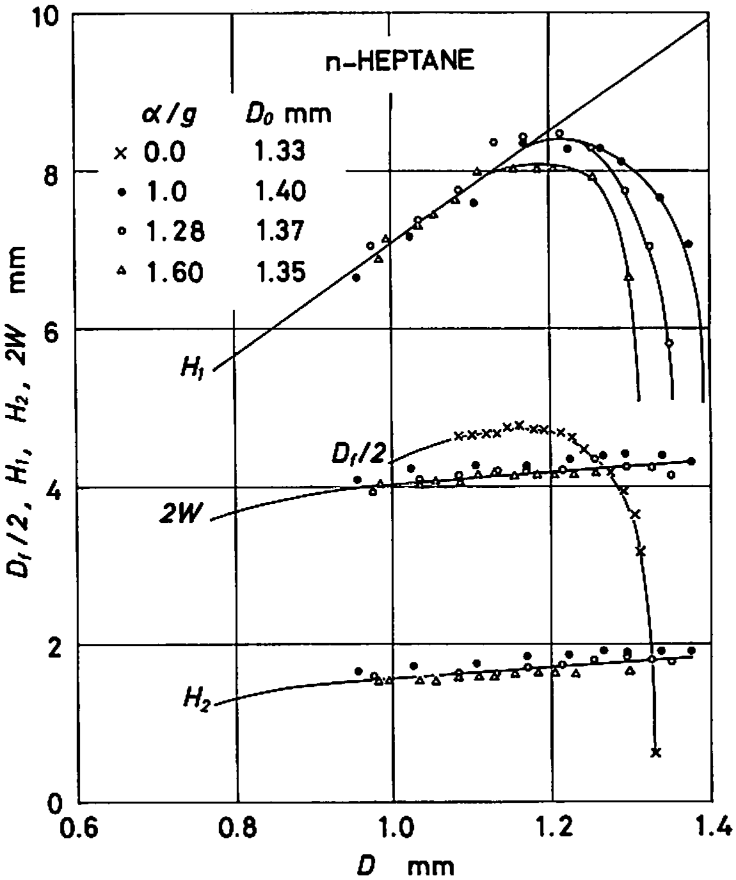


Fig. 8. Flame dimensions vs. droplet diameter of n-heptane droplets burning under various degrees of acceleration of fall.

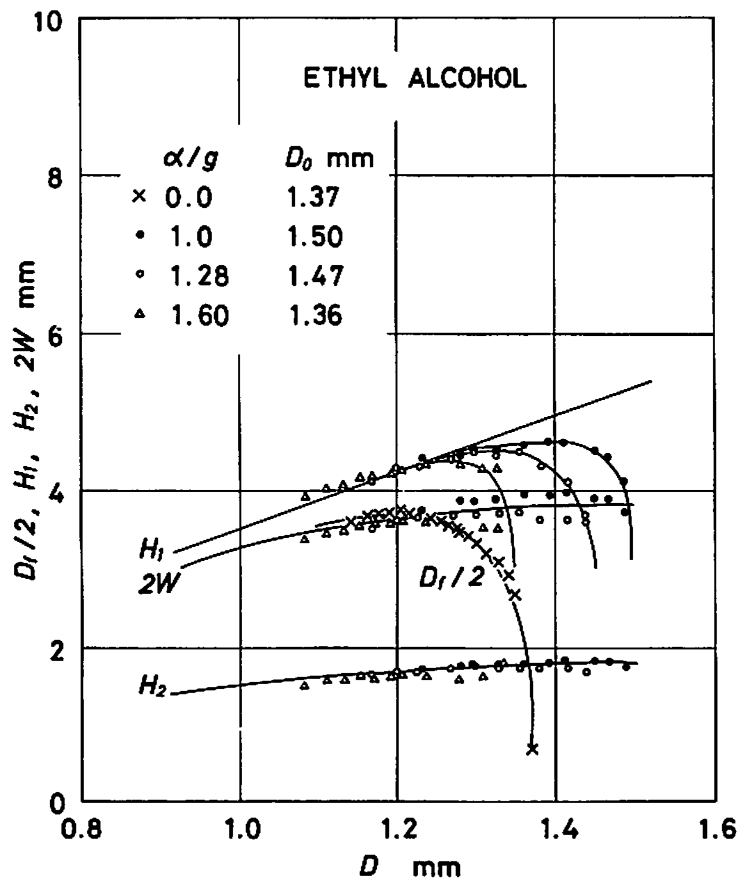


Fig. 9. Flame dimensions vs. droplet diameter of ethyl alcohol droplets burning under various degrees of acceleration of fall.

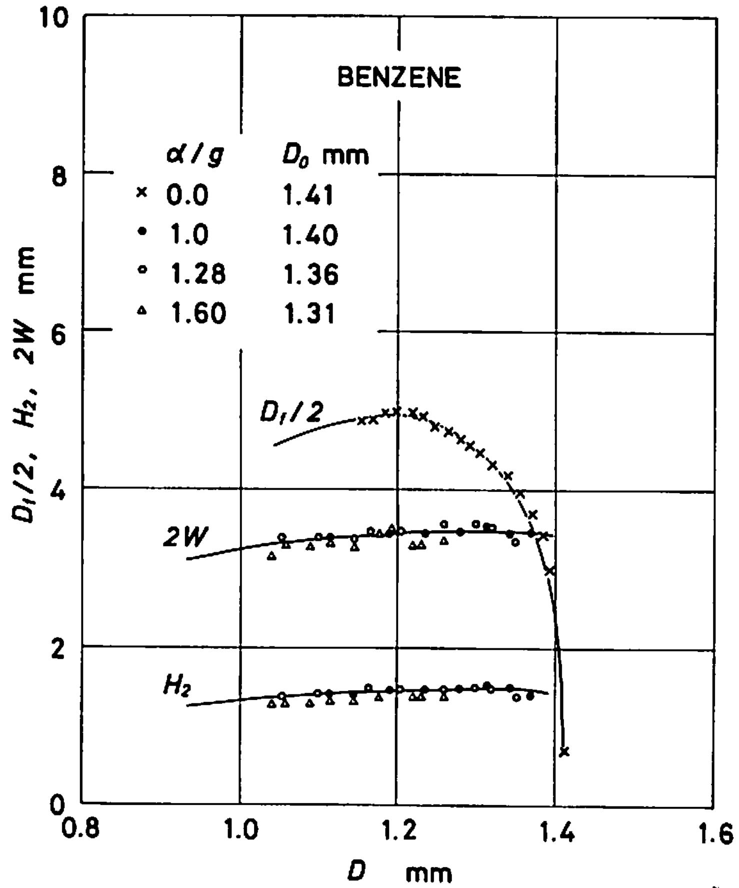


Fig. 10. Flame dimensions vs. droplet diameter of benzene droplets burning under various degrees of acceleration of fall.

10 show the variation of flame dimensions with the diameter of fuel droplets burning under various degrees of acceleration of fall including a zero-gravity, where D_f is a flame diameter of the fuel droplet burning under a zero-gravity condition. From these figures it can be seen that even at $\alpha/g=1.6$ the upper and lower part of the flame are directly proportional to droplet diameter and square root of droplet diameter, respectively. This fact indicates that the behavior of the flame does not differ greatly from that obtained under a normal-gravity condition, although the acceleration of fall exceeds the gravitational acceleration.

4. Conclusion

The authors developed a successful technique to realize and observe the combustion of fuel droplets under the condition of acceleration of fall higher than the gravitational acceleration, that is, the combustion chamber that ascended vertically with a constant acceleration, and they elucidated the effect of natural convection on the burning characteristics such as the evaporation constant and flame shape from these experimental results as well as those obtained previously under the condition of $\alpha = 0 \sim g$.

1) The experimental results indicate that, as well as under a normal-gravity condition, the plot of squared droplet diameter against time gives precisely a linear relationship throughout the burning time and it is possible to obtain the value of the evaporation constant.

2) With increasing acceleration of fall the evaporation constant increases. But, it is only 13%

larger than that for a normal-gravity condition at 1.6 x (gravity).

3) The flame around a burning droplet is not spherical but is distorted into an oval shape due to natural convection and even at $\alpha/g=1.6$ the upper and lower part of the flame are directly proportional to droplet diameter and square root of droplet diameter, respectively. Those facts indicate that, even though the acceleration of fall exceeds the gravitational acceleration, the combustion processes of fuel droplets are very similar to those under a normal-gravity condition.

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