Combustion Experiments in Reduced Gravity Space Environment Using 1second Drop Tower and Challenges Faced

Manu N.M [1], Arjun BJ*, [1], Amit Kumar[1], T.M. Muruganandam[1]
[1]Department of Aerospace Engineering, Indian Institute of Technology Madras

Abstract

Combustion experiments in space are motivated primarily by need for better fire safe environment in space. Among the various space environment platforms available, drop towers are experimental test facility that enables studies of processes and phenomena in good quality microgravity environment for about a few seconds. In this work the relevance of drop tower with regards to combustion experiments and their comparison with other microgravity platforms are discussed. The various challenges faced in achieving good microgravity environment in a drop tower along with different ways of subsystem designs to tackle the problems are also examined. At the end some interesting experimental observations with candle flame, capillary driven liquid diffusion flame and gas based diffusion flame in microgravity are presented.

Nomenclature

INR	Indian Rupee
g	Acceleration due to gravity [m/s^2]
U_R	Gravity induced velocity (m/s) of reactants
ρ_R	Density of reactants
L_R	Length of the flame
T_F	Temperature of the flame
T_∞	Free stream temperature
T	Coefficient of surface tension
θ	Angle of contact
ρ	Density of the liquid
r	Radius of the capillary tube
h	Height of the liquid column

Introduction

In this era where space systems and space explorations are finding widespread applications in various fields of science, studies related to processes and phenomenon in space environment gained increased importance. The space organizations all over the world are involved in various manned space missions and consequently the need for fire safety in space has been indispensable. Therefore, over the years researchers have been studying various aspects of combustion phenomena in reduced gravity demands to address the safety requirements.

Most of the combustion phenomena on the earth are greatly affected by earth's gravitational force. Gravity causes buoyancy to come into play which significantly alters the behavior of combustion processes. In space conditions, as buoyancy forces are absent, combustion process is driven mainly by the natural diffusion of fuel and oxidizer. To study processes in such reduced gravity (or microgravity) environments, various platforms like orbiting vehicles, airplanes, sounding rockets, balloon operated vehicles, drop towers, etc. are used. [1] These systems are examined with their advantages and disadvantages in the section below.

Microgravity Platforms and Relevance of Drop Tower in Microgravity Combustion

One way to achieve microgravity is to perform experiments in orbiting vehicles such as Indian Space Research Organization's (ISRO) Space Recovery Capsule (SRE) [2] or International Space Station which can provide good quality reduced gravity (also termed as microgravity) environment for a prolonged amount of time(~3 months) (Figure 1). But the immense cost involved, the technological expertise required in developing such platforms and less accessibility restricts the quantity and diversity of experiments possible on such platforms.

Aircrafts, balloon operated vehicles and small rockets are also used to achieve microgravity. Aircrafts following a parabolic ballistic trajectory can simulate weightlessness for a few minutes. Though the quality of microgravity attained might not be as good as that of an orbiting vehicle, microgravity experiments are being performed in such systems. Rockets and balloons achieve microgravity by controlled free fall which can give about a few minutes of microgravity of the order of up to 10^{-3} g.

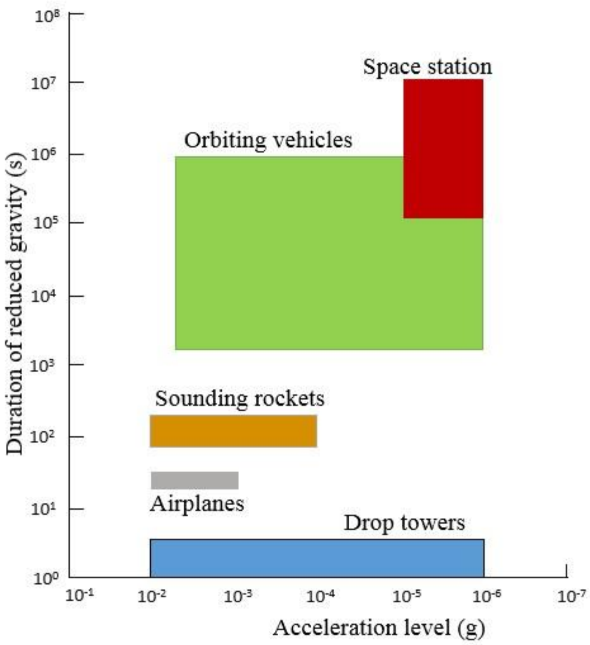

Figure 1: Quality of 'g' achievable and duration for various microgravity platforms

*Corresponding Author: arjunbj007@gmail.com

Another way to attain microgravity is by using drop towers which can provide microgravity levels of the order of 10^{-6}g for about a few seconds. Experiments which can be performed in such short periods of time can be carried out effectively in a drop tower. A drop tower, as the name suggests, is a tall tower in which microgravity is attained by dropping the experimental capsule from a height and conducting the experiment during its free fall. From Table 1, it can be seen that the cost per kg of experiment is of the range of 10^3-10^6 INR/test/kg. The upper end in the range is due to the amount of capital investment required in the initial stage for building the platform. Once the platform is made, the cost per experiment comes down to a much smaller value. Thus, with respect to cost and quality of microgravity achievable, drop tower is a better choice if the time periods of the experiments are of the order of a few seconds. (Table 1) Table 1 compares the quality of microgravity attained and the cost of performing experiments in various microgravity platforms adjusted to inflation.

Platform	Quality (g)	Cost (INR/test/kg)
Orbiting vehicles /Space Station	10^{-5} - 10^{-6}	10^6
Orbiting Vehicles	10^{-2} - 10^{-6}	10^6
Sounding Rocket	10^{-2} - 10^{-4}	10^5
Drop Balloon	10^{-2} - 10^{-3}	10^4 – 10^6
Aircraft	10^{-2} - 10^{-3}	10^5
Drop Tower	10^{-2} - 10^{-6}	10^3 – 10^6

Table 1: Various microgravity platforms, with the quality of microgravity attainable along with their operational costs [3], [4]

Such low cost per experiment and low turn-around time (time between two successive experiments) of drop towers makes them the perfect choice for experiments which can be performed within duration of a few seconds. This also increases the accessibility of drop towers for the scientific community to perform experiments.

Relevance of drop tower in combustion experiments is quite noteworthy as the time scales involved in combustion processes are comparatively much smaller, and thus they can be well performed within the time window of a few seconds. Drop tower seems to be the ideal choice as it provides good quality microgravity environment for the required time.

As introduced earlier, buoyancy significantly influences most of the combustion processes on earth, and its effect has to be reduced as much as possible. Drop tower should be able to provide the reduced gravity levels necessary to make the buoyant convective transport secondary to the diffusion process. This means, the diffusion velocity which is of the order of 1 cm/s should be greater than the gravity induced buoyant velocity. To determine the gravity level required for such a case, consider the momentum equation along the x-direction,

$$\frac{\partial \rho u}{\partial t} + \nabla \cdot (\rho u \boldsymbol{U}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + F_x \quad (1)$$

For simple buoyant convection, at steady state,

$$F_x = g(\rho_\infty - \rho_F)$$

Since buoyancy is the source for the convection term,

$$\nabla \cdot (\rho u \boldsymbol{U}) \sim g(\rho_\infty - \rho_F) \quad (2)$$

Carrying out an order of magnitude analysis with various variables scaling as u ~ U_R, U ~ U_R, $\rho \sim \rho_R$, length scale ~ L_R,
one gets

$$\rho_R U_R \frac{U_R}{L_R} \sim g(\rho_\infty - \rho_F) \quad (3)$$

where ρ_R is reference density. Densities are replaced with temperature inverses as they are inversely proportional. From Eq. (3),

$$U_R \sim \sqrt{2gL_R \frac{(\rho_\infty - \rho_F)}{(\rho_\infty + \rho_F)}} = \sqrt{2gL_R \frac{(T_F - T_\infty)}{(T_\infty + T_F)}}$$

Now, for a flame length of the order of 1cm, flame temperature of 2400K and surrounding temperature of 300K,

$$T_F \sim 2400K,\ T_\infty \sim 300K$$

$$U_R \sim \sqrt{gL_R \frac{(2100)}{(1350)}} \sim \sqrt{1.55 L_R g}\ \ for\ L_R \sim 1\ cm$$

The gravity induced velocity turns out to be of the order of

$$U_R \sim 38\ \ cm/s\, for\ 1g = 9.8\, m/s^2$$
$$U_R \sim 3.9\ \ cm/s\, for\ 10^{-2} g$$
$$U_R \sim 1.2\ \ cm/s\, for\ 10^{-3} g$$
$$U_R \sim 0.4\ \ cm/s\, for\ 10^{-4} g$$

Therefore, the microgravity levels required for removing the dominative effect of buoyancy from the flame is at least of the order of 10^{-4} g. The methods followed to achieve such high quality reduced gravity in a drop tower are discussed in the following section.

Drop Tower Subsystems and Challenges Involved

A 1 second drop tower (i.e. drop tower that provides 1s of microgravity) is constructed at IIT Madras to perform microgravity experiments. A drop tower basically consists of three subsystems, viz. the drop capsule which contains the experimental set up, release mechanism which releases the capsule from the top of the tower and the deceleration unit which captures the capsule safely and brings it to rest.

The drop capsule containing the experimental setup along with data acquisition system and other support systems required to perform the desired experiment, is dropped from the top of the tower. During the fall, atmospheric drag forces acts on the capsule and adversely affects the quality of microgravity achieved. To avoid this there are two possible methods to eliminate drag, by vacuuming the entire drop tower or by using a drag shield. Since using a drag shield can provide reasonably good quality microgravity, and as vacuuming the drop tower significantly increases the operational cost and the turn-around time, capsule in capsule methodology (using a drag shield) is preferred in IIT Madras' 1 s drop tower. The drag acting on the drag shield is reduced by streamlining the outer capsule. Due to the low relative velocities between the inner and outer capsules, the drag acting on the inner capsule is almost negligible, thus maintaining reasonably good quality microgravity environment for the experimental package. The acceleration levels during free fall are tested for single capsule mode (Figure 2) and capsule in capsule mode (Figure 3). In single capsule mode, the drag acts directly on the capsule containing the experimental setup and thus as the velocity increases, the drag also builds up making the quality of microgravity go down as time progresses which is evident in Figure 2. But in capsule in capsule mode, the outer capsule or the drag shield protects the experimental set-up from drag forces thus maintaining the quality of microgravity throughout the drop time. (Figure 3)

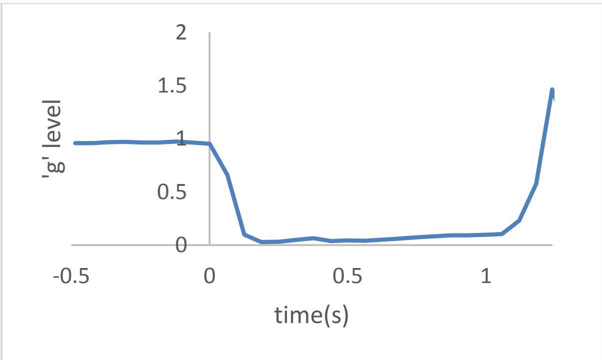

Figure 2: Variation of gravity level (normalized) with time for single capsule mode

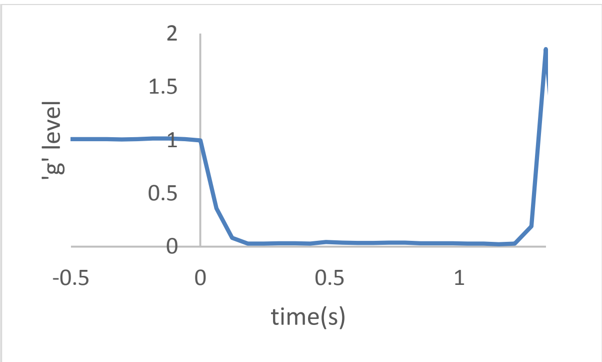

Figure 3: Variation of gravity level (normalized) with time for capsule-in-capsule mode

The capsule after loading with the experimental package is lifted to the top of the tower by the electrically powered hoisting mechanism and dropped by the release mechanism. A release mechanism to be good, has to release the capsule straight downwards without any tilting or swaying and transmitting minimal vibrational disturbances to the experimental package. Different types of release mechanisms such as electromagnetic release, wire cutting, bolt-nut release etc. can be used. Single strand wire cutting release is being used here due to its swift and smooth release capability.

Once the capsule is dropped by the release mechanism, it undergoes free fall, continuously increasing its velocity. This capsule is decelerated and captured by the deceleration unit at the bottom of the tower. Special care has to be taken in the design of the deceleration unit since the electronic equipment and other systems in the experimental setup might not be able to withstand g shocks greater than a particular value (around 30 g). A wooden box softened by foam layers on the inner surfaces and filled with polystyrene balls is used as the deceleration unit. The thickness of the foam layers and the quantity of polystyrene balls are determined to keep the peak g shock on the capsule to be less than 30 g. The schematic of the drop tower with sub-systems is given in Figure 4.

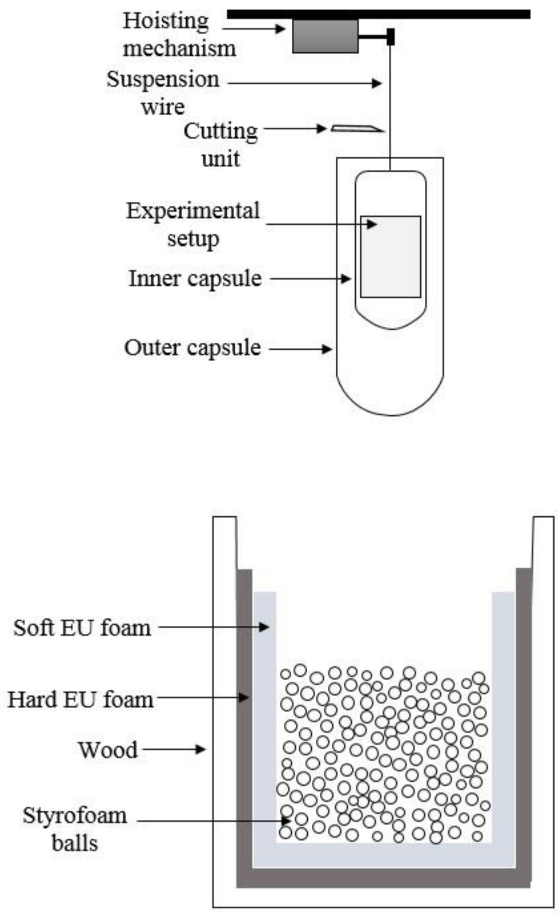

Figure 4: Schematic of drop tower system

Some Combustion Experiments in Microgravity

Candle Flame in Microgravity

Various combustion experiments were performed in the 1 s drop tower of IIT Madras. Firstly, the behavior of a candle flame in microgravity is analyzed. In a candle flame, when the wick is ignited, heat is transmitted downwards to the top of candle body to melt the wax. This wax which turns into a hot liquid forms a layer on top surface of the candle rises up the wick due to capillary action. It vaporizes at the tip of the wick, mixes with oxygen in air and catches fire. The hot gases produced during combustion rises up due to the density gradient created and forms a convection current of surrounding air towards the flame. The melted wax on the surface of the candle also vaporizes and is carried by the convection current towards the flame. This will result in the burning of more fuel and thus larger flame. (Figure 5) Hence, in normal gravitational conditions, the combustion process in a candle is mainly determined by this convection current, thus making the natural diffusion of fuel and oxidizer a secondary phenomenon.

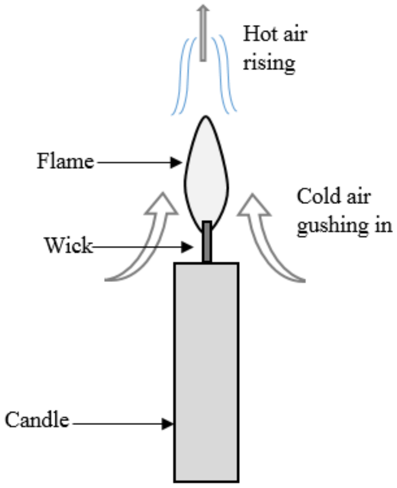

Figure 5: Schematic of candle flame combustion process

In reduced gravity conditions, the density gradient due to difference in temperatures at two locations does not produce any gravity induced buoyancy effects and thus any convection currents. In such environments, the prime decisive factor of the rate of combustion becomes the natural diffusion. Hence, the air or oxidizer approaches the wax vapors, which is the fuel, symmetrically from all directions making the flame spherically shaped in microgravity (actually hemispherical due to the presence of candle on one side). This is visualized in the IIT Madras drop tower using experiments.

A candle was kept on the experimental section in the inner capsule and its behavior was captured using a 8 MP (3264 x 2448 pixels) autofocus camera which is capable of recording video at up to 30 frames per second. Also the acceleration levels are measured using a 3 axis accelerometer (STMicroelectronics LIS3DH) to cross-check the behaviour of candle during the free fall. The candle was kept inside an acrylic chamber to ensure safety of all the systems including the camera and the accelerometer. The experimental module was kept inside the inner capsule and dropped.

The candle flame maintained its normal shape in normal gravity and in microgravity it changed to spherical shape. (Figure 6). Once it touched the catcher, gravity again came into play and the flame extinguished due to the rapid convection currents generated due to the impact causing a sudden gush of air. This phenomenon thus also ensures the safety of the entire system from fire hazards.

Figure 6: Candle flame in normal gravity (left) and microgravity (right)

Capillary driven Liquid Fuel Diffusion Flame in Microgravity

Capillary action is the reason for the melted wax to rise up the candle wick. Typically, larger sized wicks produce larger flames, larger pool of melted wax and thus results in a larger consumption of wax. This calls for the characterization of the wick and analysis of the flame thus formed and the study of capillary based combustion was carried out.

For a capillary tube of radius r, containing a liquid with coefficient of surface tension T, angle of contact θ, density of the liquid ρ, if the liquid rises to a height h inside the capillary, the vertical component of the surface tension force balances with the weight of the raised liquid column. [5]

$$2\pi rT\cos\theta = \pi r^2\rho gh$$

Hence, the height of the liquid column,

$$h = 2T\cos\theta/r\rho g \tag{4}$$

Equation (4) shows that the capillary rise is inversely proportional to the radius of the capillary. Thus, a capillary with larger diameter will raise the liquid column by a smaller height compared to one with a smaller diameter. So, the height of the capillaries must be fixed so that the liquid fuel rises up till the top free surface for proper mixing with air and hence combustion to take place. Another important factor is the number of capillaries required to sustain continuous combustion of the fuel.

Metal capillaries, 18 in number, with inner diameter of 0.4 mm and length 4 cm are held together and dipped in surgical spirit contained in a small vessel. Since the rate at which the spirit (liquid fuel used) burns is quite high, a single capillary's capillary action might not be sufficient to provide the required fuel flow rate for sustained combustion and hence the choice of multiple capillaries together is made. The height of capillaries above the liquid surface is adjusted so that the spirit rises through them due to capillary action and reaches the free surface. This height is further reduced to account for the reduction in the liquid level due to combustion. The schematic of the set-up used is shown in Figure 7.

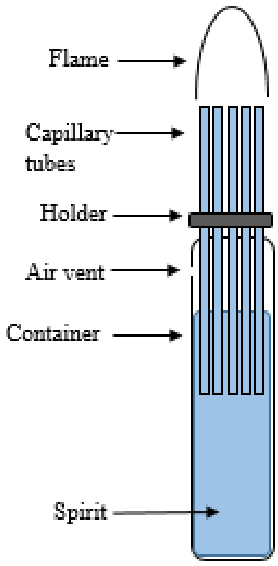

Figure 7: Schematic of the experimental set-up of capillary based combustion

The capillary flame in normal gravity displayed a semi-oval shape which, like in a candle flame can be explained as the effect of convection currents. When the experiment was performed, in microgravity, the flame size increased to a very large value compared to initial state (Figure 8). This can probably be due to the quicker response of liquid in capillaries compared to that of candle which has very small pore sizes for the wick. Also considerable reduction (or near absence condition) of downward gravitational force makes surface tension to be the dominating force. This might also cause a sudden increase in fuel flow through the capillaries and hence a larger flame.

The same experiment was performed using capillaries of 0.2 mm inner diameter (half the diameter of the previous one). To maintain uniformity between the two experiments, the number of capillaries in the second set is taken so as to preserve the same total fuel burn area.

Figure 8: Capillary based flame in normal gravity (left) and microgravity (right)

Since the diameter is halved in the second set of capillaries, the cross-sectional area (or the burn area) becomes one-fourth, and to achieve equal burning surface area as the previous set, one has to take four times the number of capillaries used in the previous set. Thus, 72 capillaries of diameter 0.2 mm were arranged in an axisymmetric manner and combustion experiment was performed as before. The flame is observed to behave in the same way in both the experiments by shooting up the size of the flame to a very large value.

As the next step, experiments can be performed with capillaries of different diameters arranged in groups of different numbers, using different fuels. This can help in quantitatively stating various properties like flame height in normal gravity and microgravity for a group of capillaries of a particular diameter, for various fuels etc.

Cigarette Lighter Flame in Microgravity

Another experiment is performed to compare the effect of microgravity on two types of diffusion flames, one from a candle and other from a cigarette lighter. As discussed before, the fuel flow in a candle is driven by the heat feedback from the flame and accelerated by convection currents, while in a cigarette flame, the fuel supply is maintained constant. A candle and a cigarette lighter are kept side by side in the experiment capsule, ignited together and are exposed to microgravity environment. During this time, the height of the candle flame reduced and it attained a hemi-spherical shape. Meanwhile, the flame from the cigarette lighter grew larger in size. This is shown in Figure 9.

In case of a candle flame, reduced conductive-convective heat transfer from the flame in microgravity reduces the fuel vaporizing from the candle. However, in case of the cigarette lighter flame as the fuel supply is fixed and convective transport of oxidizer is absent the transport is primarily by diffusion hence the flame becomes broader and taller in microgravity. This simple example also illustrates how microgravity environment can have surprising behavior for seemingly similar flame behavior in normal gravity condition.

Figure 9: Candle flame and 'Cigarette Lighter' flame in normal gravity (left) and microgravity (right)

Conclusion

Drop tower is an important ground based facility to perform microgravity experiments having durations of the order of a few seconds. The challenges in attaining microgravity in a drop tower system and the ways of tackling these challenges by effectively designing various subsystems are discussed. Combustion experiments like candle flame experiment, capillary based and gas based combustion experiments are performed in microgravity and the observations are presented. Candle flame became hemispherical in shape due to the absence of buoyancy forces in microgravity conditions. While in capillary systems consisting of capillaries having diameters 0.2mm and 0.4mm, a much larger flame was observed in microgravity. Also in gas based combustion experiment the flame was observed to enlarge in size during the experiment in contrast to that of candle flame.

Acknowledgments

Authors are grateful to Dillip Kumar Sahoo and Aditya Madabhushi, Undergraduate students in Department of Aerospace Engineering, IIT Madras for their help with the experiments.

References

[1] Zhang Xiaoqian, Yuan Longgen, Wu Wendong, Tian Lanqiao & Yao Kangzhuang, "Some key technics of drop tower experiment device of National Microgravity Laboratory (China) (NMLC)", *Science in China* Ser. E Engineering & Materials Science 2005 Vol.48 No.3 305-316

[2] http://www.isro.org/satellites/sre-1.aspx

[3] Inflation Calculator, http://fxtop.com/en/inflation-calculator.php

[4] Barnaby Osborne, "Short duration reduced gravity drop tower design and development", Microgravity sciences and processes symposium, International Astronautical Congress 2008, Vol II, Glasgow, Scotland

[5] Pierre-Gilles de Gennes, Francoise Brochard-Wyart, David Quere, "Capillarity and Wetting Phenomena: Drops, Bubbles, Pearls, Waves", ISBN 0-387-00592-7