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THE EFFECT OF GRAVITY ON TURBULENT, PREMIXED FLAME PROPAGATION

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Nomenclature

x, y, z = axis system (see Fig.3)
h = height of channel
L = integral scale
η = Kolmogorov scale
τ_{wall} = wall shear stress
u' = magnitude of large scale turbulent velocity
U_i = ith component of mean velocity
U = x component of mean velocity (i=1)
V = y component of mean velocity (i=2)
$U_{wall} = U_{belt}$ = belt velocity
U_{rms} = x component of root mean square velocity
V_{rms} = y component of root mean square velocity
$U^* = \left(\frac{\tau_{wall}}{\rho}\right)^{1/2}$ = shear or friction velocity
$U_i^+ = \frac{U_i}{U^*}$ = non-dimensional U_i
$y^+ = \frac{yU^*}{\nu}$ = non-dimensional y
$Re_h = U_{belt} h / \nu$
$Re_L = u' L / \nu$
ν = kinematic viscosity
ρ = density

Abstract

Turbulent premixed combustion, while of increased practical importance, is still not fully understood. A serious barrier to further progress in this area lies in the fact that at the high Reynolds numbers encountered in most turbulent reacting flows the Kolmogorov scale is too small to resolve experimentally. When tests at lower Reynolds number are run, the effects of buoyancy become important. The goal of the present study is to remove the effect of buoyancy from two different turbulent combustion facilities by testing them under microgravity condition. One facility uses a stirrer to create isotropic turbulence in a constant volume combustor. I has been dropped in house. The other uses a Couette flow to create sustained turbulence and will be dropped at NASA Lewis. In the work reported here, the isotropic turbulence facility was tested in the GT Aerospace Combustion Laboratory drop tower. Shadowgraph images were obtained under 1g and μg conditions. The effect of buoyancy was seen to essentially disappear under microgravity conditions. Additional test were carried out to determine whether the turbulent flow under investigation in the Couette facility could be influenced by gravity. Such an effect was clearly observed emphasizing the need for future microgravity tests.

Introduction

Recently there has been a rising interest in premixed combustion because of the ability to control local temperatures and thus reduce NO_x emissions. Practical premixed combustors are turbulent, however, and there are still a number of unresolved issues related to turbulent premixed combustion. This means that these types of reacting flows are not accurately predictable[1]. The overall objective of this study is to increase our understanding of turbulent premixed flames by characterizing their behavior. Particular attention is

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being paid to flame speeds, flame wrinkles, and flame thickness.

A number of important factors have to be considered when studying turbulent reacting flows. First of all it is important to have access to all the scales involved: from L, the integral length scale, to η, the Kolmogorov scale. Their relative magnitudes change with Re_L by the relation

$$L / \eta = (Re_L)^{3/4} \tag{1}$$

For a given experimental flow field the integral length scale is fixed. At the same time experimental resolution considerations limit the smallest Kolmogorov scales that can be measured. As a result only relatively low Reynolds number flows can be fully investigated. However, turbulence in practical devices is usually associated with high Reynolds numbers. An additional problem is encountered when trying to simulate a high Reynolds number reacting flow by one with low Reynolds number. At high Reynolds numbers large scale turbulent stresses are responsible for momentum transport. These stresses, however, can be overwhelmed by buoyancy forces in lower Reynolds number flows.

To remove the effect of buoyancy in a low Reynolds number turbulent reacting flow field a microgravity environment is required. As stated by King[2] microgravity has numerous benefits in combustion science including, but not limited to: increased scalar resolution by allowing the use of larger scales, truly one dimensional geometries, or at least geometries not deformed by buoyancy, and more uniform flames, since buoyancy is temperature dependent, and thus affects different areas of the flame differently. This enables a more accurate study of the combustion processes, which leads to an increased understanding of turbulent combustion.

In this study two approaches where taken to investigate turbulent premixed flames. The first more simple approach, involved using a stirred constant volume combustion vessel. Prior to combustion the stirrer was stopped leaving decaying isotropic turbulence for the flame to propagate in. A high speed shadow-graph was used to visualize the propagating flame front, and these images where subsequently analyzed to obtain flame properties.

This facility, being of moderate size and requiring less than half a second of microgravity, was dropped at the Georgia Tech Aerospace Engineering Combustion Lab in a drop tower facility especially developed for these tests. This drop facility allows continuos high speed shadowgraph images of the experiment to be taken during the drop.

Since this setup can not produce <u>sustained</u> high levels of turbulence a second, more elaborate facility was developed. A Couette flow configuration was selected since it generates a sustained turbulent flow at relatively low Reynolds numbers. A Couette flow is a classical shear layer flow produced between two parallel plates moving in opposite directions, each at a fixed velocity U_{wall}. This flow has the benefit that the shear stress is constant though-out the cross-section, and that the intensity of turbulent fluctuation is constant for most of the cross-section. In addition, such a flow can be generated in the confined space available in the drop tower facility at the NASA Lewis Research Center.

The NASA Lewis 2.2 Second Drop tower was chosen as the site for the microgravity experiments using the Couette facility. This drop tower facility allows a 40.64cm by 96.52cm by 83.82cm experimental rig to experience 2.2 seconds of ~ 10^{-4}g followed by 0.2 sec deceleration (at 15 to 30 g). Due to the spatial and temporal restriction imposed by this experimental facility[4] many diagnostic techniques, like laser Doppler velocimetry (LDV) or OH^- fluorescence, cannot be used to study the flow field. To interpret the results from more basic diagnostic techniques, like Schlieren imaging, it is essential to first understand the non-reacting flow field. Velocity and shear distribution in the cold flow field measured by LDV were previously mapped for different flow conditions[3]. The feasibility of carrying out 2D image mapping of a spreading scalar in the flow was tested by injecting acetone at a point into the flow field and visualizing its spread using passive species planar laser induced fluorescence. In addition, the effect of gravity at the Reynolds numbers under investigation were evaluated by generating a low density plasma in the flow and tracking the resulting density gradient using high speed Schlieren.

This paper will report the capabilities of the new facilities and preliminary microgravity combustion results obtained in the GT drop tower. It will also present the continuing cold flow study results of the Couette facility.

Experimental Facility and Methods

A small drop tower facility was designed and constructed in the Aerospace Engineering Combustion Laboratory on the Georgia Tech campus, see Fig. 1. The experimental device to be dropped is raised to it's starting position using a winch ①. Here it is lined up with an electromagnet ②. Once the magnet is powered, its 175 lbs. lifting capacity, holds the device tightly in place. The lifting cables are then disconnected. Turning off the power to the magnet results in a clean release. At the end of the free-falling drop the device is decelerated in a box filled with expanded polystyrene pellets ③, kindly donated by TechPak, Inc. Also shown in Fig. 1 is the shadowgraph system that is used to track the flame front during the drop. Light from a 0.95mW HeNe laser ④ is expanded and collimated by a set of lenses ⑤, into a 4 inch beam. This beam is sent down, through the box, and then back up, using 3 mirrors ⑥, one fixed on the drop tower and two attached to the dropping facility. The beam is then imaged onto a screen ⑦. A Kodak Ektapro intensified digital camera ⑧ running at 1000 frames per seconds records the images. These images can then be downloaded to a PC where they are enhanced and processed to obtain flame speeds, shapes, and thickness.

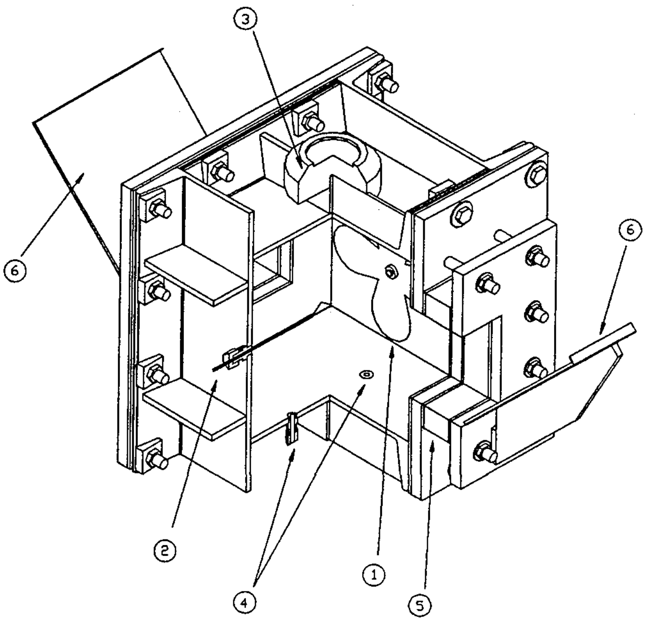

Figure 2 - Stirred Constant Volume Combustion Chamber

A stirred constant volume combustion chamber, which is used in the GT drop tower, is shown in Fig. 2. It is fabricated out of steel and designed to withstand pressures up to 150 psi. A stirrer ①, which consists of a 6 inch in diameter 4 blade fan, is mounted on one side. It is supported by two bearings, and sealed with an o-ring. A Lovejoy connector is attached to the end of the drive shaft to allow, not only easy alignment with the motor, but also a quick disconnect. Two quartz windows ⑤ allow optical access to the turbulent flame in the chamber. The two mirror ⑥ attached to the device are part of the aforementioned shadow-

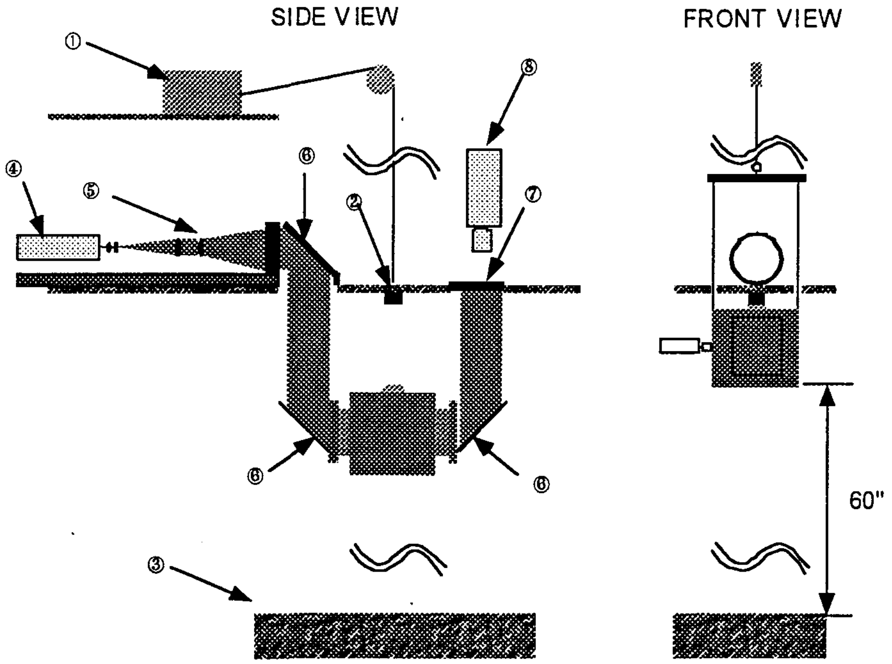

Figure 1 - GT Aerospace Engineering Combustion Laboratory's Drop Tower Facility

graph system. The stirred reactor is filled with a combustible mixture through a port located at the bottom ④. The partial pressure method was used to calculate the stoichiometry of the mixture. A home made spark plug ② and its ignition system are located on the side opposite the stirrer.

Because the electromagnet does not release the experiment immediately after its power has been turned off, switching off the magnet could not be used to trigger the igniter. Instead, a hall effect sensor, positioned on the magnet docking guide ③, senses the instant the experiment is separated from the electromagnet, and triggers a pulse. After a 50 msec delay, during which the dropping experiment has ample time to stabilize, a pulse triggers the ignition transformer. A small neon light DC transformer connected to the home made spark plug is used to ignite the flammable mixture. It is powered by two 9 volts DC batteries and provides 1500 volts AC at 20KHz and 5 mA, more than enough to created an ignition spark.

A Kistler K-BEAM capacitive accelerometer is attached to the device to be able to monitor the degree of microgravity experienced by the combustion process. This accelerometer has a range of ± 1g with a sensitivity of 1959 $^{mV}/_{g}$ and can survive a maximum of ± 40g. The manufacturer's guaranteed precision, around 0 g, is $\pm 3x10^{-2}$g.

Once the device is in position the overall drop procedure consist of turning on the ignition circuit first. This prevents a spark generated by turning on the circuit from igniting the flammable mixture prematurely. Next the methane is injected in the chamber, and the gasses are given time to mix. The pressure in the reactor is monitored by a pressure gauge and excess pressure is relieved. The external piping are then disconnected. The motor is connected to the shaft and turned on to the desired speed. After the flammable mixture has been stirred for about one minute the motor is disconnected. Then the camera is turned on, and the power to the electromagnet is turned off. The ignition circuit ignites the mixture as discussed above. After the run the combustion device is retrieved, purged, checked for possible problems, hoisted back up in position, and prepared for a new run.

The Couette device used in this study is shown in Fig. 3. The device consists of a continuos Mylar belt ① which provides the "two parallel plates" moving in opposite directions. The belt runs over a series of rollers, two of which drive the belt while four are used to adjust the spacing in the test section. A set of plates is positioned on the outside of the belt to eliminate possible vibration of the belt. These vibrations had been found to cause higher levels of turbulence with peaks in the frequency spectrum. The belt is driven by an adjustable DC motor ② connected to the drive roller by a set of pulleys and a v-belt ③. The rotational speed of the motor is sensed by a magnetic proximity sensor ④. Knowing the pulley ratio and the roller diameter, the speed of the belt can easily be determined. To prevent belt walking and to ease the insertion of a new belt, a set of tensioning screws ⑤ help position the far roller. The Reynolds number for the device, Re_h, can be changed by either changing the speed of the belt, U_{belt}, or by changing the belt spacing, h. The device is surrounded by a Plexiglas box to prevent any external influence on the flow without disturbing optical access to the experiment.

Before the Couette flow could be used to study turbulent flame propagation under microgravity it had to be established that the effects of gravity could survive in this turbulent flow field. To this end a gas

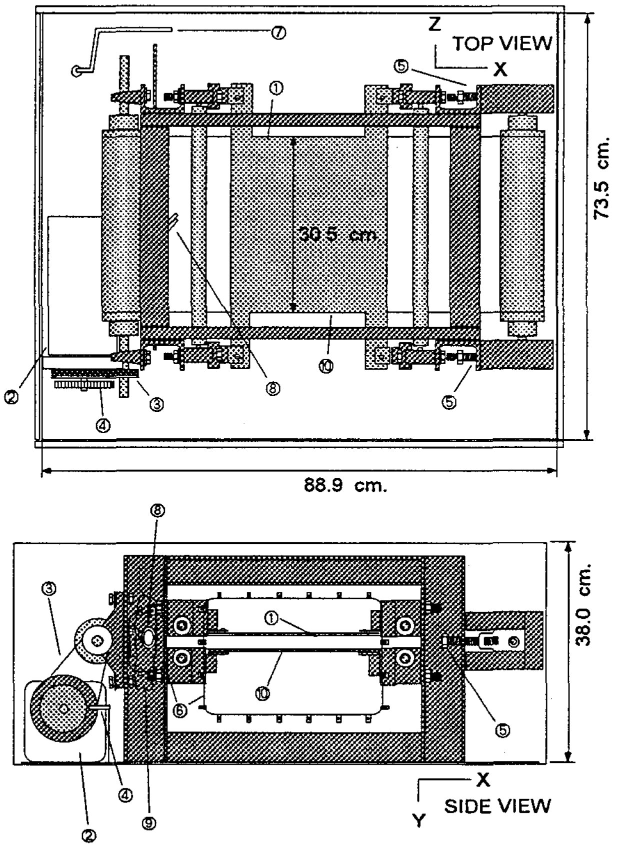

Figure 3- Current setup of the experimental device. Call-outs described in the text.

of lower density was introduced into the flow and its interface with heavier air was tracked as it progressed though the flow. Helium was injected through a hypodermic needle along the centerline of the Couette flow. The needle was equipped with micro-machined holes on four sides to limit the directional biasing associated with one hole injection. However the strong shear of the Couette flow, along with the high diffusivity of the helium caused the gas to mix with air almost instantaneously. No clearly visible helium-air interface could, therefore, be observed in these test.

Better results were obtained when a density gradient was produced by focusing a laser beam into a small volume at a point located along the centerline between the two belts. The energy furnished by the laser was sufficient to ionize the air and thus form a spark. The propagation of this point source of hot gases was then tracked with the help of a high speed Schlieren system. The laser used to generate the spark is a 300mJ per pulse tunable Lambda Physik excimer laser running with KrF, to produce a laser pulse at a wavelength of 248nm. This laser was chosen because it not only offered enough power per pulse to ionize the air, but being in the UV, scattered light did not affect the Schlieren. The Schlieren light source was a .95 mW HeNe laser. The beam stop was an opaque dot, 1mm in diameter, to avoid directional biasing. Schlieren images were captured using a Kodak Ektapro intensified digital camera running at 1000 frames per second.

Results and Discussion

Previously Reported Results

Previously reported data for this facility have proven the velocity flow field to be two dimensional[3]. Therefore, the analysis of subsequent data is performed using centerline profiles. Figures 4 and 5 show dimensional and non-dimensional mean and turbulent profiles at two different Reynolds numbers, respectively. Figure 4 clearly indicates constant levels of turbulence throughout most of the flow field, while the data in Fig. 5 clearly shows the expected behavior for a wall bounded shear flow. The flow can be divided into two regions[5], the viscous sublayer ($y^+<5$), and the inertial sublayer ($30<y^+<1000$). The flow correlates well with the linear behavior at the wall in the viscous sublayer. The logarithmic behavior in the inertial sublayer is also clearly present. However the data at different Reynolds numbers do not exactly collapse into one single line when non dimensionalized, as predicted by theory and seen by others. This is probably due to the smaller dimensions and re-circulating nature of the present device. Figure 5 also shows U_{rms}^+ and V_{rms}^+ as functions of non-dimensional distance from the belt. As expected, U_{rms}^+ has a turbulence peak close to the wall before it reaches a uniform distribution in the core, and V_{rms}^+ gradually increases to a uniform distribution in the core. Most of this information was presented in the reference[3].

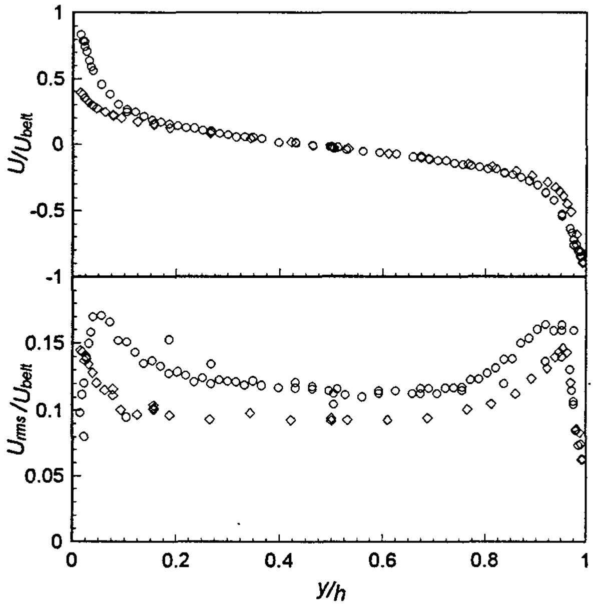

Figure 4 - Velocity distribution across the flow ◇ Re_h = 10,091, ○ Re_h = 4,366.

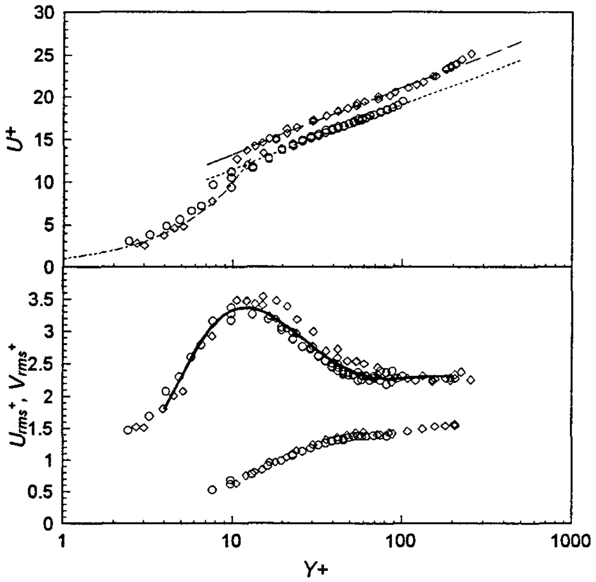

Figure 5 - Non-dimensionalized velocity distribution across the flow ◇ Re_h = 10,091, ○ Re_h = 4,366.

Density Gradient Study

The low density fluid tracking test in the Couette flow were carried out at $Re_h = 10{,}000$. The spark generated by the Excimer laser created a kernel of hot gasses which during the first two milliseconds after its generation expanded to 50% of the belt spacing. This initial expansion was so fast that it was not affected by gravity. However, it was also too fast to be considered a good representation of what would happen to a methane-air flame. After this period, however, the remains of the hot kernel of gasses are left to move and mix with the flow. When these hot gasses were further tracked they were seen to interact with the turbulent mean flow which strongly deformed the shape of the kernel. At the same time it was noted that the center of the hot gas volume rose about 5% of the total belt spacing above the centerline of the flow, in a period of 20 msec, indicating that buoyancy persists even in this turbulent flow.

To identify the center of the hot gas volume the Schlieren images were first of all processed. Each captured image was turned into its negative and the background was then subtracted from both the positive and negative images. This was done to accurately catch both the above background and the below background structures. The resulting images were then adjusted for contrast. Because of the zero mean flow that this Couette facility provides along its centerline, the kernel's center remains stationary in the horizontal direction. For images at later times, this means at the horizontal position of the point of origin, the vertical instantaneous location of the bottom and top edges of the kernel can be used to locate the position of the center of the hot gas products. At first the location of the edges were visually identified and the results used to calculate the position of the center for both the positive and negative images. The data were then averaged.

Later, a more quantitative method was adopted. The pixel intensities were plotted along a vertical axis through the point of origin of the kernel. Such a plot and the image used to obtain it are shown in Fig. 6. In these plot the dark and bright regions corresponding to the hot gasses are clearly defined. The mid level noise regions corresponding to the background are also clearly identifiable. Thus the edge of the kernel was defined as the point where these two regions met. Here again centers were determined, by the method used before, for both the positive and negative images and averages were calculated. The averages obtained by the two methods were compared and since it was felt that, especially for images later on in the sequence, both methods had an equal amount of error, they were averaged. The result was the increase in the vertical position of the center with time, mentioned above. This proves that gravity affects the flow even when the flow's Reynolds' number is as high as 10,000.

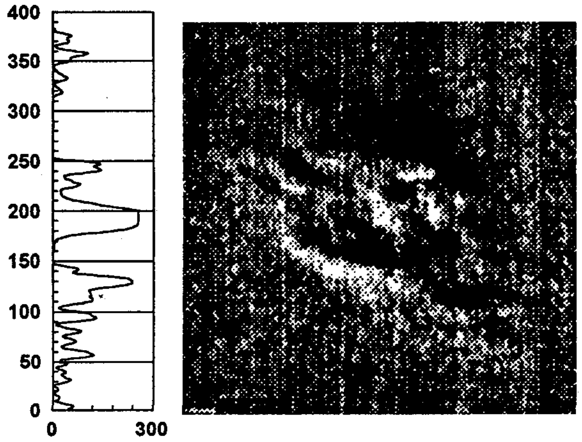

Figure 6 - Hot kernel of gasses propagating in Couette facility - corresponding pixel intensity plot.

Drop Tower Facility

The mechanics of the facility were extensively tested and the microgravity environment was quantified. It was ascertained that the 60 inch drop of this facility provides 0.4 sec of ~ 10^{-3}g or better. Gravity level trace obtained during each of the runs show that levels of 3×10^{-3}g and below are being achieved for all runs, even thought the manufacturer's guaranteed precision for the accelerometer, around 0 g, is $\pm 3 \times 10^{-2}$g. The experimental device sinks about 30 inches into the polystyrene during its deceleration. Overall the facility behaved exactly as planned and was found to be relatively user friendly. The optical system was also tested for both alignment and proof of concept. Several vibration problems associated with the start of the drop were identified, and corrected.

Stirred Constant Volume Combustion

The stirred constant volume combustor was first tested on the ground. Two dimensional LDV carried out within the first couple of seconds after the fan was turned off showed isotropic turbulence with an rms velocity of 6 to 7 cm/sec. The reactor was then filled with a methane-air mixture, stirred and ignited at 1g. A typical sequence of images from these test is shown in Fig. 7. The wrinkles of the flame are clearly identifiable, the thickness is measurable, and from the

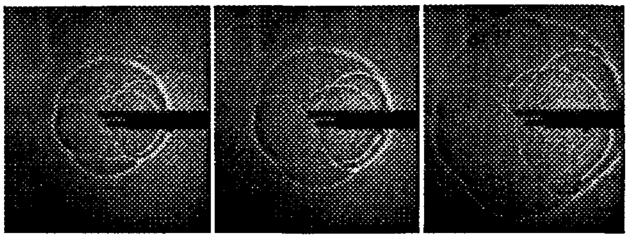

Figure 7 - Schlieren images of methane-air combustion in the stirred facility, 1g.

sequence of image flame speeds can be determined. Most importantly, it can be clearly seen that this flame ball is raising with time, its upper flame front having traveled 10% farther than the lower one. This clearly shows the effect of gravity. Figure 8 shows a shadowgraph of a turbulent premixed methane-air flame obtained while the stirred constant volume reactor was dropping in the GT drop tower. Although the contrast in the shadowgraph is not ad clear, the wrinkle in the flame front is clearly visible. Measurements of the location of the flame front clearly indicate that the center of this flame ball remained at the point of ignition. Thus, the effect of gravity on this turbulent flame has been drastically reduced, if not totally eliminated. Further testing to obtain improved images under a variety of conditions and more detailed analysis of the obtained data are currently underway.

Conclusions

A stirred, constant volume combustion chamber for studying turbulent premixed flames in a microgravity environment was designed and built. A drop tower capable of producing 0.4 seconds of microgravity at a level 10^{-3}g was developed and constructed. A shadowgraph set-up that permits constant observation of the flame front during a drop was integrated into the drop tower. The entire system was checked out. Shadowgraphs of lean, turbulent, premixed methane-air flames were obtained in 1g and microgravity environments. Comparison of the images obtained under the two conditions showed that the effect of gravity was essentially eliminated during the drop.

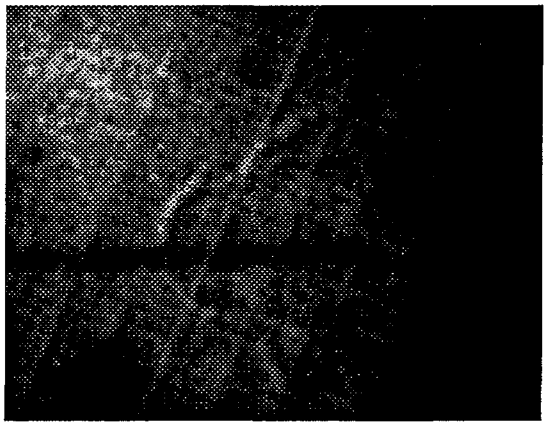

Figure 8 - Shadowgraph images of methane-air combustion in the stirred facility in μg while dropping at the GT Aerospace Engineering Combustion Laboratory drop tower.

Tests were carried out to determine whether the effect of gravity could influence the turbulent flow under investigation in the Couette facility. When a low density plasma was introduced into the cold Couette flow tracking its interface with the cold air showed that even at the relatively high turbulence intensity present in a Couette flow at Reynolds number of 10,000 buoyancy, and thus, the effect of gravity persists. A slightly modified Couette facility for combustion test in the NASA Lewis Research Center drop tower is currently under development.

Acknowledgments

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