The Effects of Buoyancy on an Acoustically Pulsed Non-Premixed Laminar Jet Flame

A Fundamental Study of Combustion Science

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Flight Week Preference

Our main preference for flight days is the time around our University spring break so that we miss the fewest number of classes in order to participate in the flight campaign. Our break begins Saturday, March 8 and ends Sunday, March 16, 2002.

Other than the time around our spring break, our team has no other preference for flight dates. If that time is unavailable, we will be flexible to any time that is assigned to us.

The Effects of Buoyancy on an Acoustically Pulsed Non-Premixed Laminar Jet Flame

A Proposal to NASA for the
2003 NASA Reduced Gravity Student Flight Opportunities Program

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Abstract

It was shown by a team of student researchers during the Spring 2002 RGSFOP campaign from our department that when an acoustically pulsed non-premixed laminar fuel jet is ignited in a microgravity environment, the structure and behavior of the resulting flame are radically different from those of an identical jet ignited in a normal gravity environment. This is because, in normal gravity, the structure of the flame is dominated by the effect of the buoyancy force that is dependent on the local gravity field. In microgravity, where there is no appreciable gravity field, there is no serious influence of the buoyancy force.

In addition to its fundamental scientific value, the analysis of buoyancy effects has important relevance to practical combustion devices such as gas turbines, boilers for electric power generation, and aircraft jet engines. Combustion modeling of these devices is very difficult in that the analyses involve fluid mechanics, diffusion, and buoyancy influences among others. A serious problem in constructing these models is that buoyancy effects tend to dominate and hide smaller effects present in a combusting gas. Flame studies done in the microgravity environment are very well suited to improve combustion models because buoyancy effects can be removed.

We propose to carry out an experiment to expand on the abovementioned work that was done by students in our department last year. To accomplish this, we will re-design the previous test setup to enable us to visualize the structure of a periodically pulsed unsteady laminar non-premixed jet flame under normal- and microgravity conditions with both a new schlieren flow imaging system and a flame luminosity imaging system similar to last year. Just as important, untested frequency and amplitude settings of the forcing signal will be analyzed to obtain a more complete picture of the gathered data than was collected last year. Therefore, our aim is to build on the results of last year's campaign that illustrated the radical differences between normal- and microgravity flames and to now attempt to characterize these differences.

1 Background and Introduction

1.1 Introduction

Gas-phase combustion is critical to a wide range of important technologies including automobile engines, gas turbines and boilers for electrical power generation, and aircraft engines. Many large-scale combustion devices operate in a “non-premixed” mode, which is where the fuel and oxidizer remain separated until they enter the combustion chamber where they mix and burn. Non-premixed combustion is preferred to premixed combustion in large-scale burners for reasons of safety, because it avoids the dangerous possibility of flame propagation upstream into the fuel and oxidizer feed streams. The problem with non-premixed combustion, however, is that it is generally associated with higher production of pollutants, such as NO_x, CO and soot (smoke), which are known to cause significant public health and environmental problems. Unfortunately, the best available predictions of pollutants in actual combustors, or even in some relatively simple laboratory flames, are not adequate for the design of combustors that are being required to meet increasingly strict emissions standards.

1.2 Relevance and Role of Gravity

Developing a fundamental understanding of combustion processes is a major goal of the NASA Microgravity Sciences Division program in Combustion. In fact, combustion is particularly well suited for microgravity research because most combustion processes are strongly affected by buoyancy. This is because buoyancy is driven by the large temperature differences that result from chemical heat release. In combustion systems, where many physical processes are at work – such as fluid convection, chemistry, diffusion, heat release, buoyancy, and often turbulence – the effect of buoyancy often masks, or at a minimum complicates, the relevant physics. The microgravity environment is unique in that it enables the researcher to "turn-off" a major physical phenomenon, which is something that can rarely be done with other important phenomena, except perhaps in numerical simulations.

Furthermore, understanding combustion in the microgravity environment is important to NASA because a very real safety concern for the International Space Station (ISS) is how accidental fires will behave in a low-gravity environment. At this time it is largely unknown whether the safety procedures that have been developed at normal gravity will be adequate for dealing with those under microgravity conditions.

1.3 Test Objectives

Because improving our understanding of combustion processes has widespread significance to many important technologies, we propose to conduct a study on the effects of buoyancy on the structure of unsteady non-premixed laminar jet flames. In carrying out this fundamental study in combustion physics, our aim is to collect information that will be relevant to important ground-based technologies and to combustion problems associated with spaceflight safety.

1.4 Test Description

1.4.1 Justification for the Microgravity Environment

An extensive amount of research has been directed at understanding the structure of acoustically forced laminar non-premixed jet flames under *normal gravity* conditions [1-5]. Periodically forced flames are useful because they enable the researcher to study the effect of an unsteady flow field on the flame structure, while maintaining a relatively simple and repeatable flow in which a wide range of measurements can be made. One of the most important advantages of a periodic flow is that measurements can be made with independent techniques at different times. Provided that the different measurements are made at the same phase of the oscillation cycle, then the combined measurements are the same as if they had been taken simultaneously.

As an example of acoustic forcing, Figure 1 shows a sequence of images of a forced laminar methane flame [4]. In this experiment, the flame was forced at a frequency of 16 Hz by modulating the pressure in the plenum with a loudspeaker. The modulated plenum pressure acts to modulate the fuel velocity at the exit of the nozzle. The figure shows the flame at three different phases of the oscillation cycle. The flame was visualized with a combination of soot emission (yellow) and laser light sheet visualization of titanium-dioxide particles that were seeded into the jet stream (green). The “flame” or the reaction zone is approximately marked by the soot emission. The figure shows that the flame is greatly distorted by the passage of the large vortical structures that result from the acoustic forcing (the structure is seen most easily in Fig. 1b). As the vortex moves downstream (Fig. 1c) the flame wraps around the vortex and is seen to extinguish near the top and underside of the vortex. Understanding this extinction process is of great interest to the combustion community because it is the extinction process that affects the stability of large-scale combustion devices such as gas turbines.

Laminar flames are characterized by low Reynolds numbers and typically low momentum fluxes, and therefore buoyancy effects are typically very important [1]. This is the case whether acoustically forced or not. In fact, we expect that buoyancy plays a large role in determining the structure of the vortices seen in Figure 1, but the exact nature of this effect cannot be known without studies of equivalent flames under microgravity conditions. Furthermore, a study that is able to determine the affects of buoyancy on the structure of a well-defined flow such as the one considered here would be particularly important to combustion modelers, who prefer to validate their results to relatively simple flows. It is only upon getting good agreement with the simplified case that they make comparisons to more complex cases. A critic of this approach could argue that an alternative means of reducing the effect of buoyancy would be to increase the jet momentum flux, but this also increases the Reynolds number, and thus creates an ambiguity as to whether the differences that are seen are due to buoyancy or Reynolds number effects. This is why the microgravity environment is ideal for studying the effects of buoyancy on unsteady laminar flames; the buoyancy can simply be “turned off,” just as can be done in the numerical models.

To date, there have been several studies of unsteady laminar flames in microgravity, but few of these have dealt specifically with periodically forced non-premixed flames. For example, a few researchers have investigated the interaction of a premixed planar flame with a single vortex [6,7]. In this case, the buoyancy effects have been shown to dominate the structure of the flame under normal-gravity conditions. These microgravity experiments have proven to be exceptionally useful for modelers, because buoyancy-generated turbulence at normal-gravity complicates comparisons between simulations and experiments. We know of only one other successful experiment dealing with periodically forced non-premixed jet flames [8]. In this study, which was undertaken in the Space Shuttle, a laminar propane jet was modulated with a mechanical diaphragm to produce an oscillatory jet flame. The Reynolds number of the jet was 400, the forcing frequencies ranged from 1-10 Hz, and the primary measurements that were made were fluctuating temperature measurements. We believe that this proposed study would complement the forced-flame work of Ref. 8 because our study emphasizes flow visualization rather than single-point temperature measurements.

1.4.2 Experiment Facility

Only a brief description of the facility will be given in this section as further details, particularly those related to safety, are discussed in Section 2. The experimental rig, shown schematically in Figure 2, is a modification of last year's rig. It will be contained in a 5' (long) by 3' (high) by 1.5' (wide) metal enclosure. The enclosure will be made with a sturdy frame of welded aluminum square tubing onto which sheet aluminum sidewalls will be affixed. The constraints on the size of the enclosure are that it needs to be tall enough to contain the flame hardware and give the flame sufficient space to develop, and it must be long enough to contain the necessary plumbing and give sufficient working distance for the camera optics.

The enclosure will be securely mounted to the floor of the aircraft with straps and will have plenty handles for loading and for the flight crew to hold during low-g phase. The enclosure will contain the jet apparatus, plumbing for the fuel gas and an inert gas purge (for safety reasons discussed below), fuel and nitrogen storage bottles, flame igniter, DC power supply, custom-built electronics and the high-speed camera head. Additionally, we will use a small instrument rack, which will hold the function generator and laptop computer. The front side of the enclosure will face the students during flight. This side will have an acrylic window installed for viewing the flame.

Once in flight and the flight crew becomes acquainted with the aircraft procedure, testing will begin during the next low-g phase. When the low-g phase is initiated the Pulsed Flame Apparatus (PFA) system (refer to Figure 3) will first be purged with carbon dioxide. The flame will then be ignited with a piezo-electric igniter that will be rotated in place over the jet exit using a rotary solenoid actuator that will be mounted inside the enclosure. Up until the time that the flame is lit, the fuel line will be purged with inert nitrogen gas. At the top of the parabola the gas will be switched to methane and the igniter will light the gas and then swing out of the way to a secure stand by position.

After the flame has been lit, it will be acoustically pulsed by the speaker mounted at the bottom of the PFA. Different frequencies and amplitudes will be used to pulse the flame throughout the flight. When the flame appears to be functioning properly we will begin to record data with a Kodak Ektapro H.S. 4550 CCD camera for approximately 5 seconds during each low-g phase. The camera will then shut off and the gas will be turned off, extinguishing the flame. After the data has been recorded, it will then be transferred to the laptop where it will be stored on the hard drive. This will all be done in the low-g phase and nearly the entire system will be automated by LabVIEW. The only manual action will be to press a button for the piezo-electric igniter and to adjust the frequency and amplitude settings on function generator and stereo amplifier, respectively, during the high-g phase.

1.4.3 Data Analysis

The data that will be acquired during a flight will be highly resolved movies of the natural luminosity of the flame at a range of Reynolds numbers (e.g. 100, 200, 300), a range of frequencies (e.g. 10, 20, 50, 100 Hz), and at perhaps two different forcing amplitudes. The exact conditions that will be studied will be determined in pre-flight ground testing at UT. The same conditions will be used to acquire equivalent normal-gravity data for comparison purposes. The luminosity, which results from soot emission, is useful because it is an approximate marker of the location of the reaction zone. The image data will be used to see if we can determine obvious structural differences between the normal- and micro-gravity flames. We will then conduct a more thorough analysis by quantifying some important flame characteristics. For example, we average the images over several oscillation cycles and compute the mean flame lengths. The flame length gives an indication of how efficiently ambient air is entrained into the flame (i.e. more entrained air means the fuel is consumed sooner), and we expect substantial differences between the normal and micro-gravity conditions. Also of interest will be to compute the root mean-square (*rms*) fluctuations of the luminosity as they are strongly affected by the large-scale structure. We will also be able to compare the magnitude of the soot emission intensities for the different cases, as the emission is strongly influenced by the production of soot particles.

First order vertical density gradients will be captured with a high frame rate CCD camera combined with a folded schlieren imaging system. The images will yield a more complete picture of changes and disturbances in the density, temperature, and pressure when the flame is pulsed. It is expected that the schlieren imaging system will capture clear and distinct vortices in the flame structure. By tracking the vortices in a sequence of flames, a good estimation of the convection velocities can be achieved.

The movies are particularly well suited to enabling the computation of time-correlated data such as vortical structure convection velocities. The convection velocities can be determined by manually tracking points from frame to frame or by using more sophisticated cross-correlation techniques. This type of convection data would be very useful for validating computational combustion models. In addition, we can use the recorded input sine wave and the resulting modulated emission intensity at a given point in the image to investigate the phase relationship between the forcing and response functions. Because of buoyant acceleration, it is possible that the phase relationship is very different for the normal- and micro-gravity flames. In summary, we expect to use the data to compute a number of important quantitative measures of the flame characteristics. These quantitative results will be useful for determining how buoyancy affects the flame, and they will be particularly useful for the validation of combustion models that are being developed at UT and other institutions.

1.4.4 Justification for Follow-up Flight

Last year, our team designed and built a test system that was used on the KC-135 on March 14 and 15, 2002 to analyze the effects of buoyancy on the structure of an acoustically pulsed non-premixed laminar jet flame. This experiment was successful as a Phase I experiment in that the team demonstrated the feasibility of carrying out this research and successfully acquiring flame luminosity data of the pulsed flame. The data obtained illustrated that, in fact, the structure of flames in microgravity are very much different than flames in normal gravity. Please see Figure 5 at the end of this document for a comparison of ground-based data to flight data that was obtained during our flight on March 14th, 2002. The differences in the structure and behavior of the flame can be shown by noting that the for the same control parameters (flow rate and acoustic forcing parameters) the microgravity flame was much taller than the normal gravity flame and, most interestingly, was not nearly as disturbed by the acoustic forcing. Whereas in the normal-gravity case the pulse disturbance carried an obvious disturbance through the flame, in the microgravity case the same pulse barely carried through the flame and was much less noticeable overall.

Last year's project was not only successful because we were able to verify our hypothesis that microgravity flames would differ from normal gravity flames in their size and shape and in the way they are disturbed by acoustic pulses. Just as important, we also set up important partnerships with the Aerospace Engineering Department and National Instruments Inc. who both heavily supported our team through their generous donations and who have pledged their continued support for any future work.

While we were successful in the above ways, the short design to development phase limited our team in the amount to which we could analyze the data due to the small amount of data collected. This year, by implementing a schlieren flow imaging system, improving upon the components of the computer and pulsing systems to have better control over the experiment, and by collecting flow luminosity data for sets of acoustic pulsing parameters that we were unable to look at last year, our aim is to collect enough data to better characterize the differences that are seen between the normal- and microgravity flames and not just see them.

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2 Safety Evaluation

All the hardware and procedures associated with this project will strictly conform to the guidelines and safety criteria found in the current versions of the *JSC Reduced Gravity Program User's Guide*. Most of the materials and components that will be used for this experiment are currently available in the laboratory that was used by the previous RGSFOP team from our department or in the laboratory of our faculty advisor.

2.1 Flight Manifest

The proposed primary flight-crew members are as follows:

Jamin S. Greenbaum: Flight-crew member during the spring 2002 RGSFOP campaign. Previous flight date: March 15th, 2002.
Jeremiah Marichalar: Ground-crew member for the March 2002 RGSFOP campaign however did not accompany the team to Ellington Field.
Matthew G. Marek: No prior RGSFOP experience.
Ravi Prakash: No prior RGSFOP experience.

The proposed primary alternate flight-crew member is:

Jerrod Kogut: No prior RGSFOP experience.

The proposed team journalist is unknown at this time. Currently, our team is awaiting response from KVUE News Austin as to whether a journalist would be available to accompany our team to Houston, and a response is expected shortly. Our team will notify the RGSFOP selection committee and facilitators as soon as a response is received from the news agency.

2.2 Experiment Description / Background

We plan to acoustically pulse a non-premixed laminar methane jet flame in both normal and microgravity conditions in order to isolate the effects of buoyancy on the flame structure.

The flame will be ignited with a piezo-electric igniter during each microgravity phase of the flights when the experiment commences. As a safety measure, to ensure that a non-reacted combustible nature does not buildup, a photodiode will detect the flame. During a preset experiment time (probably 7 seconds), with preset control-parameters for both the speaker and the flame, the computer will automatically start forcing the flame with the enclosed speaker and initiate the flow visualization. A schlieren flow-visualization system will be used to gather first-order density gradient data as described in section 2.2.1 and illustrated in Figure 4. A second camera will be used to obtain flame structure data based on natural flame luminosity data similar to what was collected in the previous RGSFO program (Figure 5 shows data collected by this team during last year's RGSFO program). When time expires, the computer will shut off the solenoid valve, stopping the fuel flow and putting out the flame. The computer will then shut off all components and transfer image, flow rate, and accelerometer data to the hard drive of the computer we will be using. LabVIEW measurement and automation software made by National Instruments Corporation will be used to control our experiment.

2.2.1 Expanding on March 2002 Flight Experience

Flight data taken on March 14th and 15th, 2002 by the previous RGSFOP team from our department successfully demonstrated the feasibility of safely producing a pulsed laminar methane jet flame in microgravity and comparing it to ground-based data. Figure 5 shows a comparison of normal and microgravity flames pulsed at 20 Hz that is from data obtained last year. We are proposing to carry out a Phase II experiment that will expand on successful methods and add new capabilities that will increase the scope of the science data obtained.

i. New Schlieren Imaging system

The proposed experiment will implement a folded schlieren flow imaging system to provide increased detail of flame structure and the evolution of pulse vortices caused by the speaker. This kind of system is ideal for this analysis because it provides a way to visualize gas density gradients. An example schlieren image is shown in Figure 6 [9]. By comparing the density gradients caused by a buoyancy-dominated pulsed flame in normal gravity to pressure gradients caused by a pulsed flame in microgravity that is dominated by the Reynolds number of gas flow through the nozzle, it will be possible to obtain a more complete picture of the test flame's behavior.

In addition to this new flow imaging system, a second camera will be used to collect video of the flame luminosity picture data similar to last year's data. The two cameras will be synchronized so that the schlieren and luminosity images will be simultaneous. It is our hope that between this and the schlieren data, a more complete understanding of the pulsed flame structure will be obtained.

ii. Additional Speaker Pulse Input Parameters

The proposed experiment will use speaker amplitude and frequency settings not tested previously. In particular, it was found during the extensive ground testing done before and after the 2002 flight tests that a phenomenon known as "flame bifurcation" occurs in our test setup in the range of pulse frequencies from 90 to 100 Hz. In this case, the high frequency of the pulsing causes the flame to shorten and split into two small flames. Among other unexplored frequency ranges, this special subset would be analyzed in this experiment.

2.3 Equipment Description

Figure 2 shows the fully assembled proposed experiment test setup with important systems and large components labeled. The outer skin is excluded to display the system components. The flight ready package will be completely enclosed with the exception of a small viewing window. The setup includes the gas flow system that connects to the Pulsed Flame Apparatus (PFA) assembly, and the imaging data system (schlieren and flame luminosity image data).

2.3.1 PFA and Gas Flow system

Figure 3 shows a cutout view of the PFA assembly with each internal component clearly labeled. The methane gas will enter through the inlet and be pulsed by the speaker below. The honeycomb and the wire mesh will streamline the flow to reduce undesired vortices and turbulence before the gas flow reaches the nozzle.

Figure 7 shows the setup of the gas flow system. Displayed in the figure are the gas flow components including the PFA, flow meter, manual shutoff valves, check valve, solenoids, gas tanks, and relief valves. The entire system will be securely mounted to the base of the test chamber. A test chamber door will allow access to the manual shutoff valves in the event of a malfunction in the automatic shutoff system. The check valve ensures no back flow in the system, and the relief valves will prevent pressure build up. Because of the importance of the gas flow system, it will be hydro tested and pressure certified by the appropriate authority.

2.3.2 Schlieren Flow Imaging System

The configuration of the schlieren imaging system that will be used for data acquisition during flight is shown in Figure 4. The schlieren setup shown in the diagram is called a "folded" schlieren setup. One pair of concave mirrors and one pair of flat mirrors will collimate and direct the light rays through the test section where the flame is located and then to the schlieren imaging camera. The entire schlieren system will be confined to a space of 20 by 35 by 35 inches. The height of the camera mount will be adjusted so that the flash lamp light rays do not interfere with the light entering the camera.

The mirrors may be mounted with hinges to allow rotational movement at least along one axis. The hinges will be outfitted with a robust locking system in order to prevent undesired movement in the mirrors if this method is selected. The alternative method would require positioning the mirrors in the exact alignment to allow data collection and mounting them in that position.

The knife-edge that will be positioned at the focal point of the concentrated light will be placed on a movable mount in order to account for necessary adjustments. The knife-edge will be mounted with a fine adjustment knob that will be used to move it into and out of the concentrated light. Because the concentrated light will be reflected off of the flat mirror, the focal length must be extended as shown in the diagram. The knife-edge will be oriented horizontally to obtain first order density gradients in the vertical direction. A vertical knife-edge orientation that yields horizontal gradients will be examined if time allows.

The schlieren imaging video-rate camera will capture real time digital photographs of the density gradients in the pulsed flame. The images will be collected in sequence with accelerometer and other imaging data.

2.4 Structural Design

The test apparatus will be a modified version of the previous one (Figure 2). The structure consists of a main chamber attached to an equipment storage rack that holds the amplifier for the speaker and the schlieren camera computer. Changes will be made in the structure of the rig to both ease transportation of the assembly and to come well within the 300 lb weight limit.

The rig on the previous flight consisted of a steel base, steel top, and a skeletal structure composed mainly of steel. After analyzing the previous rig with free body diagrams, it was determined that the majority of the steel members, including the steel top, could be replaced by aluminum and still be able to support the 9g load. Changing the vertical struts and the horizontal struts at the top of the test chamber from steel to aluminum will reduce the weight of the entire structure and will eliminate the large moment arm caused by the excess weight of these struts. Because the roof of the test chamber will support only the laptop and small, lightweight electronic devices, the aluminum struts will be able to withstand the worst case 9-g loading. In addition to coming well within the weight limit, lowering the weight of the structure will make it easier to transport the structure. Better handles will also be implemented to ease transport.

The side plates (casing) of the structure will remain aluminum while the struts for the base the structure and equipment storage rack area as well as all nuts and bolts will remain steel. A window will be on one side of the test chamber to make visual observations next to a panel door that will provide easy access to make any adjustments while in flight.

The inside of the main chamber of the structure will house the following components:

1. Pulse Flame Apparatus (PFA)
2. Flame Sensor
3. Photodiodes
4. Fuel Tanks
5. Fuel Lines
6. Pressure Regulators
7. Valves
8. Cameras
9. Spherical and flat mirrors
10. Flash lamp

The PFA will be mounted securely to the floor with the base of the PFA bolted into the base of the entire structure. The photodiodes, flame sensor, and mirrors will be mounted to the inner walls by screws and/or bolts. The fuel tanks, fuel lines, pressure regulators, valves, cameras, and flash lamp will all be securely mounted to the base of the structure with clamps and bolts.

In order to increase the safety of the experiment, all of the wires required for the electronic components will be removed from exposure to components inside the main chamber. Additionally, all sharp corners and edges will either be filed down so as not to cause an obstruction, or they will be covered with a non-toxic foam material. As was the case last year, the laptop computer will be secured to the top of the main chamber using Velcro straps.

The ESR will consist of the following components:

1. Data Acquisition System
2. Control Panel
3. Amplifier
4. Camera Controller

All ESR components will be held securely to the ESR using aluminum strips. The entire structure will be bolted to the floor of the KC-135 using the available mounting points. It will be bolted with the NASA supplied bolts at each of the four corners.

2.5 Electrical System

Several electrical components are required for the test apparatus, many of which must be synchronized to give a complete picture of the experiment. The electrical system was designed to provide simple crew interaction, redundant safety measures, and coordination of the components. Table 1 lists the components of the electrical system.

Figure 8 illustrates the electrical system of the experiment, and Table 2 is a load table listing the maximum current draw of each major component of the system. The experiment will be automated to provide more reliable and accurate data in addition to simplifying the safety systems. The automation will be accomplished using a National Instruments 6024E Data Acquisition (DAQ) board as well as an Image Acquisition (IMAQ) board, both of which will be connected to a computer running LabVIEW software. The software will be programmed to control the DAQ and IMAQ boards so that all of the electronically controlled elements can be computer automated.

2.5.1 Computer Configuration and Control

As illustrated in Figure 8, the components that will be controlled automatically by the computer will either be connected to the DAQ board, IMAQ board, or directly connected to the laptop itself. Both the visual camera and the schlieren imaging camera will be connected to the IMAQ board. The flash lamp will be calibrated to match the frequency of the schlieren imaging system. The photodiode will be connected to the DAQ as a digital input, and the relays, which include a fuel relay, purge relay, and ignition relay, will all be connected to the DAQ board as digital outputs. Sensors such as the accelerometer, methane sensor, flame sensor, flow meter, and amplifier will be directly connected to the laptop itself.

Various circuits will need to be implemented so that the computer can control the valves and regulators. The logic gates will require a 5-volt power supply from the DAQ, and the valves and regulator will require a 24-volt power supply. Two DC power supplies will convert the 115V AC signal into 5-volt and 24-volt sources. The solenoid valve will be controlled by a MOSFET that will be turned on when the digital I/O pin that is connected to the MOSFET is given a positive voltage.

2.5.2 Ignition / Data Recording Procedure

When the experiment is initiated from LabVIEW, the digital camera will begin to acquire data and output it to the computer. Two solenoids will be used to control the combination of the purge and fuel flow to the experiment. The solenoid will supply the valves according to necessary pressure and flow requirements, and the fuel flow will be digitally recorded by a flow meter. The ignition solenoid will control an arm that swings a piezoelectric lighter to ignite the flame. A photodiode installed next to the flame will allow LabVIEW to sense the presence of the flame, and then signal to the ignition solenoid to move the lighter away from the flame which will ensure that the lighter does not interfere with the behavior of the flame.

While the experiment is running, the computer will be compiling the data from the accelerometer that is connected to the DAQ Board. The experiment will run for about 5 seconds, and upon completion, the main valve will be shut off, and the program will be reset for the next experiment.

2.5.3 Safety Measures

An on/off "kill" switch will be installed on the exterior of the structure to allow for manual control of the experiment in case of a need for a quick shutdown of the experiment. If the kill switch is activated, all electrical components, with the exception of the laptop, accelerometer, and flame sensor, will shut down. The fuel and purge solenoids will fail such that the fuel supply is closed and an immediate purge commences. To preserve nitrogen, a crewmember can manually shut the purge cylinder by turning the appropriate shutoff valve. The purge cylinder must be re-opened and checked before testing can continue.

2.6 Pressure / Vacuum System

Please see Figure 9 for a schematic of the proposed gas flow system and Table 3 for a detailed list of all design specifications of the gas system components. The system will include a methane storage cylinder and a nitrogen storage cylinder attached to a series of pressure-regulation components described below. All components of the pressure system will be connected using ¼ inch stainless steel tubing with Swagelok stainless steel fittings and will be rated for the required pressure loads by a certified pressure system technician. The pressure system will be hydro-tested to 1.5 times the maximum working pressure.

The exhaust gases created by burning the methane fuel will be vented out of the KC-135 using the onboard multi-user ventilation system. We will have a male AN 12 fitting on the end of our vent system to connect to the over board vent system. The position of the vent line attached to the test chamber is illustrated in Figure 2 as the hose protruding from the chamber roughly above the flame combustion area.

2.6.1 Pressure System Components

The methane gas storage cylinder (Swagelok, model 304L-HDF4-1000) will have a volume of 1 liter and a pressure rating of 1800psi but will only need to be charged to 69.1 psi to hold the required 4.7 liters of fuel. The nitrogen storage cylinder (Swagelok, model 316L-HDF4-300) will have a volume of 0.3 liters and a pressure rating of 1800 psi but will be charged to 100 psi to hold much more than enough purge gas for each test run. Pressure relief valves set at 150 psi will be placed just downstream of the gas storage cylinders so that the cylinders cannot be over pressurized while being charged on the ground prior to flight. Manual shut-off valves will be placed right after the relief valves followed by pressure regulators that will reduce the pressure to 40 psi. For the methane gas line, the next component will be a micro-metering control valve that will be used to set the desired methane flow rate. The next methane-line component will be a solenoid valve that will be computer-actuated through LabVIEW, followed by a check valve to ensure that no nitrogen or air will get into the methane line or cylinder. For the nitrogen line, the component after the pressure regulator will be a solenoid valve that will be computer-controlled through LabVIEW. At this point the two gas lines will merge into a tee connector and feed through a flow meter. The volumetric flow meter (Omega Engineering, Inc.) will provide an output that will be sampled by the LabVIEW data acquisition system for later calculation of exact Reynolds number fuel flow values. An emergency relief valve will be installed downstream of all components and will be set to 4 psi. The gas line will then feed into the Pulsed Flame Apparatus (PFA), which is not considered a pressurized vessel because it is open to the ambient air around it.

2.6.2 Fuel and Purge Gases

Through ground testing we have determined that we will need 4.7 liters of methane fuel to perform 25 microgravity experiment test runs and 4 level-flight test equipment calibration runs. All calibration and flight runs will be 7 seconds in duration. Please see the next section, 2.6.3 Lean Flammability of Methane Fuel, for a discussion on the unlikely case of full methane release into the test chamber.

We emphasize that the flame will operate in non-premixed mode, which is inherently safe, because pure methane fuel is not combustible. Therefore, once the flame is operating, there is no danger of the flame "flashing back" and igniting the fuel in the supply stream. In addition, the nitrogen purge will be used before ignition of the methane gas to ensure that any air that may have diffused into the system lines during transport or in between test runs is removed.

As an added safety measure, a methane gas sensor will be attached inside the experiment so that the methane supply will be cutoff in the unlikely event of a gas release that is not easily detectable by the flight crew.

2.6.3 Lean Flammability Limit of Methane Fuel

It is important to note that if all methane fuel is released into the test chamber while the igniter is turned on, there is no chance of an explosion. This is because even though the methane will combine with the ambient air in the test chamber and form a fuel-air mixture, combustion cannot occur because the mixture will contain less than the critical amount of fuel that is known as the lean flammability limit (LFL) of a combustible gas [10].

Given that the lean flammability limit of methane fuel is 5%, that there will be no more than 4.7 liters of methane stored, and that the volume of free space in the chamber can be conservatively estimated to be 250 liters (total enclosure volume less the approximate volume of all inside components), it is found that for full release of the fuel, the ratio of methane fuel to total free volume would be much less than the above limit:

$$\frac{V(CH_4)}{V(free\_space)} \cong \frac{4.7 Liters}{250 Liters} = 1.9\% << 5.0\%$$

Therefore, all built-in safety measures (methane sensor, kill switch, purge gas, and the fact that the flame will be operating in non-premixed mode as described above) are redundant in terms of safety because the system will not exceed the lean flammability limit. As a result, these measures are most useful as a monitoring tool for gas leaks or flame-extinction and will be used to save gas in the event of fuel release.

2.7 Laser System

There will be no laser system for this experiment.

2.8 Crew Assistance Requirements

This experiment will not require any in-flight assistance from the KC-135A staff.

2.9 Institutional Review Board

Our experiment will not require the approval of an IRB.

2.10 Hazard Analysis

Possible Hazard	Type of Failure	Consequences	Solution
Gas Pipe System Leak	Pressurized pipes leak methane gas into test chamber	Methane gas build up in the test chamber	Exhaust system; gas detection system; automatic and manual shutoff valves
Solenoid Valve Failure	Electronic solenoid valve fails to shutoff methane gas	Methane gas build up in the test chamber	Exhaust system; gas detection system; manual shutoff valves; pressure transducer
Photo Diode Failure	Photo diode fails to recognize when/if flame extinguishes	Methane gas build up in the test chamber	Exhaust system; gas detection system; automatic and manual shutoff valves; redundant photo diode
Sensor Apparatus Failure	Electronic sensors fail to read pressure levels and photo diode feedback	Methane gas build up in the test chamber	View window; exhaust system; automatic and manual shutoff valves; redundant systems
Methane Gas Detection System Failure	Methane sensor fails to detect gas in test chamber	Methane gas build up in the test chamber	Exhaust system; automatic and manual shutoff valves
Uncontrollable Flame Height	Flame becomes too large for test chamber	Uncontrolled fire	View window; automatic and manual shutoff valves; redundant systems; fire extinguisher
Laptop Computer or LabVIEW Code Failure	Computer fails or crashes during flight testing	Methane gas build up in the test chamber; uncontrollable flame	Exhaust system; manual shutoff valves; fire extinguisher
Flame Igniter Failure	Flame fails to ignite once gas begins to flow	Methane gas build up in the test chamber	Exhaust system; gas detection system; automatic and manual shutoff valves
Fire	Non-metallic material catches fire	Possibly toxic smoke could fill test chamber and/or plane	Automatic and manual gas shutoff valves; fire extinguisher

2.11 Tool Requirements

The tools required to assemble and maintain the proposed experiment include the following:

1. Socket wrench and set of sockets
2. Pliers
3. Screwdrivers
4. Wrenches
5. Soldering iron with solder
6. Wire cutters
7. Wire stripper
8. Voltage/current meter

2.12 Ground Support Requirements

1. Ground Power
   Required to ground test the experiment prior to flight. These requirements will be the same as those described in Section 2.5 and listed in Table 2.

2. Compressed Gas Storage
   Delivery of compressed methane and nitrogen gas will be arranged to coincide with our arrival at Ellington Field. During the week, storage of these bottles will be required on site. Our team will arrange for the pickup of the bottles at the conclusion of the program.

2.13 Hazardous Materials

The proposed experiment requires the use of non-premixed methane fuel. Please see the Material Safety Data Sheet for Methane that is attached as Figure 10 at the end of this document.

4.7 liters of methane will be carried onto the KC-135 and will be stored in a 1 liter Swagelok cylinder at a pressure of only 69.7 pounds per square inch. This cylinder will be firmly and safely attached inside of the test chamber isolated from the aircraft cabin using aluminum straps bolted to an internal steel strut.

There is little danger posed by the methane gas because there will never be enough in the test chamber to reach the lean flammability limit for methane contained in the unoccupied volume of the chamber. There is therefore no risk of explosion in the proposed experiment. Please refer to Section 2.6.3 for further discussion of the lean flammability limit.

Within the gas flow system there will be a nitrogen purging system that will prevent combustion from occurring in the stainless steel tubing and pressure components internal to the test setup by expelling remaining methane from the system. In addition, there will be a methane sensor that will detect excess flammable gas not otherwise detectable by the flight crew. This measure is redundant but provides an extra level of safety to ensure that there is no danger imposed by hazardous materials.

After each run of the experiment, waste combustion products and any methane released into the test chamber will be removed by the KC-135 over board ventilation system.

2.14 Procedures

2.14.1 Ground Operations:

1. Upon arrival at Ellington Field, unload the apparatus and assemble any parts that had to be removed for shipping purposes.
2. Charge the gas storage cylinders from the storage bottles that will be shipped to Ellington Field.
3. Test fuel system and electrical system.
4. Perform a series of equipment calibration tests:
    a. Test frequency and amplitude settings
    b. Verify that the data acquisition system, laptop, cameras, and camera controllers function properly and yield expected ground test results.
5. Close all valves to the tanks
6. Verify that all safety checks are in working order and are ready for flight.

2.14.2 Pre-Flight:

1. Load the test apparatus onto the KC-135A
2. Bolt apparatus to the floor of the aircraft
3. Check fuel system

2.14.3 In-Flight:

- Level Flight:
    1. Start up electronic components.
    2. Initialize LabVIEW automation software program.
    3. Set test acoustic pulsing parameters.
    4. Verify that the computer-controlled solenoids are in the default state where the methane solenoid is in the "closed" state and nitrogen purge solenoid is in the "open" state.
    5. In LabVIEW, change the nitrogen solenoid to the "closed" state and open the manual shut-off valves to both fuel lines.
    6. Run an equipment calibration test of entire system initialized by LabVIEW and including all data gathering.
- Microgravity Flight:
    1. For each parabola: First set desired acoustic pulsing parameters.
    2. Execute LabVIEW program that automatically does the following:

    a. Purges the system with nitrogen gas to remove any methane in the pressure tubing and components.
    b. Igniter solenoid rotates piezoelectric igniter over nozzle.
    c. Gas flow is switched to methane.
    d. Methane is ignited and piezoelectric igniter rotates out of the way.
    e. Acoustic pulsing begins.
    f. Schlieren and luminosity cameras begin to acquire data.
    g. Time expires, methane solenoid closes extinguishing flame, cameras stop acquiring data, and pulsing stops.
    h. Image, accelerometer, and flow rate transferred to computer hard drive.
- High-gravity Flight:
  No operation is required during this phase.

2.14.4 Post Flight:

- Conclusion of microgravity parabolas:
  1. Purge system to expel any remaining methane fuel.
  2. Close manual shut-off valves to methane and nitrogen cylinders.
  3. Shutdown LabVIEW program.
  4. Shutdown all electronic components and secure system for landing.
- On the ground:
  1. Transfer all experiment data to an external hard drive for backup and storage.
  2. Charge the methane and nitrogen tanks for the following day’s flight.

3 Outreach Plan

Following a very successful outreach program at the conclusion of the 2002 Flight Campaign, we are excited about continuing such activities this year. Our goals for this year remain diverse in that we will be targeting many audiences for our outreach activities.

3.1 Women in Engineering Program

We will continue participating in programs sponsored by the University of Texas at Austin College of Engineering Women in Engineering program. Our relationship with this office, which has lasted since this past summer, has allowed us to regularly speak with many groups of prospective engineering students both young and old. Our focus has been on introducing not only the excitement of NASA and the RGSFO Program, but to stress that studying engineering and refining problem solving skills will lead to a fun and exciting future.

For information about WEP activities that we have already committed to participate in that will take place in the near future, please see the letter from Danielle Seabold, the WEP Programs Coordinator. The letter in included with the hardcopy of this proposal.

3.2 Activities for general audiences

Over the past summer, in addition to the abovementioned activities with the Women in Engineering Program, in particular, our team also participated in several programs for more general audiences. We will continue pursuing these opportunities because we have found they provide a means of reaching large and diverse audiences. For example, one of our favorite programs is the Explore UT event that attracts an audience from all over our county and includes presentations lasting an entire day.

For more information on such activities that we have already planned on participating in, please see the letter from Kendra Cox, the Special Projects Coordinator for the Department of Aerospace Engineering and Engineering Mechanics, which is attached to the hardcopy of this document.

3.3 Outreach through the Austin Unified School District

This year, we are planning on taking our experiment to local area schools to demonstrate our project and show footage of our flights from last year. We plan to present the test apparatus and the importance of our project to students in the junior high and high school level in order to encourage development of math and science skills and promote the pursuit of careers in science and engineering. A tentative schedule for visiting local area schools, museums, and science fairs has been outlined and will be carried out if the team is selected for this year's flight.

3.4 Publications

In addition to presentations, the team plans to follow up on the articles published after last year's flight. Articles documenting the experiment and the NASA RGSFO Program were printed in the *Vector* newsletter and *The Longhorn Liftoff* newsletter in the spring and fall of 2002, respectively. The *Vector* newsletter goes out to all engineering students, while *The Longhorn Liftoff* newsletter is sent to alumni and friends of the aerospace engineering department. The team plans to follow up on these publications, as well as look for other outlets to publish our results and documentation.

3.5 Team Webpage

A team webpage has been designed and setup in accordance with last year's outreach section. While it is still under development, it does contain links to last year's proposal, the Test Equipment Data Package, an outreach section, and a final document that contains some of our results. The web address is shown below:

http://www.ae.utexas.edu/design/kc135/

We plan to update this webpage with electronic copies of all of our documentation and include our future development plans for the pulsed flame experiment.

4 Administrative Requirements

4.1 Institution Letter of Endorsement

Please see the accompanying letter of endorsement written by Dr. David Dolling, chairman of the Department of Aerospace Engineering and Engineering Mechanics. The letter is attached to the hard copies of this proposal that was submitted to the NASA RGSFO program office.

4.2 Statement of Supervising Faculty

Please see the accompanying statement written by Dr. Noel Clemens. The letter is attached to the hard copies of this proposal that was submitted to the NASA RGSFO program office.

4.3 Funding and Budget Statement

All anticipated expenses are listed in the following funding and budget table.

For this table, please note that expenses marked with a “*” will be acquired through the generous donation of National Instruments Inc. Expenses marked with a “#” will be generously donated by or borrowed from the University of Texas at Austin Department of Aerospace Engineering and Engineering Mechanics and from our faculty advisor, Dr. Noel Clemens.

	Cost per unit	Total Cost
Gas Flow Equipment		
Methane Sample Cylinder (test chamber)	\$230	\$230
Methane Lecture Bottle (ground testing)	\$30#	\$30#
Nitrogen Sample Cylinder (test chamber)	\$104#	\$104#
Nitrogen Lecture Bottle (ground testing)	\$30#	\$30#
Shut-off Valve (×4)	\$20#	\$80#
Relief Valve (×1)	\$30#	\$30#
Pressure Regulator (×2)	\$150#	\$300#
Solenoid Valve (×3)	\$60#	\$180#
Pressure Transducer (×2)	\$100#	\$200#
Metering Valve (×2)	\$50#	\$100#
Tubing Connectors (×1)	\$150#	\$150#
Electrical System Equipment		
Laptop	\$2,000#	\$2,000#
Data Acquisition Card	\$650*	\$650*
Image Acquisition Card	\$600	\$600
SCSI Card	\$150*	\$150*
Luminosity Camera / Camera Controls	Borrowed#	Borrowed#
Schlieren Camera	Borrowed#	Borrowed#
Flow meter	Borrowed#	Borrowed#
Amplifier	\$200#	\$200#
Function Generator	\$200#	\$200#
Flame Sensor	\$150#	\$150#
Enclosed Mid-Range Speaker	\$100#	\$100#
Wiring	\$50#	\$50#
Flash-lamp	\$1000#	\$1000#
Photo Diode (×2)	\$100#	\$200#
Schileren Mirrors	\$500#	\$500#
Structural Equipment		
Aluminum Sheets	\$100#	\$100#
Aluminum Frame	\$200	\$200

Structural Frame Struts	$100[#]	$100[#]
Miscellaneous Equipment / Parts		
Tools	$200[#]	$200[#]
Transportation / Housing	$2,000[#]	$2,000[#]
Total Cost of Program	-	*$9,834*
Donations	-	*$8,804*
Anticipated Total Cost	-	***$1,030.00***

4.3.1 Current Financial State

As can be seen from the above table, much of the necessary components for this project will either be donated by or borrowed from National Instruments Inc. or the University of Texas at Austin Department of Aerospace Engineering and Engineering Mechanics. The remaining needed funds will be on the order of $1,000.00.

4.3.2 Funding search

The Aerospace Engineering Department has pledged their full support to see the successful completion of our project if we are selected for this year's RGSFO program, however, our team is actively pursuing funding from other sources. In early December, we will be applying for a University of Texas at Austin Department of Mathematics Vertivally Integrated Grant for Research and Education (VIGRE) that would cover all remaining expenses. If not selected to receive this award, our team will search for funding from the Texas Space Grant Consortium and other possible sources. Last year, the Texas Space Grant Consortium matched fifty percent of what the Aerospace Engineering department donated to the team

4.4 Institutional Review Board

The proposed experiment will not require an IRB Review.

4.5 NASA Human Research Subject Consent Form

The proposed experiment will not require any human research subjects.

4.6 Institutional Animal Care and Use Committee

The proposed experiment will not require any animal research subjects.

4.7 Parental Consent Forms

No member of the team requires a parental consent form.

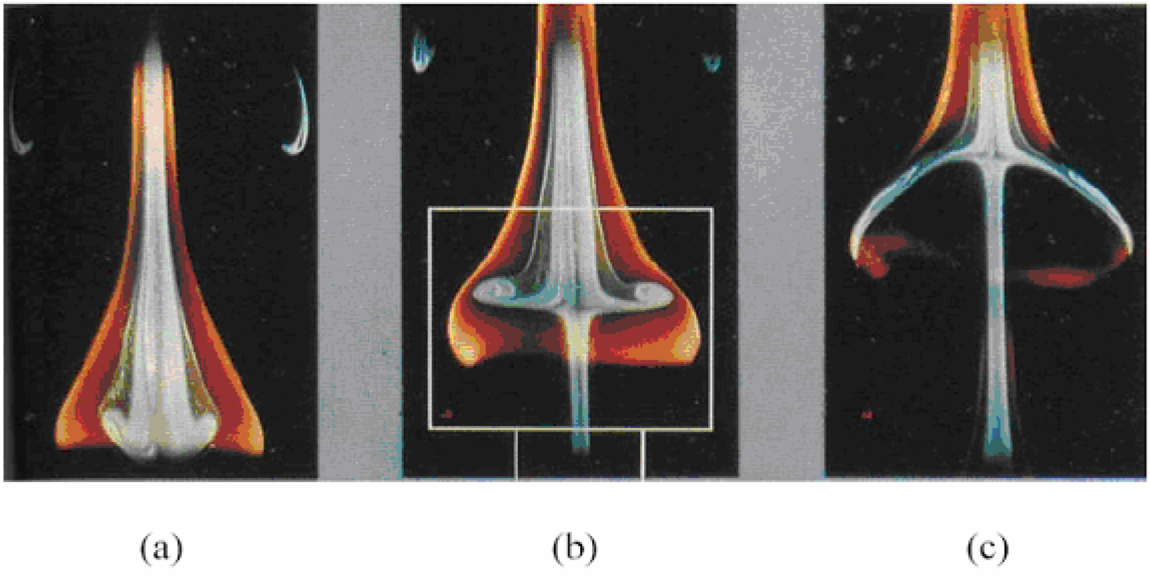


Figure 1: Sequence of an Acoustically Forced Laminar Flame in Normal Gravity [4]

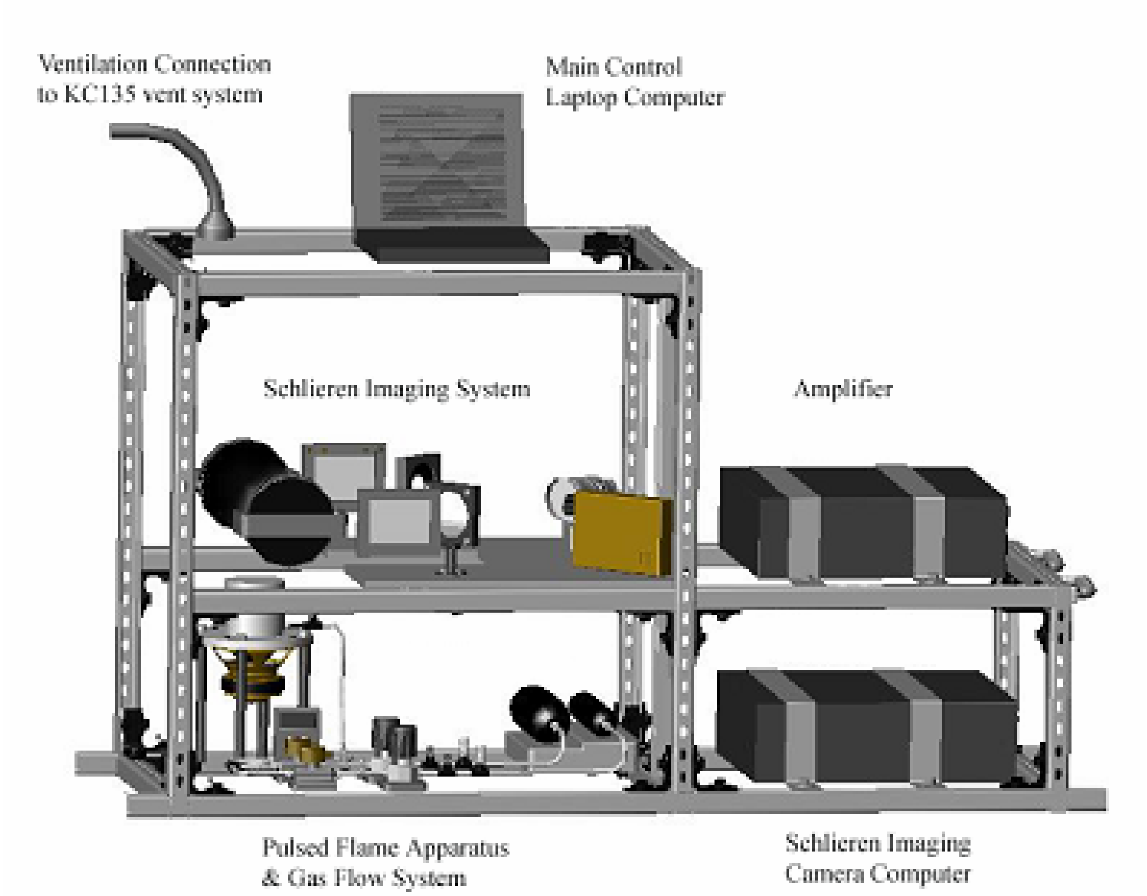


Figure 2: General View of Rig Setup

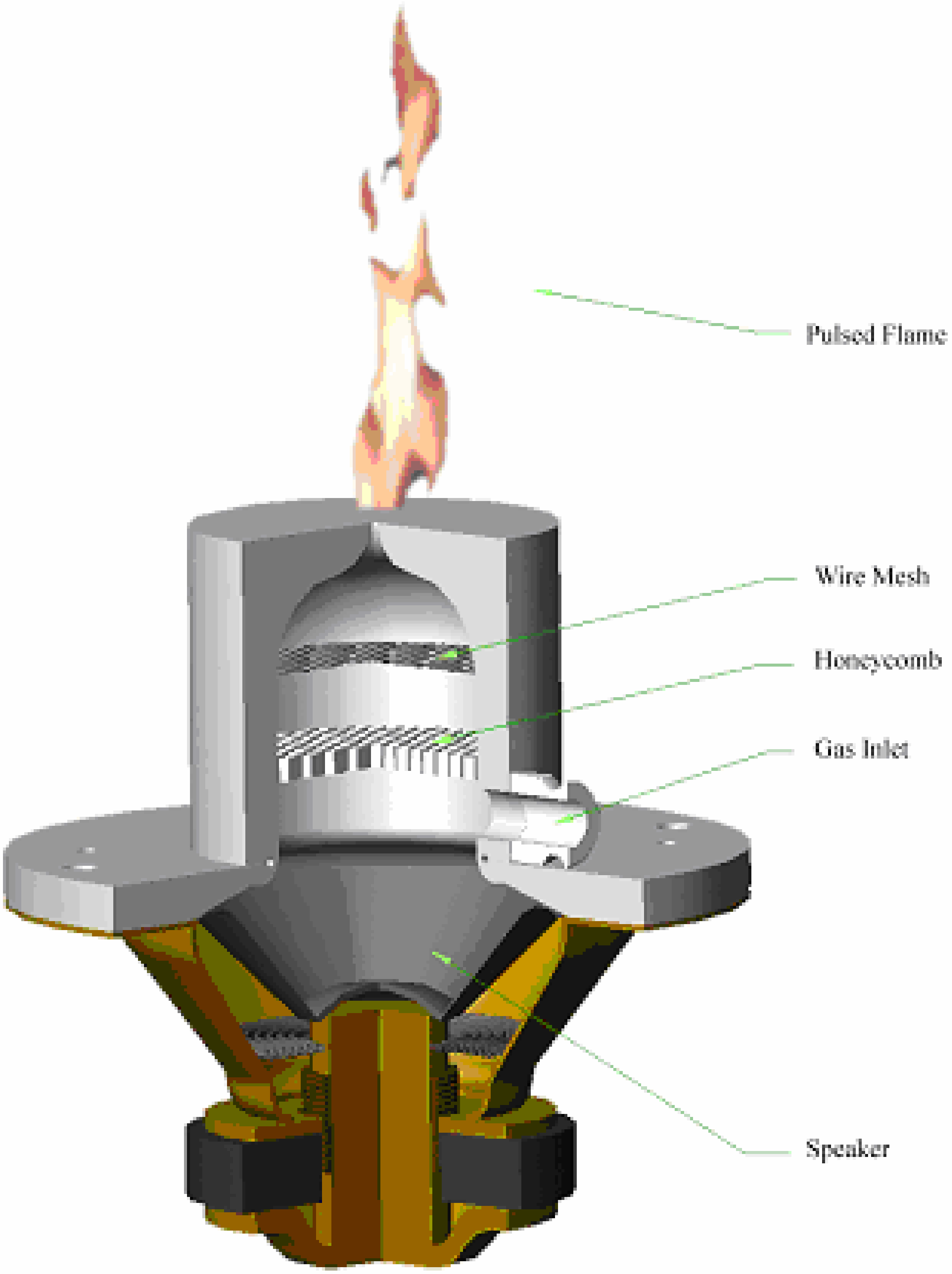
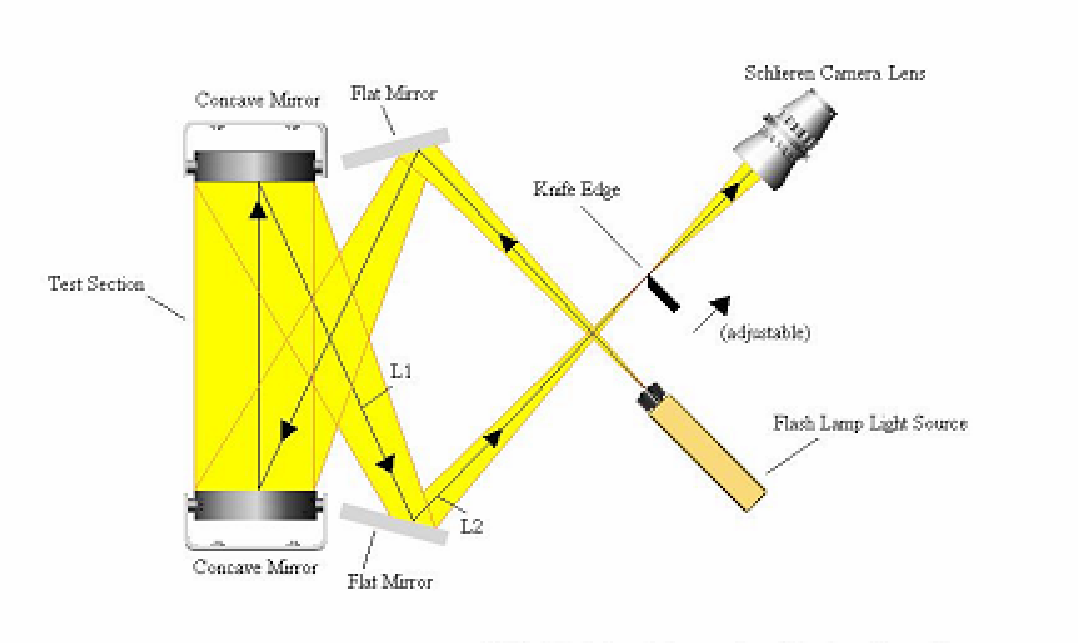
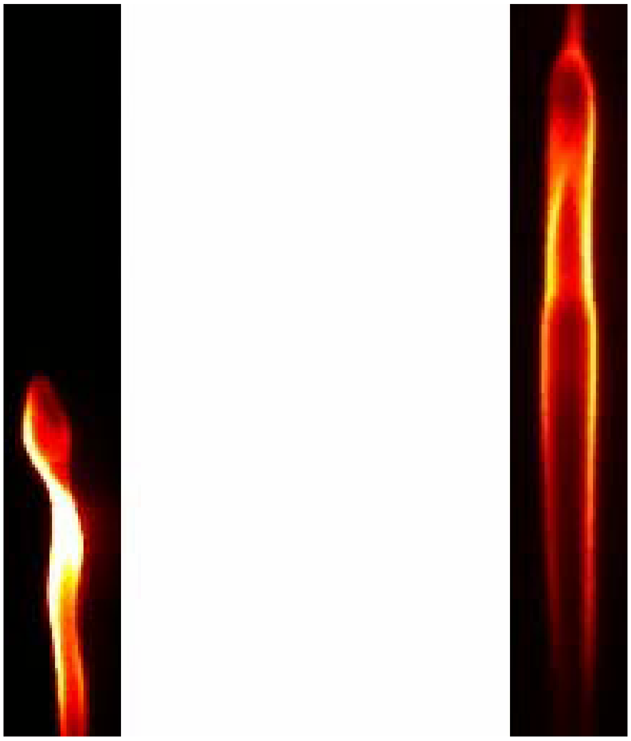


Figure 3: Cutout View of Pulsed Flame Apparatus



* Note: Orientation of mirrors not exact (lengths not to scale).

Figure 4: Schematic of the proposed Schlieren Imaging System



a) b)

Figure 5: Ground and Flight Data from Spring 2002 Campaign

a) Normal Gravity Flame pulsed at 20Hz
b) Microgravity Flame pulsed at 20 Hz

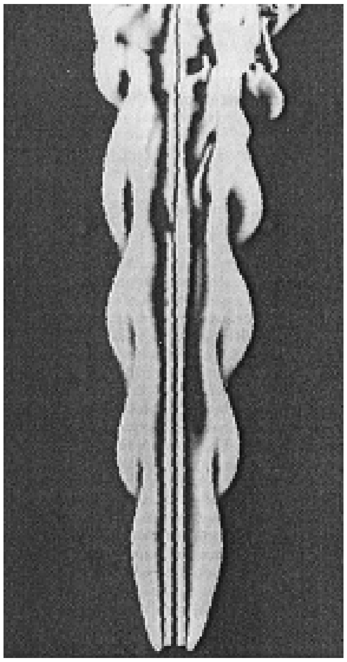


Figure 6: Schlieren Image of a Laminar Jet Flame in Normal Gravity [9]

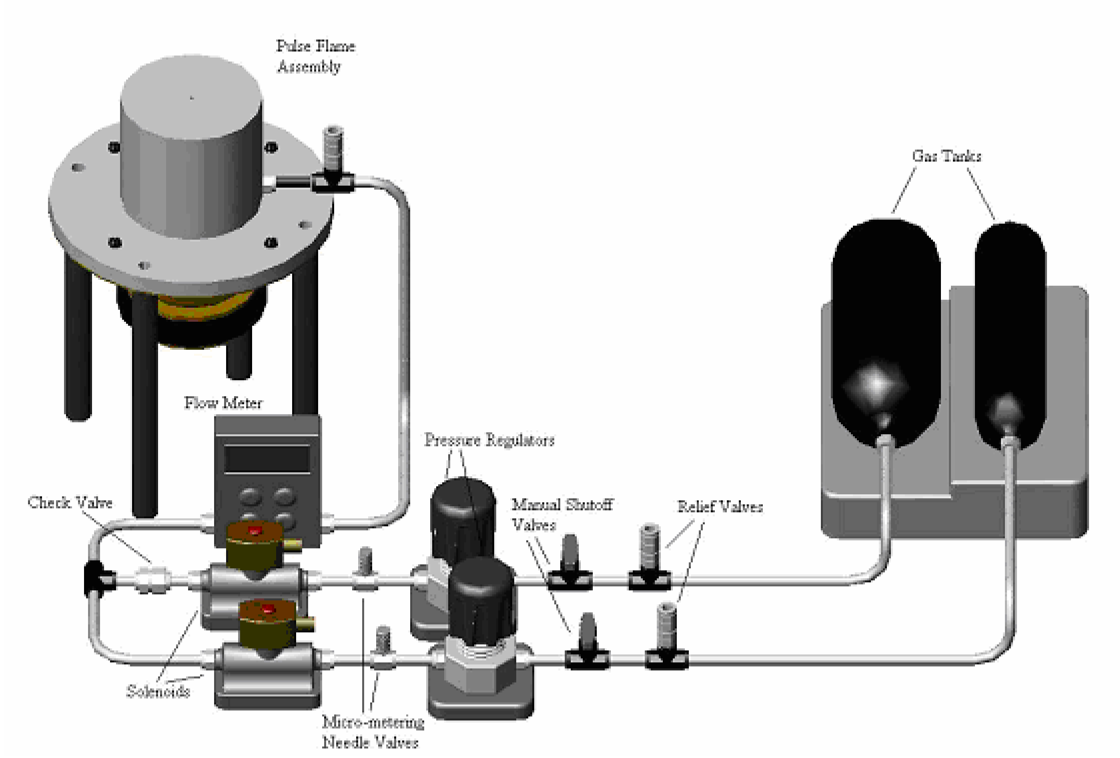


Figure 7: Detailed View of the Pressure System

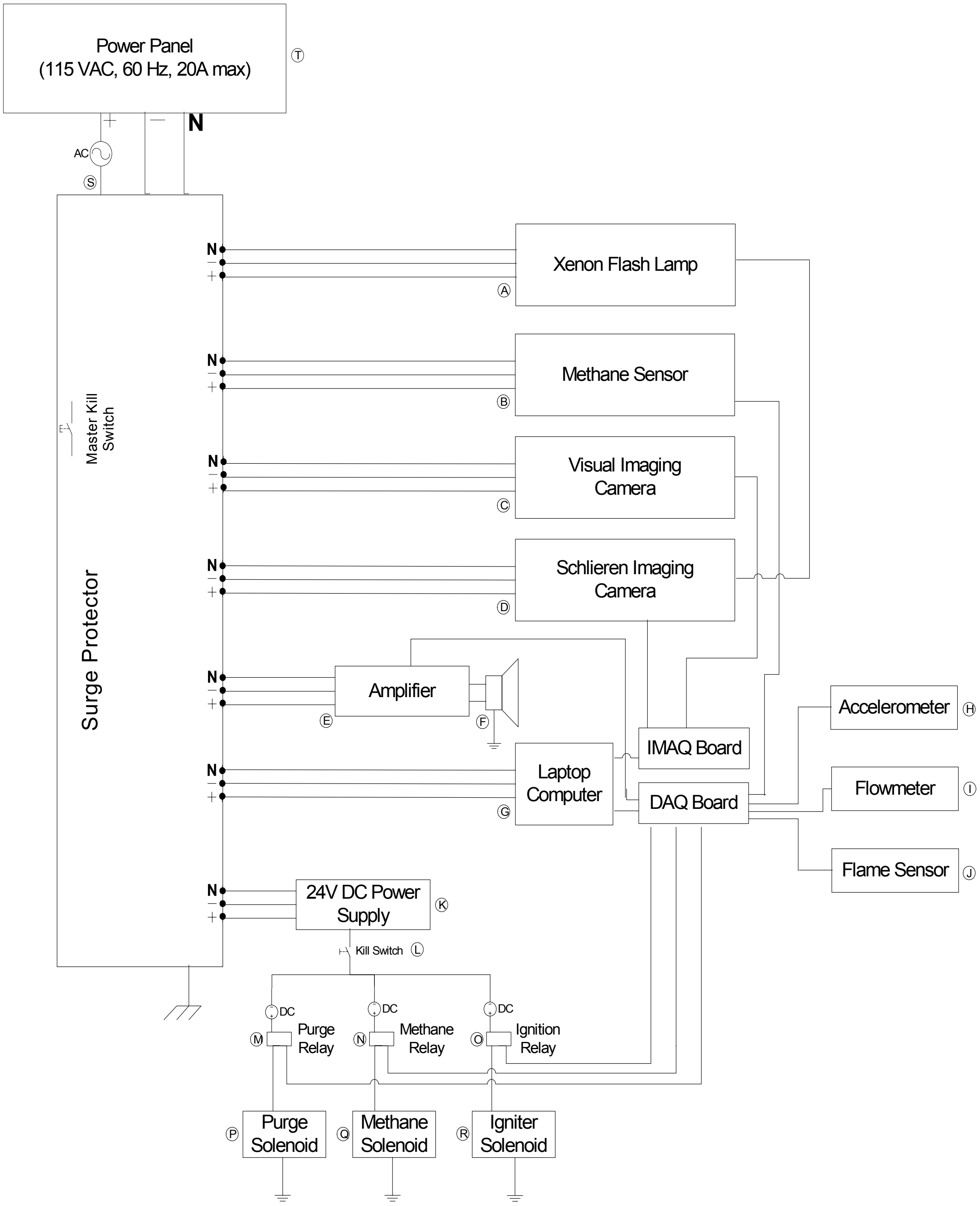


Figure 8: Schematic of Electrical System

Table 1: Electrical System Components

Label	Component	Description
A	Flashlamp	EGOG Xenon lamp
B	Methane Sensor	Will be determined
C	Visual Camera/Controller	Kodak Ektapro 4540MX high speed imager and controller
D	Schlieren Camera	Pulnix TM 540
E	Amplifier	RCA STA-3850 stereo receiver
F	Speaker	Radio Shack 40-1033 6.5-inch polypropylene woofer
G	Laptop*	Notebook computer with National Instruments PCMCIA data acquisition board, image acquisition board, and LabVIEW software
H	Accelerometer	Kistler 8304B2 accelerometer and 5210 power supply with dedicated 9V battery
I	Flow meter	FVL-1600 Volumetric Flow Meter, Omega Engineering Inc.
J	Flame Sensor	Light sensor with 5V analog output and internal power supply
K	24V DC Power Supply	115V AC input, 24V DC output power transformer
M	Purge Relay	24V DC switch relay with 0.5A carrying current
N	Fuel Relay	24V DC switch relay with 0.5A carrying current
O	Ignition Relay	24V DC switch relay with 0.5A carrying current
P	Purge Solenoid	ASCO Red Hat 8262G260 24V DC solenoid valve (normally open)
Q	Fuel Solenoid	ASCO Red Hat 8262G19 24V DC solenoid valve (normally closed)
R	Igniter Solenoid	To be determined
S	Surge Protector	Standard seven-outlet, 125V AC surge protector (15 A maximum current)
T	Power Panel	115V AC, 60 Hz receptacle on KC-135 Power Distribution Panel

* The laptop computer has its own manufacturer-supplied battery, but external power will be used to eliminate time constraints on the use of the laptop.

Table 2: Load Table

Load Source	**Expected Current Draw (A)**
Laptop Computer	2
Visual Camera/Controller	4.35
Audio Amplifier	1
24 V Power Supply	1
Methane Sensor	0.25
Schlieren Camera	Unknown, TBD in TEDP
Flash Lamp	Unknown, TBD in TEDP
Total Load	**12.1**

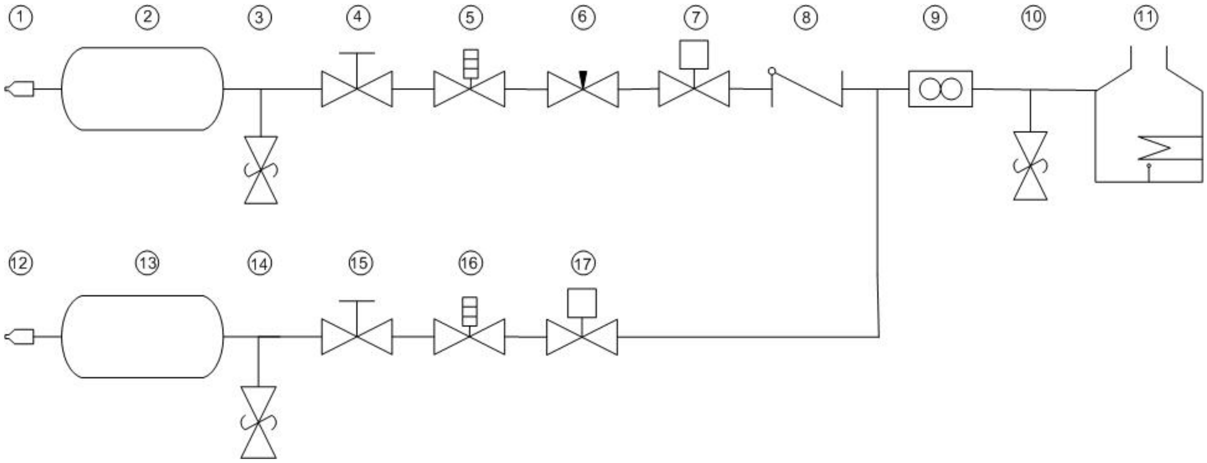


Figure 9: Schematic of Pressure System

Table 3: Pressure System Element Description

Schematic Reference #	Component	Description
1	Quick-Connect Stem	Interface to methane storage tank on the ground
2	Methane Sample Cylinder	Storage of Methane. 1 Liter bottle at 69.7 psi
3	Relief Valve	Set at 125 psi
4	Manual Shutoff Valve	
5	Pressure Regulator	Set at 40 psi
6	Micro-metering Needle Valve	Used in tandem with flow meter to set desired flow rate
7	Computer Controlled Solenoid Valve	Controlled through LabVIEW software
8	Check Valve	Max allowable working pressure is 6000 psi
9	Flow meter	Measure fuel flow rate
10	Relief Valve	Set at 4 psi
11	Pulsed Flame Apparatus	Assembly containing speaker and flame exit nozzle
12	Quick-Connect Stem	Interface to Nitrogen storage tank on the ground
13	Nitrogen Sample Cylinder	Storage of Nitrogen. .3 Liter bottle at 140 psi
14	Relief Valve	Set at 125 psi
15	Manual Shutoff Valve	
16	Pressure Regulator	Set at 40 psi
17	Computer Controlled Solenoid Valve	Controlled through LabVIEW software

Table 4: Pressure System Design Specifications

Schematic Reference #	Component Description	MAWP (psi)	Built By	Model #
1	Quick-Connect Stem	250	Swagelock	SS-QC4D1-400
2	Methane Sample Cylinder	1800	Swagelock	SS-304L-HDF4-1000
3	Relief Valve	3000	Swagelock	SS-4CPA4-150
4	Manual Shutoff Valve	2500	Swagelock	SS-42S4
5	Pressure Regulator	3000	Victor	HLP 500-125
6	Micro-metering Needle Valve	3000	Hoke	2315-F4Y
7	Computer Controlled Solenoid Valve	500	ASCO-Red Hat (normally closed)	8262-G19/DC
8	Check Valve	6000	Hoke	SS-CHS4-1
9	Flow meter		Omega	FVL-1600
10	Relief Valve	3000	Swagelock	SS-4CPA4-150
11	Pulsed Flame Apparatus	N/A	House Built	N/A
12	Quick-Connect Stem	250	Swagelock	SS-QC4-D1-400
13	Nitrogen Sample Cylinder	1800	Swagelock	SS-316L-HDF4-300
14	Relief Valve	3000	Swagelock	SS-4CPA4-150
15	Manual Shutoff Valve	2500	Swagelock	SS-42S4
16	Pressure Regulator	3000	Victor	HLP 500-125
17	Computer Controlled Solenoid Valve	500	ASCO-Red Hat (normally closed)	8262-G260/DC