AN EXPERIMENTAL STUDY OF TRANSIENT FLOWS IN
PULSE COMBUSTORS

by

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This thesis was prepared under the direction of the candidate’s thesis committee chairman, Dr. L.L. Narayanaswami, Department of Aerospace Engineering, and has been approved by the members of his thesis committee. It was submitted to the Office of Graduate Studies and was accepted in partial fulfillment of the requirements for the degree of Master of Science in Aerospace Engineering.

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ABSTRACT

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The purpose of this investigation was to experimentally characterize a pulse combustor with respect to ambient conditions, pressure amplitudes, wall temperature, combustor geometry and type of centerbody used. The wall temperatures were recorded and the pressure variation was obtained using a sampling rate of 10,000 readings per second. These parameters were recorded for two different tailpipe lengths and centerbodies, and for different ambient conditions. Power spectrums were then obtained from the pressure variations. These spectrums displayed the peak amplitudes and the frequencies at which they occurred. The experiment showed distinct repeatability. It was concluded that combustor displayed the steady, pulsing and flame-out modes. The pulse combustor behaved just like any other combustion engine in terms of its efficiency with respect to ambient temperature and pressure. It was deduced that the inlet pressures dictated the achievement of the pulsing mode. The effect of increasing the length of the tailpipe proved advantageous to a certain limit. A change in the centerbody proved advantageous in some cases and had no effect in others.
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CHAPTER 1

INTRODUCTION

This chapter states the aim of the investigation and emphasizes the significance of the research. It gives an overview as to the type of research done in the past and states the purpose of this thesis. A brief description of the problem is given and an historical background is introduced.

1.1 General Overview

The aim of this investigation is to investigate the operation of a pulse combustor. Pulse combustion has numerous applications in fossil fuel energy and aerodynamically valved propulsion, motivating an evaluation of its operational characteristics and efficiency.

In fossil fuel energy applications the acoustic waves generated from the unsteady gas motion is used in processes like coal combustion, sulfur sorbent utilization, spray drying, and atomization, by enhancing the transport of mass and thermal energy.¹

The benefits of aerodynamically valved pulse combustors can be seen in overall turbine cycle efficiency where a stagnation pressure gain, rather than a stagnation pressure loss is achieved. In propulsion applications, it is known that
ramjets are incapable of producing static thrust. In contrast pulse combustors are capable of producing static thrust. Hence, when used in conjunction with a ramjet, a propulsion device is obtained that can start at zero velocity.

The above principle was used in the “Aurora” project where pulse detonation wave engines and pulse combustors, were used. These engines were fueled by liquid methane, a fossil fuel which also had the characteristic of being an excellent coolant due to its high specific heat.

The pulse combustor consists of a combustion chamber and a tail pipe. It has no mechanical or aerodynamic valving. The pulse combustor is illustrated in figure 1.1. Air and fuel are steadily injected at high pressures and ‘well-stirred’ at the front end of the combustor. The stirring is achieved by placing the air and fuel inlets directly opposite to each other. The mixture is then ignited with the aid of an ignition system mounted on the combustor. The ignition system is a spark plug, the location of which is shown in figure 1.1.

Under the right conditions, the device exhibits oscillating behavior, with the pressure varying from below - ambient to above - ambient values. Combustion results in a pressure - rise, and the “pressure - phase” of the cycle begins. The combustion products rush out through the tailpipe and the combustor pressure and temperature drop. Even after the pressure reaches the ambient value in the combustor, gases continue to leave due to their inertia and drop the combustor pressure to below - ambient value (“suction phase”). This results in flow - reversal in the tailpipe. In the meantime, the steadily
Figure 1.1. Basic Combustor Setup.
injected fuel and air accumulate in the combustor. This mixture is compressed and heated by the reversed tailpipe flow, initiating the next cycle.

For the pulse combustor to operate as above described, the Raleigh criterion must be satisfied. The Raleigh criterion states that the fluctuations in heat release should be ideally timed such that maximum heat release is achieved at maximum pressure.

1.2 Theoretical Model

A theoretical model of the pulse combustor was developed in work performed for the U.S. Department of Energy at the Morgantown Energy Technology Center. Simulation of the pulse combustor was achieved by a simultaneous solution of the following equations:

\[
\frac{d \tilde{T}}{dt} = \gamma \left[ \frac{1}{\tau_F} + \frac{1}{\tau_{HT}} + \frac{1}{\tau_{CF}} \right] \tilde{T} - \left[ \frac{(\gamma - 1) Z_s}{\rho_o} + \frac{1}{\tau_F} + \frac{\gamma T_o}{\tau_{HT} T_w} \right] \frac{\tilde{T}^2}{\tilde{P}} \tag{1}
\]

\[
\frac{d \tilde{P}}{dt} = \gamma \left[ \frac{1}{\tau_F} + \frac{1}{\tau_{HT}} + \frac{1}{\tau_{CF}} \right] - \gamma \left[ \frac{Z_s}{\rho_o} + \frac{1}{\tau_{HT} T_w} \right] \tilde{T} \tag{2}
\]

\[
\frac{d Y_F}{dt} = (Y_{F,i} - Y_F) \frac{\tilde{T}}{\tilde{P}} \frac{1}{\tau_F} - \frac{\tilde{T}}{\tilde{P}} \left( \frac{C_p T_o}{\Delta H} \right) \frac{1}{\tau_C} \tag{3}
\]

\[
\frac{d \tilde{u}}{dt} = (\tilde{P}_c - 1) \left[ \frac{R T_o}{L_{TP} L_{C2}} \right] \tilde{T}_e \frac{F L_{C2}}{2 D_{TP} \tau_F} \frac{\tilde{u}^3}{|\tilde{u}|} \tag{4}
\]
where

\[ \tau_c = \frac{\rho_o T_o C_p}{Q} \] is the Combustion Time

\[ \tau_f = \frac{\rho_o}{Z_i} \] is the Flow Time

\[ \tau_{HT} = \frac{L_{c1} \rho_o T_o C_p}{h T_w} \] is the Heat Transfer Time

and

\[ Z_i = \frac{\dot{m}_i}{V} \] inlet mass flow rate per combustor zone volume.

\[ Z_e = \frac{\dot{m}_e}{V} \] exit mass flow rate per combustor zone volume.

\[ L_{c1} = \frac{V}{A_s} \] the first characteristic length, representing combustion zone volume to surface area ratio.

\[ L_{c2} = \frac{\dot{m}_i \tau_f}{A_e \rho_o} \] the second characteristic length, defined as the combustion volume to the tailpipe cross-section area.

The other variables used are \( \tilde{T} \) and \( \tilde{P} \) which are the normalized temperature and pressure respectively, \( t \) is the time, \( \gamma \) is the ratio of specific heats, \( \rho_o \) is the ambient density, \( T_o \) is the ambient temperature, \( T_w \) is the combustor wall temperature, \( Y_F \) is the fuel mass fraction, \( Y_{Fi} \) is the inlet fuel
mass fraction, \( C_p \) is the specific heat for constant pressure, \( \Delta H \) is the heat of reaction, \( \bar{u} \) is the normalized velocity of gas in the tailpipe, \( \bar{P}_e \) and \( \bar{T}_e \) are the normalized pressure and temperature at the tailpipe entrance, \( R \) is the gas constant, \( L_{tp} \) is the length of the tailpipe, \( F \) is the friction factor, \( D_{tp} \) is the diameter of the tailpipe, \( \dot{Q} \) is the heat release per unit volume and \( h \) is the heat transfer coefficient.

It should be noted that the combustion time used in the equations is not constant. Combustion time depends on the heat release rate. Since the heat release rate is time-dependent, so is the combustion time. Physically, the combustion time is a measure of the time required for the fuel and oxidizer to react. Also, the gases from the combustor are assumed to accelerate isentropically to the tailpipe entrance velocity.\(^1\)

1.3 Research Purpose

The purpose of this work was the experimental investigation of the pulse combustor following the work in reference 1. The fuel used in this investigation was propane. Air and fuel were injected steadily at high pressures. They were ignited by a spark plug and combustion proceeded as explained in the preceding section. In order to investigate the oscillatory characteristics of the combustor, measurements of the pressure oscillations and wall temperature were made. The effect of these characteristics on the operation of the combustor was studied with respect to various parameters. The parameters
considered were tailpipe length, ambient pressure and temperature, and fuel-to-air ratio. The recorded data were used for comparison to existing results and to ascertain new results.

There were several differences between the research done in this investigation and the work described in Reference 1. This research developed the pulse combustor as a research tool for investigating its unsteady behavior. The aspects investigated that were different were, the operation of the combustor with different tailpipe lengths, and the effect of two types of centerbodies on the 'pulsing' of the combustor.
CHAPTER 2

MODELING

The model presented in this chapter was developed at the U.S. Department of Energy. It was based on various assumptions illustrated in figures 2.1 and 2.2. The combustor was treated as a well-stirred combustor (figure 2.1). This signified instant mixing of injected fuel and air. The tailpipe flow was modeled as a slug flow, as shown in figure 2.2. The combustor wall temperature was assumed to be constant. Air and fuel were assumed to be injected at steady rates. Experimentally, this could be obtained by maintaining large fuel and air supply pressures.

Subject to these assumptions, the following equations were obtained to describe the behavior of the pulse combustor.

\[
\frac{d\bar{T}}{dt} = \gamma \left[ \frac{1}{\tau_F} + \frac{1}{\tau_{HT}} + \frac{1}{\tau_{CF}} \right] \bar{T} - \left[ \frac{(\gamma - 1)Z_t}{\rho_o} + \frac{1}{\tau_F} + \frac{\gamma T_o}{\tau_{HT} T_w} \right] \bar{T} \frac{P^2}{P} \tag{1}
\]

\[
\frac{d\bar{P}}{dt} = \gamma \left[ \frac{1}{\tau_F} + \frac{1}{\tau_{HT}} + \frac{1}{\tau_{CF}} \right] \bar{T} - \gamma \left[ \frac{Z_t}{\rho_o} + \frac{1}{\tau_{HT} T_w} \right] \bar{T} \tag{2}
\]

\[
\frac{dY_F}{dt} = (Y_{F,i} - Y_F) \frac{\bar{T}}{\bar{P}} \frac{1}{\tau_F} - \frac{\bar{T}}{\bar{P}} \left( \frac{C_F T_o}{\Delta H} \right) \frac{1}{\tau_C} \tag{3}
\]
Figure 2.2. Tailpipe Control Volume.
\[
\frac{d\bar{u}}{dt} = (\bar{P}_e - 1) \left[ \frac{R T_o}{L_{TP}} \frac{\tau_F}{L_{C2}} \right] \bar{T}_e - \frac{F L_{C2}}{2 D_{TP} \tau_F} \frac{\bar{u}^3}{|\bar{u}|}
\] (4)

where the different variables were defined in the previous chapter.

A computer program based on these equations was developed in reference 1 to simulate the operation of the combustor. This program required as input, ambient conditions, wall temperatures and fuel and air mass flow rates. From this information, the program determined the combustor mode of operation, that is, whether the combustor operated steadily, pulsed or flamed out. If the combustor did pulse, the program also determined the temporal variation of the pressure oscillations in the combustor.

The use of the computer code clearly showed that there were three possible modes of operation. At high fuel mass flow rates, the combustor operated steady. At low fuel mass flow rates, it flamed out. At intermediate fuel mass flow rates, the combustor exhibited oscillatory behavior.
CHAPTER 3
EXPERIMENTAL SETUP

This chapter describes the experimental setup and the data acquisition system used during this investigation.

3.1 Combustor Setup

A schematic of the Combustor setup is shown in figures 3.1 and 3.2. The actual setup used in the investigation is shown in figure 3.3. Stainless steel pipings were used for the construction of the combustor. The required parts were cut to size and then welded together.

In constructing the combustor an arbitrary combustor diameter and tail pipe diameter were chosen. Then, based on the these diameters, a combustor length was chosen using the specifications given in Reference 1. The length of the combustor was determined using the relation for the characteristic length from Reference 1.

The characteristic length $L^*$ is given by

$$L^* = \frac{V_{\text{Combustor}}}{A_{\text{Tailpipe}}} = 39 \text{ inches}$$

the combustor required for pulsing, $V_{\text{Combustor}}$ is the volume of the combustor, and $A_{\text{Tailpipe}}$ is the cross-sectional area of the tail pipe. This characteristic length is
Figure 3.1. Side view schematic of combustor setup.
Figure 3.2. Top view schematic of combustor setup.
chosen to ensure that the combustor pulses, it is a design condition and hence does not appear as a physical dimension. If \( L' \) is significantly less than 39 inches then a steady burning condition is observed. If \( L' \) is significantly greater than 39 inches, then the combustor flames out. For \( L' \) around 39 inches, robust pulsations are obtained. \(^1\)

The transducer cooling jacket was constructed using coaxial pipes and then circular plates were welded on either end as seen in figure 3.1. The cooling jacket was welded on to the combustor approximately 3 inches from the front end of the combustor. A half inch was left between the cooling jacket and the combustor. This spacing was provided to ensure no interference from the cooling jacket on the combustor heat transfer rates. The height of the cooling jacket was five and a half inches. The purpose of the cooling jacket was to protect the transducer from the high combustor temperatures.

The air inlet was connected to an air source using quarter inch diameter tubing. A pressure gage was installed one foot from the inlet and then another, eleven feet upstream from the first. The pressure in the pipe was controlled using regulators installed immediately before the gages. These gages were installed so as to calculate the mass flow rate of air into the combustor, as explained in the data reduction section.

In connecting the fuel inlet, a more cautious approach was required due to safety considerations. The fuel inlet was connected to a propane tank using special tubing rated for propane. A check valve was mounted in the tubing one
half foot from the combustor. Then one foot from the combustor a pressure gage was installed. The next pressure gage was installed downstream, 11 feet from the first, with another check valve immediately following the gage. As in the case of the air, pressure regulators were installed immediately preceding the gages to enable calculation of the mass flow rate of propane into the combustor. The purpose of the check valves was to prevent any backward flow of air or flame, from entering the propane tank.

The transducer and tail pipe were thread-mounted using wrenches to enable easy installation and removal. This procedure was necessary for the transducer due to cost and maintenance reasons. As for the tail pipe, this was necessary so that the tail pipe length could be varied as the experiment required.

Initially no center body was used for the experiment. During this time no ignition of the combustor reactants was observed. This behavior was probably due to improper mixing of the reactants. Hence a coaxial solid steel rod was inserted into the combustor as shown in figures 3.1 and 3.2. This enabled better mixing of the fuel and air, and ignition was successfully achieved. The steel centerbody was used in the initial experiments. In later experiments an hollow alumina rod was slipped over the steel rod. It was found that larger pulsations were obtained with the alumina rod.

The pressure measurements were made by a piezotron transducer model 206, from the Kistler Instrument Corporation. All temperature
measurements were made using Flow-Thru thermocouples made by the Nanmac Corporation. The model numbers are D1-4-K-E the E standing for the installation specifications. These thermocouples were installed as shown in figure 3.2. In order to obtain a temperature reading, a hand held device giving a digital readout was used as shown in figure 3.4. The first thermocouple was installed to measure the temperature inside the combustor. The second thermocouple was installed so that the outside wall temperature could be measured. The thermocouples were welded on to the combustor.

Ignition of the reactants was obtained by the use of an automobile spark plug and it was installed as shown in figure 3.2. An ignition system capable of sustaining a constant spark was required for the experiment. This was required first for safety reasons, so that the reactants would not accumulate and explode when ignited, and to enable easy sparking of the mixture, as opposed to constantly regulating the spark manually. The ignition system, see figure 3.5, was designed using a series of capacitors so as to store the electrical charge. The concept is similar to that used in the ignition system of an automobile, except that instead of a single spark from a given spark plug, a constant spark was obtained. The system was powered by two six volt batteries. The voltage coming from the battery was transformed by the coil to a much higher voltage in the order of ten thousand volts so as to produce a spark of the desired intensity. The charge was dissipated from the capacitors to the spark plug. While this was happening, another set of capacitors was being charged, ready to dissipate their
Figure 3.4. Photograph showing setup for temperature measurements.
Figure 3.5. Ignition System.
charge to the spark plug. This charge-and-dissipation procedure was repeated with almost no lapse in time, in essence producing a constant spark.

3.2 Data Acquisition Setup

The pressure measurement was crucial for defining the operation of the combustor. This was because the frequency of the pressure fluctuations varied from seventy to a hundred and fifty hertz. The pressure measurements were made using a Kistler transducer, model 206, as described earlier. While it would have been desirable to measure the combustor temperature fluctuations, thermocouples capable of measuring them were not available. Thus the only temperatures measured were the combustor wall temperatures. The temperature measurements were obtained with the help of a hand held temperature scanner model H18A-30, made by the Nanmac Corporation, as shown in figure 3.4. As described earlier, temperatures were obtained (1) inside the combustor and (2) on the outside of the combustor wall. Later on it was found that the thermocouple (1) did not provide reliable data. Hence, the only temperatures discussed were the temperatures on the outside of the combustor wall. The pressure measurements were a little more involved and an explanation is given in the following paragraphs.

A pressure calibration had to be done to ensure reliable data. First an electrical calibration was done, with the setup shown in figure 3.6. An actual photograph of the calibration setup is shown in figure 3.7. A signal generator
was used, to put out a sinusoidal signal of a known voltage and frequency. The signal generator was connected to an oscilloscope and to an am tape recorder. The output signal from the tape recorder was passed to the oscilloscope. This was done so the signal going in and coming out of the tape recorder could be observed on the oscilloscope, and any amplification or attenuation between the two signals recorded. From this observation the calibration factors were calculated.

During the initial stages of the experimentation only an electrical calibration was performed. However, a Sound Pressure Level Calibrator later became available and was incorporated into the calibration procedure. In the electrical calibration only an indication of the amplification or attenuation of the electrical signal was achieved. This resulted in a calibration factor in terms of voltages. Then the sensitivity value provided by the manufacturer was used to convert the raw data to readings in units of pressure.

In performing the analog calibration, see figure 3.8, all the equipment used in the experiment was calibrated, as opposed to only a part of it. A calibration factor could be thus obtained that gave a direct relation between the voltage and the units of pressure. This meant that it was necessary to use the manufacturers value of sensitivity. Instead, a sensitivity factor specific to the experiment was obtained.
Figure 3.6. Electrical calibration setup for data acquisition.
Figure 3.7. Photograph of actual electrical calibration setup for data acquisition.
Data Acquisition System 3

Figure 3.8. Analog calibration of data acquisition setup.
A schematic of the experimental setup is shown in figure 3.9. The actual experimental setup, used in the experiment, is shown in figure 3.10. The transducer is fitted in the combustor as indicated earlier. The transducer is then connected to a charge amplifier to amplify the measured signals. The charge amplifier used is model 504D made by Kistler Instrument Corporation. The rest of the connections are identical to those in figures 3.9 and 3.10.

All the data were recorded with the aid of the am tape recorder using an audio metal tape. This raw analog data then had to be digitized for the purpose of data reduction and analysis.

In order to digitize the data the setup shown in figure 3.11 was used. The actual data acquisition program used to digitize the data is given in Appendix A. The oscilloscope was used again in this setup to ensure that there was no external interference when the signal was being digitized. The hardware used for digitizing the data was the DAS-8 card installed in an IBM-Compatible computer shown in figure 3.11.
Figure 3.9. Data acquisition setup for recording analog data.
Figure 3.10. Photograph of actual data acquisition setup for recording analog data.
CHAPTER 4

EXPERIMENTAL PROCEDURE

The experimental procedure was broken up into two parts (1) The combustor setup and (2) The data acquisition setup. The combustor was always setup first, as location was crucial due to the hazardous nature of the experiment. Once the combustor was setup all the other components shown in figures 3.4, 3.5 and 3.10 were setup.

The combustor was fastened to a stand with the help of standard C-clamps inside the Embry-Riddle Aeronautical University engine test cell. Then the air and propane tubes were connected to the combustor with the help of quick release fasteners. The transducer and spark plug were then mounted and the ignition system fitted. Care was taken to ensure that the ignition system was not on, in case of any leakage of propane.

Before any measurements could be taken an electrical calibration had to be performed, as explained before. For this calibration, the setup shown in figure 3.7 was used. The signal generator was set to 150 Hz and the voltage was varied so that the signal was easily read on the oscilloscope. The characteristics of the raw experimental data recorded had peak to peak voltage of approximately 1 volt. Hence, the voltage used from the signal generator was
set at approximately 1 volt. The known signal was then recorded on tape, and the voltages in and out of the tape recorder were read off the oscilloscope and recorded. This concluded the initial calibration. A similar calibration was done at the end of the experiment to determine if any changes had occurred during the experiment.

The signal generator was then removed from the circuit and, in its place, the transducer and charge amplifier were introduced as shown in figure 3.10. The charge amplifier was set to the piezotron mode and the sensitivity set at 86 mv/psi, as suggested by the manufacturer.

In the case of the calibration system shown in figure 3.8, the transducer and all the other components described in the experimental setup for recording analog data, figure 3.10, were connected. Then, immediately prior to turning the ignition system on, the transducer was put into the sound pressure level calibration device shown in figure 3.8. The calibrator put out a sound pressure level of 94 dB at 20 micropascals. The signal was recorded on tape and also the input and output voltages were read directly off the oscilloscope and noted.

At this point water was introduced into the transducer cooling jacket to protect the transducer from high temperatures in the experiment. The ignition system was then turned on to ensure no large explosions. The air regulators were then adjusted to the required pressures at the two gage locations. In the case of propane, a little more care had to be taken, because too little propane would not cause any ignition and too much would cause an “explosion”. Hence,
the regulator on the bottle was first opened all the way so that it was at tank
pressure, while the other regulator was kept fully closed. The second regulator
was then opened very slowly till ignition was obtained. All the pressures used in
both the air and propane ducts were recorded. Once the combustor was running
steady, the fuel mass flow rate was reduced until the combustor started pulsing.

Now the data acquisition system was utilized to take readings. The
spark plug was turned off momentarily, so that it’s signal would not interfere with
the readings. The tape recorder was then turned on and the data recorded,
while the combustor continued to operate. While the tape recorder was
recording, the hand held temperature scanner was used to take temperature
readings at the two locations. Once a sufficient amount of readings was
obtained, the tape recorder was stopped and the ignition system turned on. This
was done to ensure that any unburned fuel was burned and flushed out. Care
was taken to leave gaps in the tape recording as a clear demarcation between
different sets of readings. The above procedure was repeated for various air
and propane mass flow rates.

During shut down the propane regulators were closed first and the air
pressure was increased to cool the combustor and flush any unburned propane.
The ignition system was then turned off. At this point the microdot wire
connecting the transducer to the charge amplifier was removed. The transducer
was then removed and stored in its casing. Then the water into the cooling
jacket was turned off and so was the air into the combustor. All the air and fuel
connections were then removed and stored. Finally, the data acquisition system was disconnected and stored.

Once all the analog data were recorded on the tape recorder, they had to be digitized for data reduction and analysis. For this purpose the setup shown in figure 3.11 was used. The oscilloscope, tape recorder and computer were all turned on. The program listed in Appendix A, was loaded. Then the sampling rate and time information were entered. The tape was adjusted to the desired location and then played. At the same time the computer was triggered and the digitizing began. The digitized data were stored in a lotus-compatible file. Then using a spread sheet the calibration factors were applied to convert the digitized data from voltages to pressure units (psi). Then a Fast-Fourier-Transform (FFT) was obtained of the data and results plotted.
CHAPTER 5
DATA ANALYSIS

The pulse combustor setup described in the previous chapter was used to perform several experiments. In these experiments the combustor operation was studied for different tailpipe lengths, ambient temperatures and pressures and wall temperatures. This chapter describes the different characteristics observed during the pulse combustor operation.

5.1 Experimental Observations

In performing the experiment there were several modifications that were implemented into the experimental setup. Depending on the observations made during the experiment, modifications had to be made in order to obtain results. These modifications were made in (1) the analog calibration and (2) the measurement of temperatures. These modifications will be explained in detail later in the chapter.

During the initial experiments it was observed that the air inlet pressure was high and the propane inlet pressure was relatively low. Consequently, to avoid “blow-back” of propane, check valves were introduced into the setup as described in chapter 4.
No combustion was observed during the initial experiments. The reason for this was thought to be due to improper mixing of the reactants. Hence a steel centerbody was inserted as shown in figures 3.1 and 3.2. The centerbody was placed such that it was directly in the path of the fuel and air as they entered the combustor. This promoted a mixing of the reactants after entry into the combustor. Upon ignition, the combustion process was successfully established.

As mentioned earlier, the use of an alumina centerbody in place of a steel centerbody resulted in larger pulsations in the combustor. This behavior can be explained as follows. The alumina rod dissipates thermal energy, and prevents establishment of a hot spot in the combustor. Such a hot spot would lead to the combustor operating steady. This conclusion is supported by the observation that the combustor operated in a steady mode without the alumina centerbody.

It was observed that the type of combustor operation was dependent on the fuel and air mass flow rates. At large fuel mass flow rates, the combustor operated in a steady manner. In order to obtain pulsing, the fuel mass flow rate had to be reduced.

During the model discussions presented earlier, it was suggested that the flame temperature would be measured as another factor in characterizing the combustor operation. However, to accurately measure the flame temperature, a thermocouple would have to be mounted in the centerbody. This would have to
be done with care so that the flow would not be disrupted, which in turn would interfere with the rate of the reaction. In figure 5.1, the Alumina centerbody on the inside of the combustor is seen during it’s operation. Here the centerbody can be seen to be glowing red hot. This is important to note, as any thermocouple or temperature measuring device would have to sustain very high temperatures.

The importance of the above observations is that measuring the flame temperature is not a trivial task. It has been found however, that the behavior of flame temperature is similar to that of wall temperature; that is, if flame temperature goes up, then wall temperature goes up, and vice-versa.\textsuperscript{12} Hence at this stage the combustor operation will only be characterized with reference to the wall temperature. This is believed to be sufficient first step towards a more accurate characterization of the combustor operation.

It should be noted that the measured wall temperature is only an average over the length of the combustor. This is due to the fact that the temperature variation along the combustor is quite large. This can be seen in figure 5.2 and 5.3. Figure 5.2 shows the combustor operating with a 1 foot tail-pipe. Figure 5.3 shows the combustor operating with a 2 foot tail-pipe. Both photographs show the front end of the combustor to be quite cool as opposed to the end that is close to the tail pipe, which is glowing red-hot. In the case of the 1 foot tail pipe it can be seen from figure 5.2 that only the tailpipe i.e. the end
Figure 5.1. Photograph showing the glowing alumina rod on the inside of the combustor.
Figure 5.2. Photograph showing the temperature variation on the combustor for a one foot tail pipe.
Figure 5.3. Photograph showing the temperature variation on the combustor for a two foot tail pipe.
that is joined to the combustor, is red hot. However, in the case of the 2 foot tail pipe both the combustor and the tailpipe are red hot.

Another compromise that had to be made during the experimentation was in the analog calibration. In order for the calibration to have any value to the experiment, the calibration should be performed at about the pressure levels expected in the experiment. The pressure put out by the sound Pressure Calibrator was only one-tenth of that expected from the experiment. Hence, only an electrical calibration was done.

A computer simulation of the pulsing characteristics of the combustor was obtained using the computer program developed by the author of reference 1. This simulation gave the different operational modes of the combustor. The inputs required were the geometric characteristics of the combustor, and the mass flow rates in terms of the flow time as described in chapter 2. The program displayed steady operation for low flow times, pulsing for medium flow times and flame-out for high flow times. It should be noted that the simulation only gives a qualitative comparison and not a quantitative one. This was because the program did not account for different conditions or the different possible geometric variations possible. In the experiment it was noted that at high mass flow rates the combustor was in the steady operating mode. At medium mass flow rates the pulsing mode was achieved and at lower mass flow rates the combustor flamed-out. Hence the operational modes displayed by the simulation were in accordance with the modes observed experimentally.
Different fuel to air ratios were used in conducting the experiments. It was observed that the combustor would only pulse at certain fuel to air ratios, as expected. However, it was found that the inlet pressures of the fuel and air also affected the combustor operation. Varying the inlet air and fuel pressures caused the combustor to operate in a steady manner, pulse or flame out.

5.2 Data Reduction Technique

For the purpose of discussing and analyzing the data and results obtained from the experiment the data had to be reduced. The main variables that had to be obtained were the fuel and air mass flow rates, and the combustor pressure.

The mass flow rates of the fuel and oxidizer were obtained from the following expression for flow through a pipe:

\[ \dot{m} = Q \cdot \rho = \frac{\pi \cdot R^4}{8 \cdot \mu \cdot l} \cdot (P_1 - P_2) \cdot \rho \]

where \( P_1 \) is the pressure at the inlet of the pipe, \( P_2 \) is the pressure at the exit of the pipe, \( \dot{m} \) is the mass flow rate into the combustor, \( Q \) is the volume flow rate into the combustor, \( \rho \) is the density of the fluid, \( R \) is the radius of the pipe, \( \mu \) is the dynamic viscosity and \( l \) is the length of the pipe. The values used for the different constants in the equation are given below.

Air

\[ \rho = 1.23 \, \text{kg/m}^3 \]

\[ \mu = 1.79 \times 10^{-5} \, \text{N.s/m}^2 \]
\( l = 7.1628 \text{ m} \)

\( R = 0.003175 \text{ m} \)

Propane

\( \rho = 1.97 \text{ kg/m}^3 \)

\( \mu = 0.85 \text{ E-5 N.s/m}^2 \)

\( l = 3.7338 \text{ m} \)

\( R = 0.003175 \text{ m} \)

The values obtained for air were from reference 13 and those for propane were from references 14 and 15.

The analog pressure data on tape was digitized at a sampling rate of 10,000 samples per second. Table 5.1 shows a typical portion of the type of data obtained. This raw data had to be manipulated with reference to calibration factors in order to obtain values in units of pressure (Psi).

The first item that had to be computed was the calibration factor. The calibration factor varied from experiment to experiment. This was due to the differences in the equipment being used in different runs. For example, on one run a dual trace oscilloscope was used and for another a single trace. This involved different calibration voltages and hence different calibration factors. In order to compute the calibration factor the raw data had to first be plotted, and the peak to peak amplitude of the wave determined (figure 5.4). The calibration factor \( C.F \) was then obtained from
### RAW DATA

0.03173828  
0.08056641  
0.1293945   
0.06835938  
0.1147461   
0.05859375  
0.07324219  
0.04638672  
0.078125    
0.1171875   
0.06103516  
0.1342773   
0.05126953  
0.06835938  
0.1196289   
0.05859375  
0.1220703   
0.04394531  
0.05859375  
0.08789063  
0.05126953  
0.078125    
0.1171875   
0.04638672  
0.04638672  
0.06591797  
0.1098633   
0.05126953  
0.07080078  
  0.15625    
0.078125    
0.1220703   
0.04638672  
0.07324219  
0.1391602   
0.06103516  
0.09765625  
0.05126953  
0.07568359  
0.1245117

**Table 5.1.** Raw data for run 3.
\[ C.F. = \frac{\text{voltage} \times 1000}{\text{units} \times \text{sensitivity}} \]

where the voltage used was the value of voltage recorded from the oscilloscope; that is, the voltage input from the signal generator into the oscilloscope or the tape recorder, recall the discussion on calibration in the section on experimental procedure. The sensitivity value used was the one provided by the manufacturer. The factor of 1000 was used to convert the sensitivity from millivolts per Psi to volts/Psi. The calibration factor was then applied to all the 10,000 data points.

An example of the computation of the calibration factor for run 3 is shown below.

Peak to Peak Amplitude = 0.325 units [Shown in figure 5.4]

Voltage = 1 volt

Sensitivity = 124.7 mV/Psi [Reference 12]

Substituting into the equation, the calibration factor is obtained as

C.F. = 24.6746 Psi/Volt

Table 5.2 shows the digitized information after use of the calibration factor. The units of these numbers are in psi.

At this point a FFT (Fast Fourier Transform) analysis was performed on the data. This analysis was done to obtain the spectral characteristics of the signal. The FFT program required input data in a single column. On output a new file
Figure 5.4. Graphical representation of raw data for the determination of the calibration factor for run 3.
<table>
<thead>
<tr>
<th>DATA IN Psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.783129</td>
</tr>
<tr>
<td>1.987944</td>
</tr>
<tr>
<td>3.192758</td>
</tr>
<tr>
<td>1.68674</td>
</tr>
<tr>
<td>2.831314</td>
</tr>
<tr>
<td>1.445777</td>
</tr>
<tr>
<td>1.807222</td>
</tr>
<tr>
<td>1.144574</td>
</tr>
<tr>
<td>1.927703</td>
</tr>
<tr>
<td>2.891555</td>
</tr>
<tr>
<td>1.506018</td>
</tr>
<tr>
<td>3.313239</td>
</tr>
<tr>
<td>1.265055</td>
</tr>
<tr>
<td>1.68674</td>
</tr>
<tr>
<td>2.951795</td>
</tr>
<tr>
<td>1.445777</td>
</tr>
<tr>
<td>3.012036</td>
</tr>
<tr>
<td>1.084333</td>
</tr>
<tr>
<td>1.445777</td>
</tr>
<tr>
<td>2.168666</td>
</tr>
<tr>
<td>1.265055</td>
</tr>
<tr>
<td>1.927703</td>
</tr>
<tr>
<td>2.891555</td>
</tr>
<tr>
<td>1.144574</td>
</tr>
<tr>
<td>1.144574</td>
</tr>
<tr>
<td>1.6265</td>
</tr>
<tr>
<td>2.710833</td>
</tr>
<tr>
<td>1.265055</td>
</tr>
<tr>
<td>1.746981</td>
</tr>
<tr>
<td>3.855406</td>
</tr>
<tr>
<td>1.927703</td>
</tr>
<tr>
<td>3.012036</td>
</tr>
<tr>
<td>1.144574</td>
</tr>
<tr>
<td>1.807222</td>
</tr>
<tr>
<td>3.433722</td>
</tr>
<tr>
<td>1.506018</td>
</tr>
<tr>
<td>2.409629</td>
</tr>
<tr>
<td>1.265055</td>
</tr>
<tr>
<td>1.867462</td>
</tr>
<tr>
<td>3.072276</td>
</tr>
</tbody>
</table>

Table 5.2. Pressure data in Psi for run 3.
POWER SPECTRUM

<table>
<thead>
<tr>
<th>FREQUENCY</th>
<th>POWER</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.7656</td>
<td>1.373</td>
</tr>
<tr>
<td>19.531</td>
<td>0.76223</td>
</tr>
<tr>
<td>29.297</td>
<td>-0.32182</td>
</tr>
<tr>
<td>39.063</td>
<td>-0.98982</td>
</tr>
<tr>
<td>48.828</td>
<td>-0.91033</td>
</tr>
<tr>
<td>58.594</td>
<td>-0.86633</td>
</tr>
<tr>
<td>68.359</td>
<td>-0.81773</td>
</tr>
<tr>
<td>78.125</td>
<td>-0.63651</td>
</tr>
<tr>
<td>87.891</td>
<td>-0.27856</td>
</tr>
<tr>
<td>97.656</td>
<td>0.14245</td>
</tr>
<tr>
<td>107.42</td>
<td>0.47247</td>
</tr>
<tr>
<td>117.19</td>
<td>0.60598</td>
</tr>
<tr>
<td>126.95</td>
<td>0.47843</td>
</tr>
<tr>
<td>136.72</td>
<td>0.12074</td>
</tr>
<tr>
<td>146.48</td>
<td>-0.072204</td>
</tr>
<tr>
<td>156.25</td>
<td>-0.14666</td>
</tr>
<tr>
<td>166.02</td>
<td>-0.4123</td>
</tr>
<tr>
<td>175.78</td>
<td>-0.66638</td>
</tr>
<tr>
<td>185.55</td>
<td>-0.78718</td>
</tr>
<tr>
<td>195.31</td>
<td>-0.85686</td>
</tr>
<tr>
<td>205.08</td>
<td>-0.91137</td>
</tr>
<tr>
<td>214.84</td>
<td>-0.94966</td>
</tr>
<tr>
<td>224.61</td>
<td>-0.93678</td>
</tr>
<tr>
<td>234.38</td>
<td>-0.92702</td>
</tr>
<tr>
<td>244.14</td>
<td>-0.97475</td>
</tr>
<tr>
<td>253.91</td>
<td>-1.0679</td>
</tr>
<tr>
<td>263.67</td>
<td>-1.1097</td>
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<td>273.44</td>
<td>-1.0916</td>
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<td>283.2</td>
<td>-1.1675</td>
</tr>
<tr>
<td>292.97</td>
<td>-1.3007</td>
</tr>
</tbody>
</table>

Table 5.3. FFT power and frequency data for run 3.
was created containing two columns of data with 511 points in each column. A
sample output is shown in table 5.3. The first column contained the
frequencies, the second the power. The values were then plotted with
frequencies on the x-axis. The dominant frequency and pressure amplitude
were noted in each case. The amplitude was then obtained as

$$\text{Pressure} = \frac{\sqrt{10^{\text{Power}}}}{2}$$

were the pressure is the peak to peak pressure in psi, and the power is the
amplitude read of the FFT power spectrum.\(^{16,17}\)

An example of the FFT spectrum is shown for run 3 in figure 5.5. Applying
the formula given above the peak-to-peak pressure variation is calculated to be
1 Psi which is 6895 Pascals. It is important to note that for the purpose of
discussion all values have been converted to standard S.I. units.
CHAPTER 6
RESULTS

This chapter states the results in table format. A discussion of the results is also presented.

6.1 Statement of Results

In stating the results it should be noted that the experiment was performed approximately fifty times. Hence, an enormous amount of data was obtained. This made it impractical to include and discuss all the data obtained. Instead data were selected so that an accurate and concise discussion of the important results could be made.

In the operation of the combustor there were three distinct operational modes as stated in the section on experimental observations. Data were collected on all three modes. It was noted that for a large range of air and fuel mass flow rates, the combustor either operated steady or flamed out. It was only in a narrow window of fuel and air massflow rates, sandwiched between those for steady and flame-out modes, that the device exhibited pulsing behavior. Also this mass flow rate window shifted with other operating conditions (ambient temperature and pressure, tailpipe length). Furthermore,
the experimental equipment available did not permit fine variations of air and 
fuel mass flow rates. Consequently, it was not possible to exercise much 
control over the flow rates. In order to obtain pulsing, the flow rates were 
roughly varied until pulsing was established, and the rates noted.

Tables 6.1 through 6.11 present a compilation of results obtained from 
the experiments. These results will be discussed in the next section.

6.2 Discussion of Results

In discussing the results obtained it is important to note that 
comparisons would only be valid if they are made under the same conditions. 
Hence, more numbers are stated in a specific table than are required for the 
discussion. This simply enables a particular inference to be made by choosing 
one set of conditions, and then the reader can draw similar inferences by 
selecting another set of conditions. For example, a discussion will be presented 
on the relation between ambient conditions and the fuel to air ratio's. These 
values will be compared only for the case with a one foot tailpipe and a steel 
centerbody. From this comparison the reader can draw the same inference if the 
values were compared for an alumina centerbody or for a two foot tailpipe. In 
runs 1-4 and 7,8 a one foot tailpipe was used and in runs 1-6 a steel centerbody 
was used while in runs 7-10 an alumina centerbody was used.

In Appendix B, the Power Spectra of the various experimental runs 
discussed in this section, are included. The spike denotes the peak-to-peak
<table>
<thead>
<tr>
<th>Run Number</th>
<th>Ambient Pressure (Pa)</th>
<th>Ambient Temperature (°C)</th>
<th>Tail Pipe Length (ft)</th>
<th>Fuel to Air Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>101626</td>
<td>13.89</td>
<td>1</td>
<td>0.84</td>
</tr>
<tr>
<td>2</td>
<td>101863</td>
<td>11.11</td>
<td>1</td>
<td>0.54</td>
</tr>
<tr>
<td>3</td>
<td>101896</td>
<td>23.33</td>
<td>1</td>
<td>0.32</td>
</tr>
<tr>
<td>4</td>
<td>101896</td>
<td>23.33</td>
<td>1</td>
<td>0.43</td>
</tr>
<tr>
<td>5</td>
<td>101896</td>
<td>23.33</td>
<td>2</td>
<td>0.65</td>
</tr>
<tr>
<td>6</td>
<td>101896</td>
<td>23.33</td>
<td>2</td>
<td>0.22</td>
</tr>
<tr>
<td>7</td>
<td>101693</td>
<td>18.33</td>
<td>1</td>
<td>0.50</td>
</tr>
<tr>
<td>8</td>
<td>101693</td>
<td>18.33</td>
<td>1</td>
<td>0.86</td>
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<td>9</td>
<td>101693</td>
<td>18.33</td>
<td>2</td>
<td>0.76</td>
</tr>
<tr>
<td>10</td>
<td>101693</td>
<td>18.33</td>
<td>2</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Table 6.1. Table of Ambient Conditions and Fuel to Air Ratios for varying Tailpipe lengths.
<table>
<thead>
<tr>
<th>Run Number</th>
<th>Ambient Pressure (Pa)</th>
<th>Ambient Temperature (°C)</th>
<th>Oxidizer Inlet Pressure (Pa)</th>
<th>Fuel Inlet Pressure (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>101626</td>
<td>13.89</td>
<td>289580</td>
<td>20684</td>
</tr>
<tr>
<td>2</td>
<td>101863</td>
<td>11.11</td>
<td>303369</td>
<td>34474</td>
</tr>
<tr>
<td>3</td>
<td>101896</td>
<td>23.33</td>
<td>344738</td>
<td>13790</td>
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<td>4</td>
<td>101896</td>
<td>23.33</td>
<td>275790</td>
<td>13790</td>
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<td>5</td>
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<td>23.33</td>
<td>344738</td>
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<td>101693</td>
<td>18.33</td>
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<td>13789</td>
</tr>
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</table>

Table 6.2. Table of Ambient Conditions and Inlet Pressures of the fuel and Oxidizer.
<table>
<thead>
<tr>
<th>Run Number</th>
<th>Ambient Pressure (Pa)</th>
<th>Ambient Temperature (°C)</th>
<th>Amplitudes (Power)</th>
<th>Pressure (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>101626</td>
<td>13.89</td>
<td>0.95</td>
<td>10342</td>
</tr>
<tr>
<td>2</td>
<td>101863</td>
<td>11.11</td>
<td>1.50</td>
<td>19305</td>
</tr>
<tr>
<td>3</td>
<td>101896</td>
<td>23.33</td>
<td>0.60</td>
<td>6895</td>
</tr>
<tr>
<td>4</td>
<td>101896</td>
<td>23.33</td>
<td>0.85</td>
<td>8963</td>
</tr>
<tr>
<td>5</td>
<td>101896</td>
<td>23.33</td>
<td>1.30</td>
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</tr>
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<td>0.60</td>
<td>6895</td>
</tr>
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<td>18.33</td>
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<td>18.33</td>
<td>2.40</td>
<td>55158</td>
</tr>
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</table>

Table 6.3. Table of Ambient Conditions and the Pulsing Amplitudes.
<table>
<thead>
<tr>
<th>Run Number</th>
<th>Ambient Pressure (Pa)</th>
<th>Ambient Temperature (°C)</th>
<th>Amplitudes (Power)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>101626</td>
<td>13.89</td>
<td>0.95</td>
<td>127</td>
</tr>
<tr>
<td>2</td>
<td>101863</td>
<td>11.11</td>
<td>1.50</td>
<td>117</td>
</tr>
<tr>
<td>3</td>
<td>101896</td>
<td>23.33</td>
<td>0.60</td>
<td>117</td>
</tr>
<tr>
<td>4</td>
<td>101896</td>
<td>23.33</td>
<td>0.85</td>
<td>110</td>
</tr>
<tr>
<td>5</td>
<td>101896</td>
<td>23.33</td>
<td>1.30</td>
<td>88</td>
</tr>
<tr>
<td>6</td>
<td>101896</td>
<td>23.33</td>
<td>1.55</td>
<td>78</td>
</tr>
<tr>
<td>7</td>
<td>101693</td>
<td>18.33</td>
<td>0.60</td>
<td>108</td>
</tr>
<tr>
<td>8</td>
<td>101693</td>
<td>18.33</td>
<td>1.80</td>
<td>117</td>
</tr>
<tr>
<td>9</td>
<td>101693</td>
<td>18.33</td>
<td>1.60</td>
<td>98</td>
</tr>
<tr>
<td>10</td>
<td>101693</td>
<td>18.33</td>
<td>2.40</td>
<td>78</td>
</tr>
</tbody>
</table>

Table 6.4. Table of Ambient Conditions and the Pulsing Amplitudes with the Corresponding Frequencies.
<table>
<thead>
<tr>
<th>Run Number</th>
<th>Ambient Pressure (Pa)</th>
<th>Ambient Temperature ($^\circ$C)</th>
<th>Amplitudes (Power)</th>
<th>Wall Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>101626</td>
<td>13.89</td>
<td>0.95</td>
<td>--</td>
</tr>
<tr>
<td>2</td>
<td>101863</td>
<td>11.11</td>
<td>1.50</td>
<td>--</td>
</tr>
<tr>
<td>3</td>
<td>101896</td>
<td>23.33</td>
<td>0.60</td>
<td>982</td>
</tr>
<tr>
<td>4</td>
<td>101896</td>
<td>23.33</td>
<td>0.85</td>
<td>928</td>
</tr>
<tr>
<td>5</td>
<td>101896</td>
<td>23.33</td>
<td>1.30</td>
<td>1050</td>
</tr>
<tr>
<td>6</td>
<td>101896</td>
<td>23.33</td>
<td>1.55</td>
<td>960</td>
</tr>
<tr>
<td>7</td>
<td>101693</td>
<td>18.33</td>
<td>0.60</td>
<td>1001</td>
</tr>
<tr>
<td>8</td>
<td>101693</td>
<td>18.33</td>
<td>1.80</td>
<td>973</td>
</tr>
<tr>
<td>9</td>
<td>101693</td>
<td>18.33</td>
<td>1.60</td>
<td>1151</td>
</tr>
<tr>
<td>10</td>
<td>101693</td>
<td>18.33</td>
<td>2.40</td>
<td>1101</td>
</tr>
</tbody>
</table>

Table 6.5. Table of Ambient Conditions and the Pulsing Amplitudes with Wall Temperatures
<table>
<thead>
<tr>
<th>Run Number</th>
<th>Ambient Pressure (Pa)</th>
<th>Ambient Temperature (°C)</th>
<th>Amplitudes (Power)</th>
<th>Frequencies (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>101626</td>
<td>13.89</td>
<td>0.95</td>
<td>127</td>
</tr>
<tr>
<td>2</td>
<td>101863</td>
<td>11.11</td>
<td>1.50</td>
<td>117</td>
</tr>
<tr>
<td>3</td>
<td>101896</td>
<td>23.33</td>
<td>0.60</td>
<td>117</td>
</tr>
<tr>
<td>4</td>
<td>101896</td>
<td>23.33</td>
<td>0.85</td>
<td>110</td>
</tr>
<tr>
<td>7</td>
<td>101693</td>
<td>18.33</td>
<td>0.60</td>
<td>108</td>
</tr>
<tr>
<td>8</td>
<td>101693</td>
<td>18.33</td>
<td>1.80</td>
<td>117</td>
</tr>
</tbody>
</table>

Table 6.6. Table of Ambient Conditions and the Pulsing Amplitudes with Frequencies for a 1-Foot Tailpipe.

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Ambient Pressure (Pa)</th>
<th>Ambient Temperature (°C)</th>
<th>Amplitudes (Power)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>101896</td>
<td>23.33</td>
<td>1.30</td>
<td>88</td>
</tr>
<tr>
<td>6</td>
<td>101896</td>
<td>23.33</td>
<td>1.55</td>
<td>78</td>
</tr>
<tr>
<td>9</td>
<td>101693</td>
<td>18.33</td>
<td>1.60</td>
<td>98</td>
</tr>
<tr>
<td>10</td>
<td>101693</td>
<td>18.33</td>
<td>2.40</td>
<td>78</td>
</tr>
</tbody>
</table>

Table 6.7. Table of Ambient Conditions and the Pulsing Amplitudes with Frequencies for a 2-Foot Tailpipe.
<table>
<thead>
<tr>
<th>Run Number</th>
<th>Fuel to Air Ratio</th>
<th>Oxidizer Inlet Pressure (Pa)</th>
<th>Fuel Inlet Pressure (Pa)</th>
<th>Amplitudes (Power)</th>
<th>Frequencies (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.84</td>
<td>289580</td>
<td>20684</td>
<td>0.95</td>
<td>127</td>
</tr>
<tr>
<td>2</td>
<td>0.54</td>
<td>303369</td>
<td>34474</td>
<td>1.50</td>
<td>117</td>
</tr>
<tr>
<td>3</td>
<td>0.32</td>
<td>344738</td>
<td>13790</td>
<td>0.60</td>
<td>117</td>
</tr>
<tr>
<td>4</td>
<td>0.43</td>
<td>275790</td>
<td>13790</td>
<td>0.85</td>
<td>110</td>
</tr>
<tr>
<td>7</td>
<td>0.50</td>
<td>303369</td>
<td>27579</td>
<td>0.60</td>
<td>108</td>
</tr>
<tr>
<td>8</td>
<td>0.86</td>
<td>448159</td>
<td>13789</td>
<td>1.80</td>
<td>117</td>
</tr>
</tbody>
</table>

Table 6.8. Table of Fuel to Air Ratios, Inlet Pressures and the Pulsing Amplitudes with Frequencies for a 1-Foot Tailpipe.

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Fuel to Air Ratio</th>
<th>Oxidizer Inlet Pressure (Pa)</th>
<th>Fuel Inlet Pressure (Pa)</th>
<th>Amplitudes (Power)</th>
<th>Frequencies (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.65</td>
<td>344738</td>
<td>20684</td>
<td>1.3</td>
<td>88</td>
</tr>
<tr>
<td>6</td>
<td>0.22</td>
<td>275790</td>
<td>20684</td>
<td>1.55</td>
<td>78</td>
</tr>
<tr>
<td>9</td>
<td>0.76</td>
<td>510212</td>
<td>13789</td>
<td>1.6</td>
<td>98</td>
</tr>
<tr>
<td>10</td>
<td>0.57</td>
<td>482633</td>
<td>13789</td>
<td>2.40</td>
<td>78</td>
</tr>
</tbody>
</table>

Table 6.9. Table of Fuel to Air Ratios, Inlet Pressures and the Pulsing Amplitudes with Frequencies for a 2-Foot Tailpipe.
<table>
<thead>
<tr>
<th>Run Number</th>
<th>Fuel to Air Ratio</th>
<th>Oxidizer Inlet Pressure (Pa)</th>
<th>Fuel Inlet Pressure (Pa)</th>
<th>Amplitudes (Power)</th>
<th>Frequencies (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.84</td>
<td>289580</td>
<td>20684</td>
<td>0.95</td>
<td>127</td>
</tr>
<tr>
<td>2</td>
<td>0.54</td>
<td>303369</td>
<td>34474</td>
<td>1.50</td>
<td>117</td>
</tr>
<tr>
<td>3</td>
<td>0.32</td>
<td>344738</td>
<td>13790</td>
<td>0.60</td>
<td>117</td>
</tr>
<tr>
<td>4</td>
<td>0.43</td>
<td>275790</td>
<td>13790</td>
<td>0.85</td>
<td>110</td>
</tr>
<tr>
<td>5</td>
<td>0.65</td>
<td>344738</td>
<td>20684</td>
<td>1.30</td>
<td>88</td>
</tr>
<tr>
<td>6</td>
<td>0.22</td>
<td>275790</td>
<td>20684</td>
<td>1.55</td>
<td>78</td>
</tr>
</tbody>
</table>

Table 6.10. Table of Fuel to Air Ratios, Inlet Pressures and the Pulsing Amplitudes with Frequencies for a Steel Centerbody.

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Fuel to Air Ratio</th>
<th>Oxidizer Inlet Pressure (Pa)</th>
<th>Fuel Inlet Pressure (Pa)</th>
<th>Amplitudes (Power)</th>
<th>Frequencies (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.50</td>
<td>303369</td>
<td>27579</td>
<td>0.60</td>
<td>108</td>
</tr>
<tr>
<td>8</td>
<td>0.86</td>
<td>448159</td>
<td>13789</td>
<td>1.80</td>
<td>117</td>
</tr>
<tr>
<td>9</td>
<td>0.76</td>
<td>510212</td>
<td>13789</td>
<td>1.60</td>
<td>98</td>
</tr>
<tr>
<td>10</td>
<td>0.57</td>
<td>482633</td>
<td>13789</td>
<td>2.40</td>
<td>78</td>
</tr>
</tbody>
</table>

Table 6.11. Table of Fuel to Air Ratios, Inlet Pressures and the Pulsing Amplitudes with Frequencies for an Alumina Centerbody.
pressure variation during the pulsing mode. It can be seen that the largest amplitudes in every case occur around the same frequency. They are of similar shape and pattern.

In Table 6.1 the ambient conditions are shown with the corresponding tailpipe length and fuel to air ratio's. At this point it is important to note, that pulsing is obtained only for a few values of fuel to air ratios. These fuel to air ratios are fixed for a given combustor geometry or specification and for a given set of ambient conditions. At all other fuel to air ratios the combustor either operates steadily, or flames out. It can be seen that in most of the cases as the ambient temperature and pressure are increased the fuel to air ratio would have to be decreased in order to sustain pulsing. This can be seen in runs 1, 7 and 4. However, run 2 shows a distinct exception to this result. In the case for run 2 the temperature and pressure are significantly different from runs 4 and 7.

Table 6.2 shows the different oxidizer and fuel inlet pressures required for pulsing, with the ambient conditions. It is known that the rate of the reaction is dependent on the initial partial pressures of both fuel and oxidizer.\(^7\text{,}^6\) In the experiment, the initial pressures are the inlet pressures of the fuel and oxidizer. The partial pressures of the fuel and oxidizer depend on the inlet pressures of the fuel and oxidizer. Hence, the higher the inlet pressures of the fuel and oxidizer, the higher the partial pressures and the higher will be the rate of the reaction. Thus, at these states the combustor runs steady. This implies at medium reaction rates the combustor exhibits pulsing behavior.
In table 6.3 the variation of peak pressures or amplitudes with ambient conditions can be seen. If runs 3, 1 and 2 are compared it can be seen that as the ambient temperature and pressure are decreased the pressure amplitudes increase. Hence to optimize the combustor in terms of efficiency, low ambient temperatures and pressures will produce the highest pulses. This is a characteristic that is exhibited by any combustion engine.\textsuperscript{14}

It can be seen that the frequency of pulsing does not depend on ambient conditions alone. This can be seen in table 6.4. If comparing runs 2, 3 and 8 it can be seen that the frequency is the same for different ambient temperatures. Hence, other variables would have to be factored in before a relationship can be determined between the frequency, and the ambient temperature and pressure. However, the amplitudes increase as the ambient temperatures decrease, exhibiting a pattern.

In table 6.5 the variation of wall temperature is shown for different ambient conditions and combustor configurations. It can be seen that for a fixed set of ambient conditions, as the pressure amplitudes increase the wall temperature decreases. This inference is obtained by comparing runs 4 and 5 with runs 7 and 8.

In comparing tables 6.6 and tables 6.7 the most distinct observation that can be made is the magnitude of the frequency. It can be seen that when the tail pipe is increased from one foot to two feet, the frequency of pulsing is reduced. This would almost seem obvious as in the case of the two foot tailpipe the flow
has a longer distance to travel as it flows forward and then reverses. However, it should be noted that there is a limiting case for which, if the tailpipe were increased beyond a certain length, only flame-out would occur.\textsuperscript{1} It should also be noted that the amplitudes increase significantly. This is probably due to the build up in pressure inside the combustor due to the longer tailpipe.

The comparison made in tables 6.8 and 6.9 are between the fuel to air ratio’s required for pulsing and the length of tailpipe. It can be seen that in order to achieve pulsing with large pressure amplitudes the fuel to air ratio has to be increased in the case of the one foot tailpipe and decreased in the case of the two foot tailpipe. This inference is made by comparing runs 3-8 to runs 5-10.

Finally, the most important characterization is that with regards to the centerbody. This is important as the centerbody is used to control the pulsing, as explained earlier. It can be seen that in the case of the steel centerbody the frequencies show a steady decline as the pressure amplitudes increase. This can be seen in runs 3 to 6. However, in the case of the alumina centerbody when the pressure amplitudes are increased the frequencies are increased, in the case of the one foot tailpipe, as shown in runs 7 and 8. Hence, a direct relation is obtained between frequency and amplitude, for an alumina centerbody and a one foot tailpipe. The combustor however, displays a contrasting result when the tailpipe is increased to two feet with the alumina centerbody. It shows an inverse relationship between the amplitudes and the frequencies.
As far as the fuel to air ratios are concerned between the steel centerbody case and the alumina centerbody case, the combustor displays similar results. In comparing runs 3-6 with runs 7-10, it can be seen that in the case of the steel centerbody or the alumina centerbody the fuel to air ratio's required for pulsing show a steady increase with amplitude. However, at the highest pressure amplitude a drop in the fuel to air ratio is observed.
CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS

This chapter states the conclusions obtained from this investigation and then provides a plan for future investigations.

7.1 Conclusions

- The combustor displays the three modes of combustion, the steady mode, the pulsing mode and flame-out.

- In general it can be concluded that the fuel to air ratio required for pulsing is inversely related to the ambient temperature and pressure. Thus a pulse combustor behaves like any other combustion engine i.e. as the ambient temperature increases the efficiency decreases. However, for extremely low pressures and temperatures this conclusion is not valid.

- The inlet pressures directly dictate the achievement of the pulsing mode.

- No distinct relationship is observed between the frequency of pulsing and the ambient conditions.

- The wall temperature is inversely related to the pressure amplitudes.

- An increase in the tailpipe length reduces the frequency of pulsing while increasing the magnitude of the pressure amplitude. However, in reference
1 it is stated that there is a characteristic length for the tailpipe, beyond which flame-out occurs.

- In the case of the one foot tail pipe, the fuel to air ratio required for pulsing is directly related to the pressure amplitudes and inversely related in the case of the two foot tailpipe.

- For the steel centerbody the frequencies are inversely related to the pressure amplitudes in both the one and two foot tail pipe cases.

- In the case of the alumina centerbody, the frequencies and amplitudes behave similar to the case with the steel centerbody, in the two foot tailpipe case. However, in the case of the one foot tailpipe a direct relationship is obtained between the frequency and the pressure amplitude.

7.2 Recommendations for Future Work

In performing this investigation it should be noted that every possible avenue of research was neither planned nor accomplished. As stated earlier, the investigation was performed as a first step towards obtaining a finer characterization of the combustor operation.

As can be seen in Appendix C, the fuel pressure gage has the highest relative error. Hence, in order to improve the accuracy of the experiment this gage would have to be improved for a more precise pressure gage.

A first step towards a finer characterization of the combustor, from this investigation, would be to improve the code used for digitizing the data. The
data acquisition system used in the present investigation has a limitation on the sampling rate of a maximum of 30 kHz. Hence, if the time frame is increased the sampling rate has to be reduced. Thus to achieve a larger sampling time frame while maintaining sampling frequency it will be necessary to change the data acquisition system. Also, if a card with a higher sampling rate can be obtained, a finer characterization would be possible.

A more thorough set of temperature measurements can be made to obtain a temperature spectrum. This would enable a temperature characterization of the combustor as opposed to only having a pressure type characterization. The temperature sensor would have to be mounted in the centerbody. A more elaborate investigation could measure the temperature at several points along the centerbody.

In this investigation only a cylindrical combustor design was selected. Other combustor shapes may be investigated for their possible advantages in terms of pressure amplitudes and frequencies of pulsations.

Another line of investigation could involve experimentation with different fuels. In this investigation propane was used. However, higher octane fuels might provide larger pulsations.

Several combustors of varying sizes can be used in an investigation to obtain a scaling factor. This would be useful in the event that these combustors have to be scaled-up for practical applications.
REFERENCES


2. Sweetman Bill, Aurora - The Pentagon’s Secret Hypersonic Spyplane, Mil-Tech Series, Oseola, Wisconsin.


10. Low-Pressure Piezotron Transducer Type 206 Operating Instructions (Kistler Instrument Corporation, 1980).


18. Flow-Thru Thermocouples Type-K Operating Instructions (NANMAC Corporation, 1994).

APPENDIX A

COMPUTER PROGRAM USED FOR DIGITIZING DATA

This program was obtained from reference 11. A few modifications were required so as to ensure compatibility with the card and settings used.

******************************************************************************
*                             *
* Demonstration program for DAS-8 used in array mode 5               *
*                             *
******************************************************************************

DIM d%(6)
COMMON SHARED d%(1)
DECLARE SUB das8 (mode%, BYVAL dummy%, flag%)
******************************************************************************

DIM a%(13000)
******************************************************************************

'a%(1) will be filled with the acquired data. In Rev's earlier than 4.32
'this array would have to be placed in the COMMON area. As a result only
'small amounts of data could be acquired. In Rev's 4.32, Mode 5 has been
'changed. Here if d%(0) is a -1 then d%(2) will have the offset and d%(3)
'will have the segment of the array one wishes to place the data in. This
'allows a user to acquire up to 32k of readings.
'NOTE that if d%(0) is not -1 then Mode 5 will operate as before
******************************************************************************

SCREEN 0, 0, 0: KEY OFF: WIDTH 80

'Make initial screen announcement

CLS

PRINT "This program demonstrates the operation of the DAS-8 in the array "

69
PRINT "conversion, mode 5. Before running the program make sure of the following:"
PRINT "  1. Jumper Counter 2 output (pin 6) to the interrupt"
PRINT "        input (pin 24) on rear connector."
PRINT "  2. If IP1 (pin 25) is held low or grounded then the start of"
PRINT "        conversions will be delayed until IP1 is taken open circuit or "
PRINT "        connected to a logic high level (+2.4 to +5.0v)."
PRINT "After data has been collected into array A%, you may generate an ASCII file"
PRINT "that can be used to import the data into Lotus 1-2-3. Alternatively, you can"
PRINT "generate a file that will link to the standard graphics package on "
PRINT "this disk, or you can simply display data on the screen."
PRINT : PRINT : PRINT : COLOR 0, 7: PRINT " - Do you wish to continue (y/n)?" "; COLOR 7, 0
330 a$ = INKEY$
340 IF a$ = "y" OR a$ = "Y" THEN GOTO 484 ELSE IF a$ <> "" THEN CLS : END
350 GOTO 330
360 '
400 '--- Step 1: Initialize DAS-8 with mode 0 -----------------------------
484 CLS : INPUT "Enter Base address or CR if 300 Hex is ok ", B%
486 IF B% = 0 THEN B% = &H300'Set this for correct base address
490 d%(0) = B% 'I/O address of DAS-8 (change to suit)
500 MD% = 0 'initialize mode
510 flag% = 0 'declare error variable
520 CALL das8(MD%, VARPTR(d%(0)), flag%)
530 IF flag% <> 0 THEN PRINT "Error in initialization"; STOP
540 '
600 '--- Step 2: Set timer rate -----------------------------
610 MD% = 10 'Mode 10 for setting counter configuration
620 d%(0) = 2 'Operate on counter #2
630 d%(1) = 3 'Configuration #2 = rate generator
640 CALL das8(MD%, VARPTR(d%(0)), flag%)
650 IF flag% <> 0 THEN PRINT "Error in setting counter 2 configuration"; STOP
660 '
670 'Prompt user for desired sample rate
680 CLS
690 INPUT "Enter desired sample rate (samples/sec) : ", F
700 ' Output frequency = 2386.4/N KHz
710 N = 2386.4 * 1000 / F
720 IF N < 2 OR N > 65535! THEN PRINT "Warning! A sample rate of "; F; "samples/sec is outside the range of Counter 2"; GOTO 690
730 MD% = 11 'Mode 11 to load counter
740 d%(0) = 2 'Operate on counter #2
750 IF N < 32767 THEN d%(1) = N ELSE d%(1) = N - 65536! 'correct for integer
760 CALL das8(MD%, VARPTR(d%(0)), flag%)
770 IF flag% <> 0 THEN PRINT "Error in loading counter 2": STOP
780 'Pin 6 (Counter 2 Out) should now be producing the selected frequency.
790'
800 'Now fetch duration of scan
810 PRINT : INPUT "Duration of scan (in seconds) : ", DS
820 'Translate duration in a number of conversions for mode 5
830 'Number of conversions = duration x sample rate
840 NC = DS * F
850'
900' --- Step 3: Select the channel to scan  -------------------------------
910 'Note this program only looks at one channel, but by setting LL% and UL%
920 'to the desired scan limits, the channels will be stored in array A%
930 'in the order scanned, for example if LL%= 1 and UL%= 3 then:-
940 '
950 ' A%(0) = channel 1 data
960 ' A%(1) = channel 2 data
970 ' A%(2) = channel 3 data
980 ' etc.
990 'The rest of the program can be modified to handle multiple channel
990 'graphs and data files.
1000 MD% = 1
1010 PRINT : INPUT "Enter channel number to be scanned (0 - 7) : ", LL%:
1020 d%(0) = LL%
1030 UL% = LL%: d%(1) = UL%'s sample on one channel only
1040 CALL das8(MD%, VARPTR(d%(0)), flag%)
1050 IF flag% <> 0 THEN PRINT "Error in setting channel scan limits": STOP
1060'
1200' --- Step 4: Set mode 5 going and acquire data  ----------------------
1210 'Note: Counter 2 output (pin 6) should be jumpered to interrupt input
1220 '(pin 24).
1230 PRINT : COLOR 0, 7: PRINT " Press any key to start A/D conversions ", : COLOR 7, 0
1240 IF INKEY$ = "" GOTO 1240
1250 MD% = 5
1260 d%(0) = -1
1260 'Set to -1 to indicate that d%(2) will have offset
1270 'and d%(3) will have segment of array
1300 IF flag% <> 0 THEN PRINT "Error in setting mode 5", flag%: STOP
1310 CLS
1320 '  
1400 '--- Step 5: Choose type of file required -----------------------------
1410 CLS: PRINT "Choose from the following: -"  
1420 PRINT: PRINT " <1> - Generate a Lotus 1-2-3 compatible import file"  
1430 PRINT: PRINT " <2> - Generate a data file & plot using the DAS-8 graphics package"  
1440 PRINT: PRINT " <3> - Display data on screen"  
1450 PRINT: PRINT " <4> - Exit to BASIC"  
1460 PRINT: PRINT "Enter selection number (1-3) : ";  
1470 a$ = INKEY$: IF a$ = "" GOTO 1470  
1480 PRINT a$  
1490 IF VAL(a$) = 1 THEN GOTO 3000  
1500 IF VAL(a$) = 2 THEN GOTO 2000  
1510 IF VAL(a$) = 3 THEN GOTO 4000  
1520 IF VAL(a$) = 4 THEN CLS: STOP  
1530 PRINT "["; a$; "] is not a valid entry. Please re-enter": GOTO 1460  
1540 '  
2000 '--- Generate DAS-8 graphics package data file & plot -------------------
2010 CLS  
2020 LOCATE 1, 1: INPUT "DATA FILE NAME [DRIVE]:NAME.EXT"; FILX$  
2030 OPEN FILX$ FOR RANDOM AS #1 LEN = 30  
2040 FIELD #1, 15 AS X$, 15 AS Y$  
2050 '  
2060 'Get display mode, dot, line or no plot  
2070 LOCATE 3, 1: COLOR 0, 7: PRINT "L"; : COLOR 7, 0: PRINT "line, or "; : COLOR 0, 7: PRINT "D"; : COLOR 7, 0: PRINT "ot plot mode?"  
2080 LOCATE 3, 29: INPUT " "; a$  
2090 IF a$ = "L" OR a$ = "L" THEN M = 1: GOTO 2130  
2100 IF a$ = "D" OR a$ = "d" THEN M = 0: GOTO 2130  
2110 LOCATE 4, 1: PRINT "RE-ENTER": LOCATE 3, 1: PRINT SPC(79);: GOTO 2070  
2120 '  
2130 'Enter number of data points and plot mode in record 1  
2140 LSET X$ = MKS$(NC): LSET Y$ = MKS$(M)  
2150 PUT #1, 1  
2160 'Enter data in remaining records  
2170 FOR I = 2 TO NC + 1  
2180 LSET X$ = MKS$((I - 2) / 5): LSET Y$ = MKS$(a%((I - 2) * 5 / 2048))  
2190 PUT #1, I  
2200 NEXT I  
2210 'Write file  
2220 CLOSE #1  
2230 'Generate RLINPLT.LNK plotting file for LINPLT.BAS to use  
2240 OPEN "RLINPLT.LNK" FOR RANDOM AS #1 LEN = 30  
2250 FIELD #1, 30 AS RLNK$
2260 LSETRLNK$ = MKI$(1) 'one data file
2270 PUT#1, 1
2280 CLS
2290 INPUT "Enter graph Y axis label : ", Y$
2300 IF LEN(Y$) > 30 THEN Y$ = LEFT$(Y$, 30)
2310 LSETRLNK$ = Y$ 'Y axis label
2320 INPUT "Enter graph X axis label : ", X$
2330 IF LEN(X$) > 30 THEN X$ = LEFT$(X$, 30)
2340 PUT#1, 2
2350 LSETRLNK$ = X$ 'X axis label
2360 PUT#1, 3
2370 LSETRLNK$ = FILX$ 'data file name
2380 PUT#1, 4
2390 CLOSE#1
2400 RUN "LINPLT" 'run plotting program
2410 '
3000 '----- Generate a Lotus 1-2-3 .PRN import file ---------------------------
3010 CLS
3020 LOCATE 1, 1: INPUT "LOTUS .PRN FILE NAME [DRIVE]:NAME
(automatic .PRN ext.) : "; Fs
3030 Fs = Fs + ".PRN"
3040 OPEN Fs FOR OUTPUT AS #1
3050 FOR I = 0 TO NC
3060 PRINT #1, STR$(a%(I) * 5 / 2048)
3070 NEXT I
3080 CLOSE#1
3090 END
3100 '
4000 '----- Display data on screen and return to menu ----------------------
4010 CLS
4020 LOCATE 25, 1: PRINT "Press any key to STOP/START display, <ESC>
key to return to data storage menu "; : LOCATE 1, 1
4030 PRINT "Time Channel data (volts)"
4035 OPEN "conti2.dat" FOR OUTPUT AS #1
4040 FOR I = 0 TO NC
4050 PRINT #1, I, F, a%(I) * 5 / 2048
4060 a$ = INKEY$
4070 IF a$ = CHR$(27) THEN I = NC + 3
4080 IF a$ <> "" THEN GOTO 4140
4090 NEXT I
4095 CLOSE#1
4100 IF I = NC + 3 GOTO 1400
4110 COLOR 0, 7: PRINT " Press any key to return to data storage menu ";
COLOR 7, 0
4120 IF INKEY$ = "" GOTO 4120
4130 GOTO 1400
4140 FOR K = 1 TO 50: NEXT K  'delay
4150 IF INKEY$ = "" GOTO 4150
4160 GOTO 4090
4170 END
APPENDIX B

LIST OF POWER SPECTRUMS

POWER SPECTRUM

FREQUENCY (Hz)

POWER

Figure B.1. Power spectrum for run 1.
Figure B.2. Power spectrum for run 2.
Figure B.3. Power spectrum for run 3.
Figure B.4. Power spectrum for run 4.
Figure B.5. Power spectrum for run 5.
Figure B.6. Power spectrum for run 6.
Figure B.9. Power spectrum for run 9.
Figure B.10. Power spectrum for run 10.
APPENDIX C

EXPERIMENTAL ERROR ESTIMATION

In measuring any experimental data errors are always present. In this experiment, error resulted from three primary sources. First, the measurement of the fluctuating pressures by the transducer involved an error. Errors were also present in the measurement of wall temperature using a K-type thermocouple, and the mass flow rates of the fuel and oxidizer.

There are two types of errors involved in the experimental data. The first type are the instrument errors. Instrument errors come about due to measuring a quantity with a particular instrument. Hence, if a quantity is given, such as a known constant, then there is no instrument error associated with it. Also, if the measured quantities are used to compute other variables, propagation of the instrument errors becomes important. For example, in this investigation, pressures measured using the gages are used to determine fuel and air mass flow rates, giving rise to propagated errors in them. The other type of error is the relative error. This error compares the error of the instrument to the "correct" value of the variable. Hence, every reading has a different relative error associated with it. However, it is clear that the smallest measurement taken will have the largest error. Hence, only the least or smallest
measurement's relative error is calculated, as all the other measurements have smaller relative errors than this value.

In obtaining the relative error for the instrument the following expression is used

\[
\text{Relative Error} = \frac{\text{Instrument Error}}{\text{Least Measurement}} \times 100 \quad (1)
\]

The relative error gives us an indication as to which instrument contributes the most to the errors in the experiment.

**Pressure Fluctuations**

The error from the transducer as given in reference 10 is ±0.0008 psi which is ±5.516 Pa. Hence this is the error involved in measuring the pressure fluctuations. The least measurement taken was 6895 Pa. Hence, the relative error, calculated using equation (1), is ±8.0 E-06 %.

**Wall Temperature**

The instrument error for the Flow-Thru thermocouple given in reference 18 is ±0.3% full scale. In reference 18 the full scale reading is 1300 °C or 1543 K. Hence, the instrument error will be ±3.9 K. The least measurement taken was 928 K. Therefore the relative error calculated using equation (1) is ±0.4 %.
Mass Flow Rates

The formula used in the calculation of the mass flow rates is given by

\[
\dot{m} = Q \cdot \rho = \frac{\pi \cdot R^4}{8 \cdot \mu \cdot l} \cdot (P_1 - P_2) \cdot \rho .
\]

All the terms have been explained in the section on data reduction. The only values that have instrument errors are the two pressures, the length and the radius. All the other values are constants. The instruments used to measure the different quantities, and the instrument errors associated with them are given below.

Radius - Vernier Caliper - Error = ±5.0 E-05 m

Air Pressure - Air Pressure Gage - Error = ±1 psi = ±6895 Pa

Fuel Pressure - Fuel Pressure Gage - Error = ±0.5 psi = ±3447 Pa

Length - Meter Stick - Error = ±5.0 E-04 m

The error in the changes in pressure in both the air and fuel cases is obtained by adding the errors in the individual pressures.

In order to calculate the propagated error in the mass flow rate the standard deviation method is used. This gives

\[
\sigma_m = \dot{m} \otimes \sqrt{\left(4 \otimes \frac{\sigma_R}{R}\right)^2 + \left(\frac{\sigma_{AP}}{\Delta P}\right)^2 + \left(\frac{\sigma_l}{l}\right)^2} \quad \text{..................(2)}
\]

where the \(\sigma\)'s stand for the errors in the particular quantities.\(^{19}\) Using equation (2) the propagated error in the fuel mass flow rate for run 3 is calculated to be
±0.053 Kg/s. Similarly, the propagated error in the air mass flow rate for run 3 is calculated to be ±0.002 Kg/s.

All the instrument and propagated errors are presented in Table C.1. The relative errors for the instruments used are presented in Table C.2.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Fluctuations</td>
<td>±5.516 Pa</td>
</tr>
<tr>
<td>Wall Temperature</td>
<td>±3.9 K</td>
</tr>
<tr>
<td>Air Mass Flow Rate</td>
<td>±0.002 Kg/s</td>
</tr>
<tr>
<td>Fuel Mass Flow Rate</td>
<td>±0.053 Kg/s</td>
</tr>
</tbody>
</table>

Table C.1. Table of Instrument and Propagated Errors

From Table C.1 it can be seen that the errors associated with obtaining the required parameters, are not very large. Also, from Table C.2 it can be seen that the least precise instrument was the Fuel Pressure Gage and the most precise instrument was the Pressure Transducer. Hence, in order to improve the experimental data acquisition, better methods for fuel flow rate measurement should be used.
<table>
<thead>
<tr>
<th>INSTRUMENT</th>
<th>RELATIVE ERROR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Pressure Gage</td>
<td>±2.5 %</td>
</tr>
<tr>
<td>Fuel Pressure Gage</td>
<td>±25 %</td>
</tr>
<tr>
<td>K-type Thermocouple</td>
<td>±0.4 %</td>
</tr>
<tr>
<td>Meter Stick</td>
<td>±0.01 %</td>
</tr>
<tr>
<td>Pressure Transducer</td>
<td>±8.0 E-06 %</td>
</tr>
<tr>
<td>Vernier Caliper</td>
<td>±1.6 %</td>
</tr>
</tbody>
</table>

Table C.2. Table of Relative Errors