INVESTIGATION OF THE PRECOMBUSTION INJECTION OF A WATER SPRAY INTO THE HYDROGEN OXYGEN FLAME FRONT

By

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PREFACE

This study was concerned with an investigation of water injection into a hydrogen-oxygen combustor for the production of steam. The purpose for the study was to inject the water prior to the combustion reaction and describe the effects and limits of the water injection. This investigation is the first experimental approach to a partially quenched hydrogen-oxygen (Aphodid) reaction at Oklahoma State University, and it is hoped that the information presented in this thesis will be improved upon by continued studies at Oklahoma State University.

I wish to express my appreciation to my major adviser, Dr. Jerald D. Parker, and to my committee members, Dr. W. G. Tiederman and Dr. J. A. Wiebelt, for their advice, guidance and extra patience given during my graduate degree program. I would like to acknowledge Mr. Bob Sompayrac and Mr. Ken Nuss for their expert photographic assistance, and gratitude is also extended to my many comrades for their expressed interest in my research and the bull sessions that were encountered with them. Special thanks is extended to my family and long time friend Mr. Glen Needham for their unquestioning confidence and encouragement in my work. I dedicate this thesis to the memory of my brother, John A. Johnson, for he shared great respect for science and interest in its future.

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CHAPTER I

INTRODUCTION

The aphodid burner is a modified combustor which produces steam directly from the combustion of hydrogen and oxygen. Brauser and Hughes proposed that the hydrogen-oxygen combustor could be modified by injecting water into the combustion chamber (1). The water injection reduces the high temperatures of the reaction which gives control of the exiting steam temperature. By incorporating this steam generator with a complementing steam turbine and condenser a new power cycle is established; Brauser and Hughes call it the "Aphodid Power Cycle" (see Figure 1).

If it is assumed that hydrogen and oxygen are available as fuel and oxidizer for the aphodid power cycle, then the cycle can be compared with present power cycles used for electrical power production (1). Compared with the typical vapor power (Rankine) cycle the aphodid cycle is more efficient because:

1) There are no stack losses such as exist in the Rankine cycle.
2) Heat is added in the cycle at a relatively high and controlled average temperature.
3) By the direct production of steam from the combustion process the aphodid burner is much more compact in size.

The major difference between the Brayton cycle and the aphodid cycle is that for equal mass flow rates of working fluid the aphodid cycle gives a much greater specific net work (1).

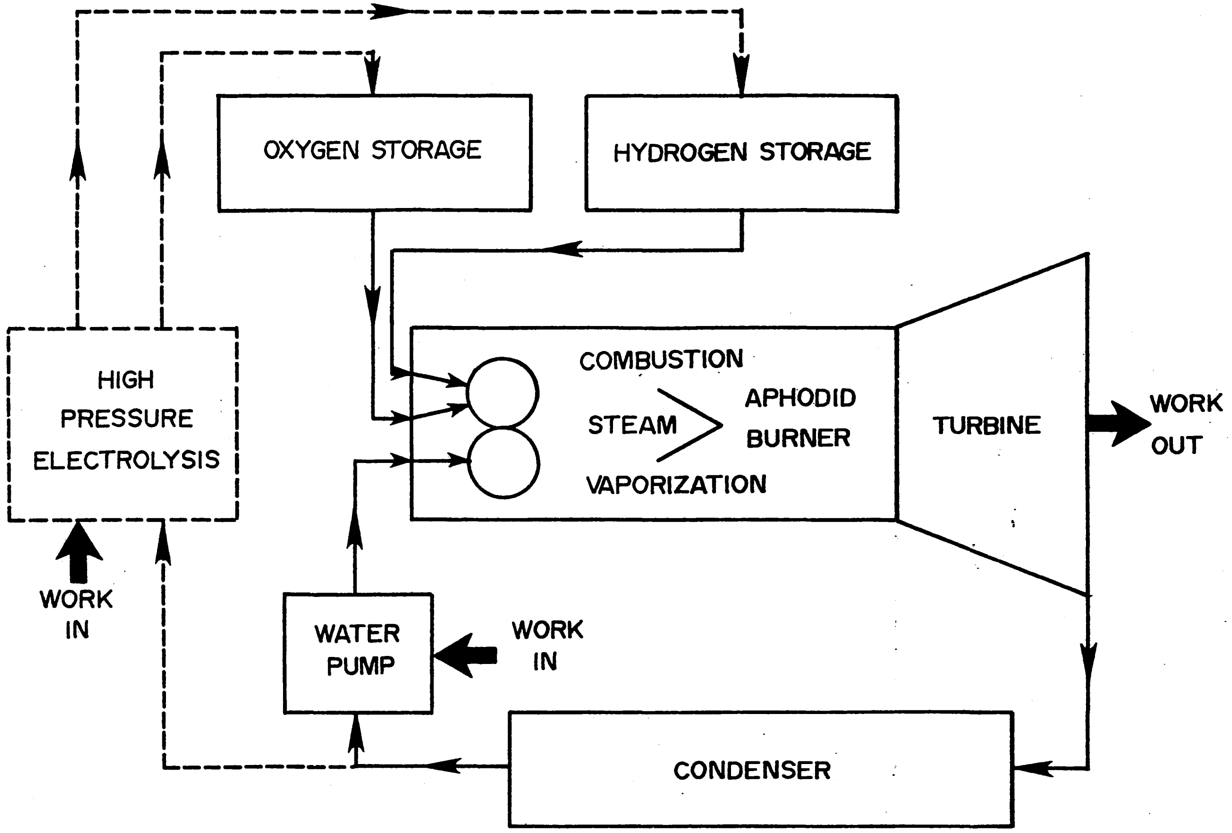


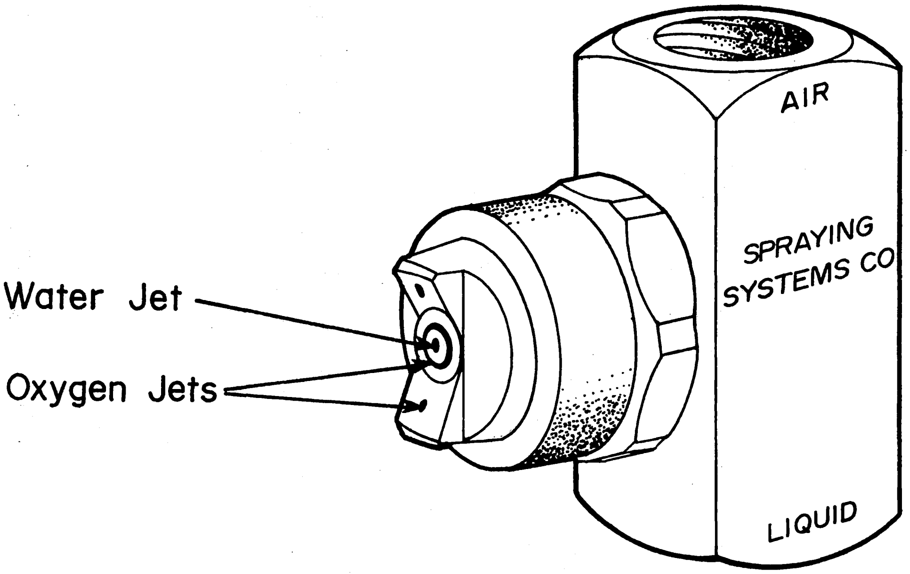
Figure 1. Aphodid Power Cycle Diagram

1) Steam has a larger specific heat than air.
2) There is only small work of compression required in the aphodid cycle.
3) Heat is rejected at a much lower temperature in the aphodid cycle.

The aphodid cycle is a non-polluting power cycle and when it is coupled with an electrolysis system, it stands as a unique energy storage cycle. One of the most promising applications of the aphodid cycle is when it is linked with an intermittant energy source. Such sources are common and include solar, wind, and tidal energy production. These sources are available on an intermittent basis depending on the weather or their natural cyclic process. During the on part of the cycle of the intermittent source excess energy production would be diverted to the production of hydrogen and oxygen; thus storing energy. At times when the intermittent source could not supply enough power the hydrogen and oxygen would be combusted; reclaiming the stored energy through the aphodid cycle. The aphodid power cycle could then help provide an efficient means of energy storage both on the local, small scale basis as well as on the central plant, large scale basis. Another prospective use of the aphodid power cycle would be to supplement present large electrical generating facilities with peaking power. During low energy demand periods hydrogen and oxygen would be produced by the high pressure electrolysis process, then, during a period of high power demand the aphodid burner would supply the needed energy to meet momentary power demand peaks. This combination could ultimately increase the overall plant efficiency by allowing the main plant to generate full time at a constant, designed high efficiency output.

There have been investigations into the feasibility of adopting rocket thruster technology to aphodid type steam generators. The NASA Lewis Research Laboratories at Cleveland, Ohio have conducted tests with such combustors, attempting to lower the high hydrogen-oxygen flame temperature by injection of liquid water downstream of the combustion region (5). Their success has been limited since the injected water droplets cannot readily be vaporized. Thus, streams of water are retained within the steam flow at the exit of the chamber. The method of water injection and the limits of water injection into the combustion chamber present a major problem for study. Analysis of this problem and the method of water injection suggested that the total surface area of the water injected is relatively small, disallowing the largest possible heat transfer to the water for vaporization. This immediately suggests that increasing the exposed surface area of the water or simply decreasing the size of the water droplets would improve vaporization. Methods of producing such droplets is termed atomization, where the most common atomizers are categorized as pneumatic and hydraulic (9). Hydraulic atomizers depend on the shearing forces of a fluid injected through a small orifice, but pneumatic atomizers add the additional shearing forces of a gas injected at high velocities with the fluid to be atomized (Figure 2). The pneumatic atomizers give the highest atomizing efficiencies, with the production of very small droplets. It was decided then to use pneumatic atomization of the water injected with the oxygen injected as the atomizing gas. This meant that water would be injected with the oxygen into the flame front.

The object of this investigation was to construct and test an aphodid combustion chamber with emphasis on studying the effect of a pneumatically atomized water spray into the precombustion region of the hydrogen-oxygen flame, hereafter termed wetted combustion. The experimental study consisted of both a qualitative description of the wetted combustion detailing the physical observations, and a quantitative analysis of an energy balance on the combustor. The statements and analogies will be supported by experimental results and hypothesis of the physical mechanism, which occurs as a result of the precombustion water injection. The combustion chamber design and construction is described in detail including an analysis of the experimental procedure noting the instrumentation usage. The results and conclusions are then presented with reference to possible important problems to be research in the future.



Pneumatic Atomizing Sprayer

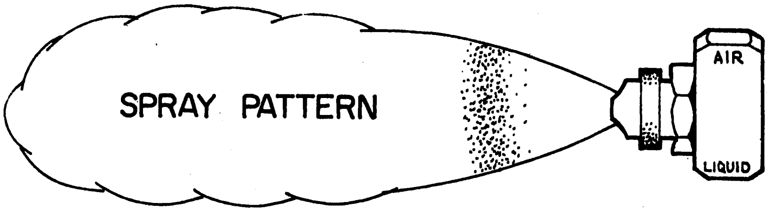


Figure 2. Flat Spray Pattern for Above Sprayer

CHAPTER II

COMMENT ON THE PERTINENT LITERATURE

In this investigation the primary objective was to construct and test an aphodid burner which utilized the precombustion injection of water directly into the flame front. This research was the first attempt to study the burner system in the aphodid power cycle at Oklahoma State University. The aphodid burner is very similar to a hydrogen gas fueled rocket thruster with the primary difference being that water is not injected into the combustion chamber in thruster applications. Technical literature is abundantly full of thruster application studies of hydrogen fueled combustors, but no published articles were found for reference where water was injected into the combustor. Although the research with combustors for thruster applications is important to this research project, much of the literature is extremely diversified into many branches of advanced study. An example is the concern of the effect of combustor length on high frequency instabilities (11). Basic combustor design is of utmost importance to aphodid burner construction, but the change brought about by water injection into the combustion region will greatly affect problems of instability as well as the complete combustor design. It is believed the references that describe the basic design criteria for combustors will be of most importance. The following references serve as good starting points for combustion literature (2 4 6 9 14), with the text by Fristrom and Westenburg (4) giving a good bibliography of combustion literature.

The only reference of significance to water injection into a combustor that was found was associated with the Walter cycle. The Walter cycle involves the catalytic conversion of hydrogen peroxide to steam and oxygen. The oxygen is then used with the combustion of diesel fuel, and water is injected into the combustion chamber reducing the high flame temperatures and cooling the chamber. The Walter cycle was under development by the German Navy at the close of the Second World War; their interest in the Walter cycle was that it was a power cycle independent of the atmosphere and therefore lent itself to submarine applications. The technology went to England after the war and in 1951 the Navy launched a submarine utilizing the Walter cycle. All references found in the search for information regarding the Walter cycle resulted in simple news release type articles with no technical description of the water injection process (see for example reference 12). The information at that time was considered confidential and was not released to public periodicals. Communication was not made with the English Navy, but they may be the only available source of information regarding the technology of the Walter power cycle.

CHAPTER III

EXPERIMENTAL PROGRAM

Apparatus

Combustion Chamber

The first aphodid burner for investigating the precombustion injection of a water spray into the hydrogen and oxygen flame front was of simple construction utilizing inexpensive, low-carbon steels. In constructing the chamber the primary objective was to build a cylindrical vessel which could withstand short, high temperature reactions at low pressures (1 to 3 Atm.). By meeting this requirement with a thick walled steel cylinder, the vessel could also withstand momentary high pressurizations. High pressurizations could possibly have occurred with delayed ignition (hard starting) or with partial quenching of the reaction and reignition.

The physical dimensions of combustion chambers are of primary importance in determining the modes of pressure instabilities present during combustion. The subject of pressure instabilities, although not considered part of the scope of this study, will be of importance in final design applications. In thruster applications it has been found that baffling in the chamber increases stability, but heat transfer to the baffling and weight considerations decrease the desirability of their addition. In this sense, a power plant combustor application is not limited by protective cooling necessary for the baffling and the weight of the baffling so important to the rocket designer. A parameter of importance to all combustor applications is that of an adequate chamber length for completed combustion, (see Reference 6, pages 378-381). Several processes of importance in the combustion reaction are fuel vaporization (liquid fuels), fuel oxidizer mixing and the actual combustion completion. In gaseous combustion applications this length is extremely short, requiring only a few inches for combustion completion (2). However, in this investigation the combustion process was altered by the added cooling of the precombustion water injection. This addition of the water prevented a prediction as to when the combustion process would be completed, and thus made necessary the arbitrary choice of a longer chamber length. The chamber length was then arbitrarily chosen to be three feet with the option of increasing the length by simple flanging at the exit of the original length. The actual chamber was constructed from six inch outside diameter drill stem which had a wall thickness of 3/8-inch. Flanging for the chamber was chosen on the basis of size and the pattern used was that of five-inch National Standard Pipe flange which has a ten-inch outside diameter and uses eight one-inch bolts for support. The flanges for both ends of the chamber were fitted over the outside of the chamber tube, butting the ends of the tube flush with the outside face of the flange (see Figure 3). Both edges were welded once around and a second bead was welded on the inside flange face to chamber edge for additional strength. The supporting stand was built in an "A" frame type construction with pipe clamps at the top of the frame.

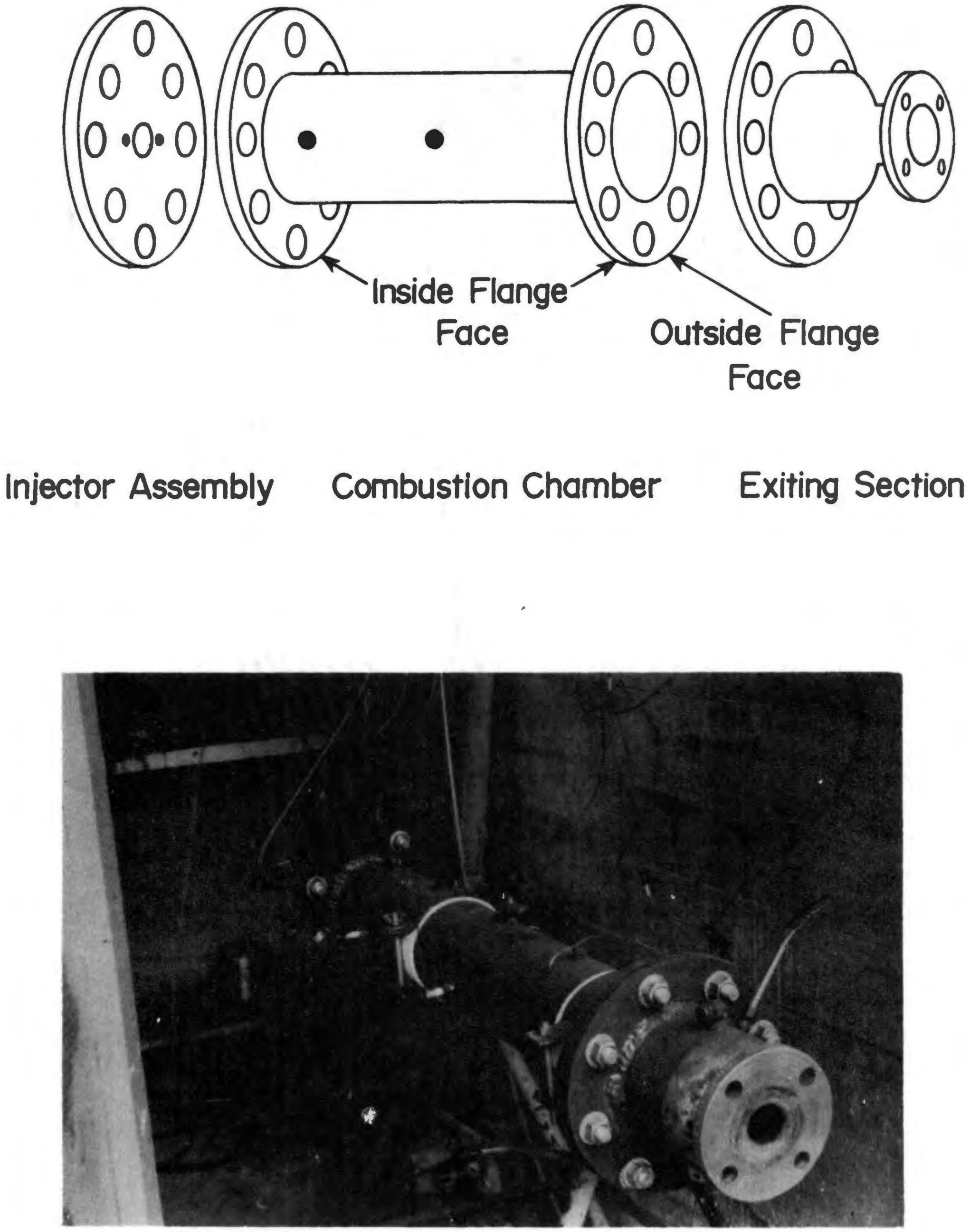
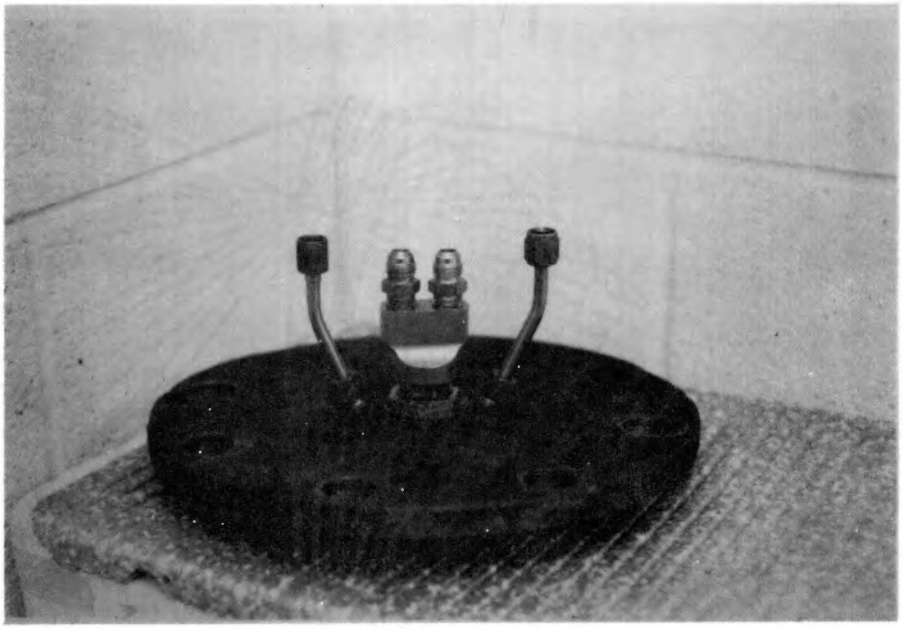


Figure 3. Aphodid Combustion Chamber

The injector assembly was made up of one half-inch steel plate mated to the chamber flange. Drilling a 1-5/32 inch hole in the center of the plate and tapping it with one-inch pipe thread allowed the adaptation of a Spraying System's pneumatic atomizer. The pneumatic atomizer, Spraying System's number (JBC-E45 A), was selected on the basis of having the largest flow capabilities for water and retaining adequate atomization features. This requirement was felt necessary at the time of purchase for the expected need of large water flow rates, but as it turned out large flow rates of water were not used as lower rates were found to give temperature control for the limited range of hydrogen injection rates.

The hydrogen injector was built from a 1/4-inch stainless steel tube with a 3/4-inch long brass insert silver soldered into the end of the tube and a 0.09 inch diameter hole drilled through its center. Two of these injector tubes were built, and holes 30° to the normal of the injector face were drilled so that the injector tubes would inject the hydrogen into the oxygen-water spray (see Figure 4). These tubes were secured to the injector assembly by 1/4-inch compression fittings which threaded into the angled hole in the plate. Adjustment of the depth of the hydrogen injector tubes was performed by doing open cold flow tests replacing the hydrogen and oxygen flows with compressed air. The goal of this procedure was to obtain a symmetric, stable spray pattern. It was found that the best spray pattern was achieved when the hydrogen tubes were placed so as to inject the hydrogen into the center of the spray pattern and at least one-inch downstream of the oxygen-water injection. It was also found that injection angles to the plate normal greater than 30° began to disturb the atomization



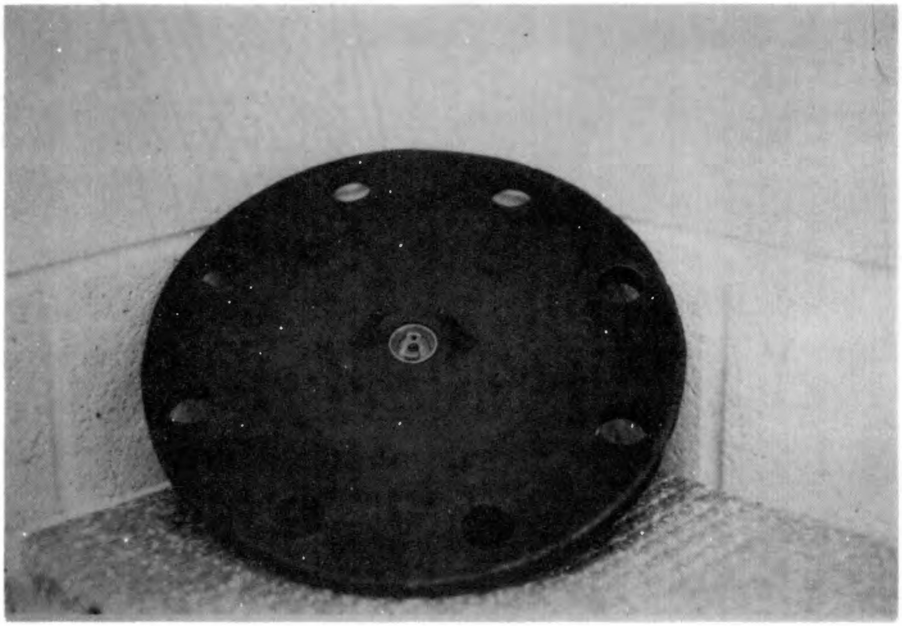


Figure 4. Injector Assembly Front and Back

process causing the frequency of formation of large droplets to increase greatly.

The exiting section was simply a converging nozzle reducing the flow cross section to a two-inch exit. The section was flanged to mate the chamber flange and also mate with a standard four bolt pattern flange (2" 150 A 182 f) at the exit. The nozzle added approximately five-inches of length to the chamber and was used as the measurement section of the chamber. It was believed that an added length of two-inch pipe could provide additional temperature measurement checks by allowing the flow to better mix and become fully developed. Therefore, 50-inches of two-inch pipe was flanged and attached to the chamber by first connecting an elbow to the chamber exit. The addition isolated measurement probes from the radiation of the flame and increased the exiting fluid mixing; it was also hoped that any escaping water droplets would impinge at least once with the hot elbow surface.

Associated Hardware

Hydrogen and oxygen gases were supplied in K-type high pressure cylinders by Sooner Gas Products. The hydrogen tank contained 191 standard cubic feet at 2000 PSIG, approximately one pound mass when full. The oxygen tank contained 240 standard cubic feet at 2200 PSIG, approximately 20 pounds mass when full. Both gas flows were pressure regulated by Air Products regulators, then transferred by 1/4-inch stainless steel lines to remotely controlled solenoid valves. The hydrogen and oxygen were piped to the injectors from the valves by high pressure flex tubing with pressure measurement taps at the exit of the valves.

Water was supplied to the chamber by a six-gallon tank which was pressurized with a regulated air supply to obtain the water flow. Water was stored in the tank inside the building along with the measurement instrumentation. The water was first pumped through a calibrated rotameter then through the protective wall via 3/8-inch copper tubing to a remotely controlled valve which was normally open to the chamber. When this valve was on, the water flow bypassed the chamber and when it is off the water was injected into the chamber and atomized by the oxygen gas injection (see Figure 5).

The ignition system incorporated an automotive coil, distributer and a 12 volt battery. The distributer was driven by a small 1/4-horsepower motor, and the high voltage discharge was distributed to four spark plugs. These plugs were located on opposite sides of the chamber with two plugs to each side, the first pair located eight inches from the injector plate and the second pair 12 inches from the first pair. The primary purpose of this placement of spark plugs was to guarantee ignition.[*] This same ignition system could be replaced with a simpler discharge circuit obtained with elementary electronics.

The probe drive which was used to sweep a thermocouple around and across the exiting section was of simple construction (see Figure 6).

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[*] It was noted in experimentation that even a single plug provided perfect ignition. In the future it should be necessary only to use a single ignitor at the injector plate.

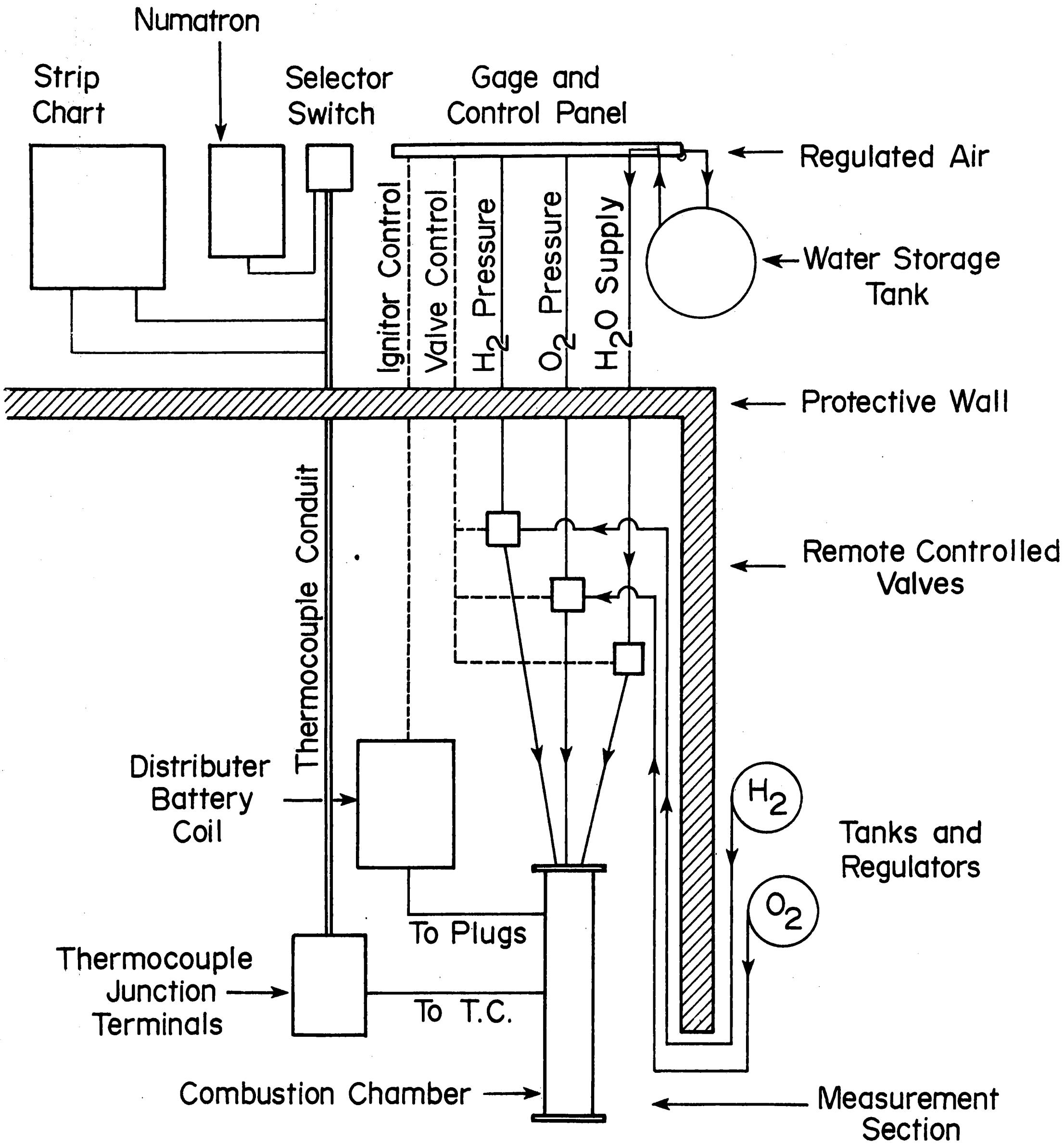

Figure 5. Experimental System Diagram

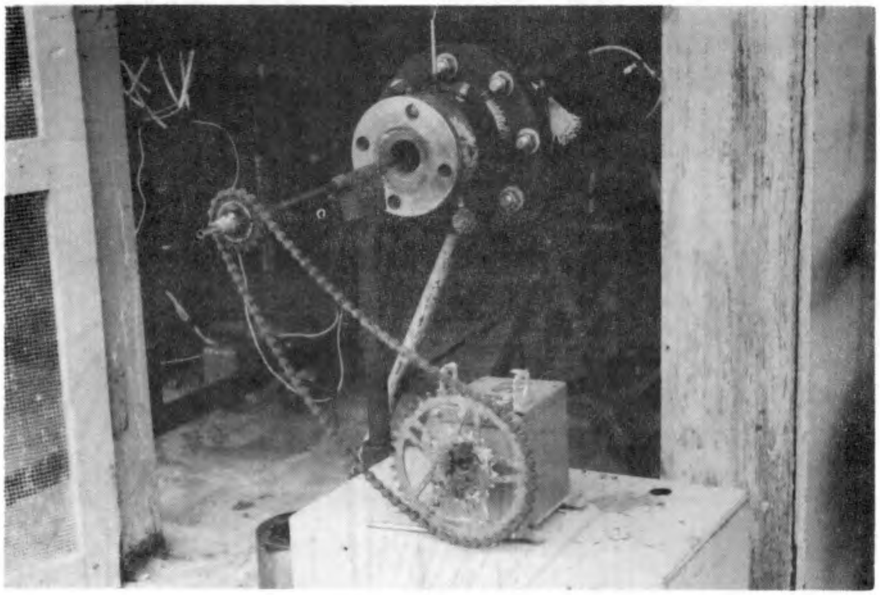

Figure 7. Radial Traverse Probe Drive

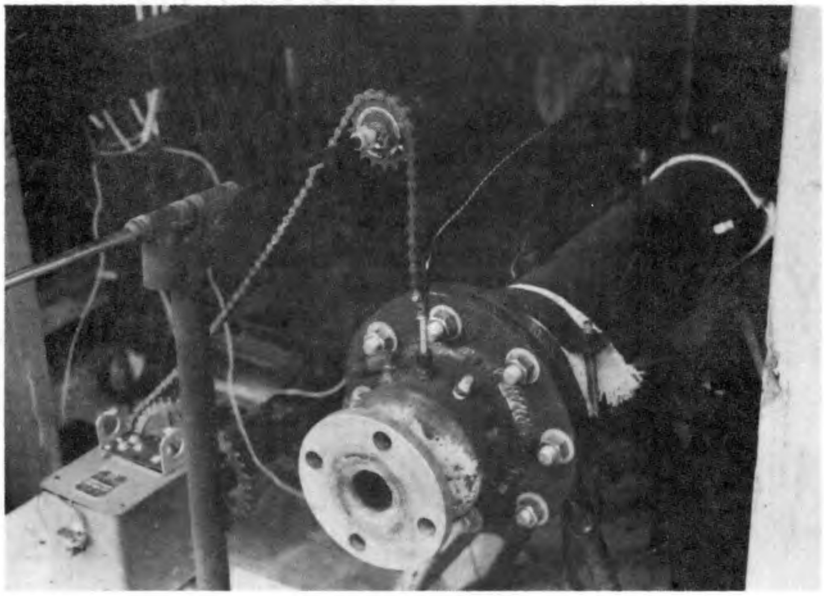

Figure 6. Angular Traverse Probe Drive

A modutrol motor with slow rotation (1/2 cycle/minute) was mounted to a small stand with a sprocket (40 teeth) attached to the motor's shaft. A smaller sprocket (16 teeth) was attached to a 3/8-inch diameter stainless steel tube which served as the probe. This tube was supported in a tee shaped adjustable support and was parallel with the motors shaft. The motor and probe tube were connected by a chain, which caused the probe to rotate 1.25 cycle/minute with the rotation direction switched after each cycle. The thermocouple wire was inserted through the tube with the junction supported at the end of the tube by a ceramic holder. When the probe drive was used to traverse across the flow, the chain was broken and one end connected to a 1/4-inch stainless steel tube inserted into and perpendicular to the flow. When the motor was on, it pulled the probe out of the chamber crossing the flow (see Figure 7).

Instrumentation

To describe the operation of the chamber and determine the effect of precombustion water injection, the temperature of the exiting steam had to be monitored. Iron-Constantan and Chromel-Alumel thermocouples are the standard thermocouples used for temperature measurements of 500 to 2000°F, both types of thermocouples were used in this study. To monitor these thermocouples two instruments were used: for a continuous record of temperature a two channel strip chart recorder (Leeds and Northrup Speedomax XL) was used, and for all other measurements during the same run a digital readout potentiometer (Leeds and Northrup model 914 Numatron) was used. The Numatron was connected to a rotary switch which could scan up to 12 thermocouples while the strip chart monitored only two thermocouples.

The water flow rate was monitored by a standard rotameter which was calibrated using timed bucket collection. Oxygen and hydrogen flow rates were determined after each trial was completed by calculating the mass of hydrogen and oxygen consumed and the time elapsed during the run. The pressure and temperature of the hydrogen and oxygen was known before and after each trial, refer to Appendix C for the details of the calculation. Knowing the temperature of the steam and the mass flow rates of water, hydrogen and oxygen; then an energy balance on the chamber could be completed. Other measurements which were noted include the deviation of the chamber pressure from atmospheric pressure and the injector pressures of the hydrogen and oxygen.

Procedure

The procedure in this investigation was experimentally simple and straight forward. In order to determine the exiting conditions many temperature measurements were made across the exit of the chamber. These temperatures and temperature measurements further downstream in the two-inch extension pipe yielded information, which was analyzed and presented as a description of the precombustion water injection into the aphodid burner.

Throughout the entire study a fixed experimental format was followed, the only differences in experimental trials being the relocation of the thermocouple probe positions. The procedure for each experiment was the same, and Table I is given as the general format. Usual procedure following step 16 in Table I was to continually note

TABLE I

GENERAL FORMAT FOR EXPERIMENTAL PROCEDURE

---

1. Hydrogen and oxygen tanks - off.
2. Numatron and strip chart recorder - on.
3. Air compressor - on.
4. Solenoid valve's power supply - on.
5. Solenoid valves - off.
6. Check and fill water tanks.
7. Ignitors - on. Observe the ignition system noting whether operational.
8. Ignitors - off. Make all final checks of combustion chamber making sure that all probes are in place.
9. Cell fan and warning lights - on.
10. Start water flow, bypassing the chamber. The water flow rate should be approximately 0.2 gallons/minute.
11. Turn the hydrogen and oxygen tanks on then adjust the regulators to the desired pressure. The hydrogen regulator was adjusted between 50 and 100 PSIG. This yielded injection pressures of 15 to 40 PSIG. The oxygen regulator was adjusted between 70 and 110 PSIG. This gave pressures of 25 to 50 PSIG at the injector.
12. Record the pressure and temperature of the tanks.
13. Turn ignitors on, start audio recorder and strip chart drive.
14. Turn on the hydrogen and oxygen valves simultaneously starting the stop watch. Ignition should be noted by the sound of the reaction.
15. Immediately switch ignitors off and route the water to the chamber. The water flow rate should be about 0.10 gallons/minute.

TABLE I (Continued)

16. Allow the chamber and system to operate at elevated temperatures while recording the hydrogen and oxygen injector pressures. Increase the water flow rate to the appropriate level.

the hydrogen and oxygen injector pressures and the water flow rate while recording these points verbally on a tape recorder. Temperature scans of all thermocouples were recorded where the first reading was marked for time reference by lifting the strip chart pens momentarily. This procedure was continued throughout the experiment. If the probe drive was started notation was also made as to the time of starting, both on the strip chart and the audio tape recorder. Other verbal notation as to observations of the chamber pressure and sound of the combustion reaction were made on tape. When quenching was reached or shutdown of an experiment was desired the hydrogen and oxygen valves were manually switched off simultaneously. The strip chart drive and water injection were switched off and further temperature scans made. The hydrogen and oxygen tanks were closed, recording the temperature and pressure of the tanks. Immediately following an experiment all of the taped information and other recordings were transferred to the lab notebook.

The experimental study was divided into three general areas which are detailed in the next chapter. The results of these experiments are presented with discussion interjected in each section.

CHAPTER IV

EXPERIMENTAL RESULTS

The temperature, pressure and the flow rate of the steam exiting the chamber were the dependent variables of this study with the mass flow rates of hydrogen, oxygen and water the independent variables. The primary objective of the experimental program was to measure the above parameters, establishing their correlation and explain the associated phenomenon of wetted combustion. It was first necessary to determine qualitatively the extent to which water could be injected prior to combustion of the hydrogen and oxygen. The initial investigation for this proof-of-principle was simply to test the apparatus and add water in increasing amounts. From simple observations reasonable amounts of water could be injected until final quenching occurred. Because the exiting conditions from these runs were unknown, bare thermocouples were installed in the flow stream and several runs were made at atmospheric and at two atmospheres of pressure. The results showed no significant change in the exiting temperature for the small increase in pressure, with temperatures maintained at about 1500°F. These increased pressure measurements confirmed that the injection rates of hydrogen, oxygen and water were very dependent on the chamber pressure.

To proceed with measurements detailing the exiting steam properties two secondary objectives were formulated. First a temperature profile of the exit section was necessary to describe the extent to which water droplets remain in the steam flow. Secondly the input properties of the reactants and the exiting properties of the steam were needed to quantitatively describe the degree of combustion completion and water vaporization.

In the ensuing experiments several probe designs and placements in the chamber were attempted. These tests cannot be interpreted for absolute accuracy but serve as valid descriptions of the exiting steam flow. The first series of tests were attempts to discover the difference in shielded and unshielded thermocouples at the centerline of the flow at the exit of the chamber. The probe used in this study was constructed so that the entire probe was immersed in the flow to reduce stem conduction losses and facilitate mobility in measurement location (see Figure 14c, Appendix D). With water retained in the flow as droplets the unshielded thermocouple junction would record a lower temperature with droplets impinging on the open junction. It was found that the unshielded thermocouple recorded a higher temperature, and in most cases approximately 40°F difference was noticed. The open thermocouple having the higher temperature might suggest a stagnation effect from the velocity of the flow, however, the average velocity was calculated to be 24 ft/sec which gives a stagnation increase in temperature of only 0.02°F.* Assuming

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*The velocity was calculated by assuming mass conservation and that the steam was at a density for a temperature of 1500°F, ($v=m/A$). The increase of temperature was then calculated by the equation:

$$(T = v^2/2 \times c_p).$$

both thermocouples retained their calibration to these high temperatures then the only possible difference should be the radiation of the flame seen by the open thermocouple since both thermocouples view the colder chamber walls. With only a three percent difference in temperature measurements between the unshielded and shielded thermocouples, it was decided that the unshielded thermocouple probe was adequate for acquiring temperature maps of the exit section. These temperature plots were to yield more information about the exiting steam quality.

Using an unshielded thermocouple design a probe was constructed to traverse the steam flow cross section, (see Figure 14b, Appendix D). The probe was inserted into the chamber so that it could move a thermocouple around the chamber axis while protecting the thermocouple junction lead wires from the high steam temperatures. The thermocouple junction was to traverse the exit at a two-inch radius from the center of the chamber which would provide information about the water content of the outer regions of the flow. Again if water droplets were retained within the flow the small thermocouple junction would record the impinging droplets and with large droplets or streams of liquid water the thermocouple would record temperatures close to 212°F.

Figure 8b shows the results of a single cycle around the chamber cross section; the plot is the temperature difference from the temperature at the bottom of the chamber versus the probe location in the chamber. The results of these trials show smooth and continuous differences in the temperature as a function of increasing time and as a function of the probe's location in the chamber, however, definite

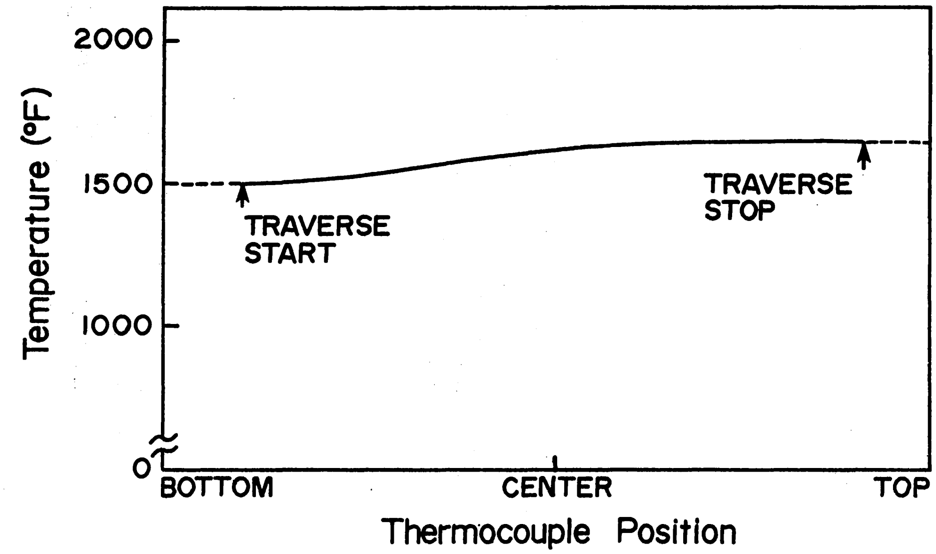

Figure 8a. Thermocouple Traverse Across the Chamber Diameter

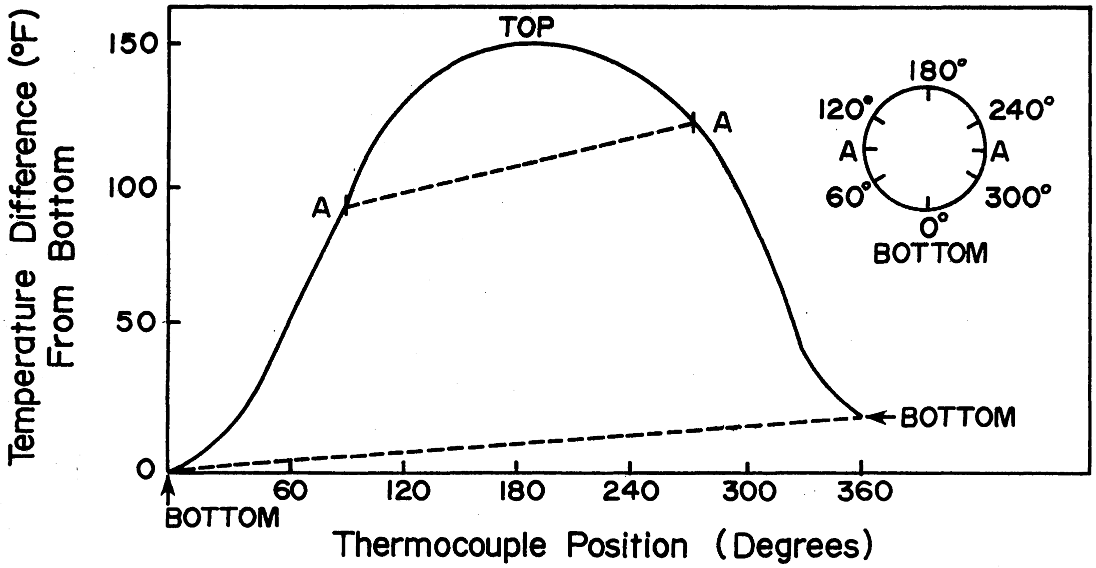

Figure 8b. Thermocouple Traverse Around the Chamber
(Radius = 2 inch)

temperature profiles were found to exist across the chamber's exiting section. Figure 8b shows the increase in the whole systems temperature with increasing time, where less heat is being lost to the chamber walls as the chamber increases in temperature. From the top to the bottom this plot shows a temperature difference of 135°F but there exists almost 100°F difference from the bottom to the center of the chamber and only 35°F difference across the top half of the chamber. In later experimentation radial traverses were made in the exit section of the chamber by pulling a shielded thermocouple probe across the diameter of the flow. Again the results illustrated that there was a larger temperature gradient across the bottom half of the chamber (see Figure 8a). Although these two measurements were made along different paths both suggest the same result, that the profile was reasonably flat over the top section and the bottom half had a definite temperature gradient from the center of the flow to the bottom.

A comparison of the Grashof number to the Reynolds number squared indicated that free convection was probably occurring, where cooler gas from the walls was circulating to the bottom of the chamber while hotter currents were moving to the top. With different drop sizes initially in the spray the larger drops that escape early vaporization may move to the lower region of the chamber where further vaporization could also cause a temperature gradient across the flow. The temperature profile, however, could also be a function of the injector orientation where a slight deflection of the injector axis to the chamber axis could cause the higher temperatures on the top.

To describe the combustion-water injection process, several water injection flow rates were investigated for different hydrogen injection rates. An energy balance was set up for each experiment which yielded information about the precombustion water injection into the flame front. This was done by noting changes in the enthalpy of the steam exiting the chamber for different water injection rates. To determine the total enthalpy at the exit for each trial the temperature profile across the section was needed. If the temperature profile was to be determined for each run, then only a few trials would be possible due to the time necessary for a probe traverse. By mixing the flow and reducing the flow cross section a flat temperature profile was produced. The measurements for the energy balance were then taken at the exit of a two-inch elbow by a shielded thermocouple probe (see Figure 15, Appendix D). Table II lists the experimental and calculated data points including the steam temperature at the exit of the extension pipe.

To facilitate an analysis of each experiment the mass ratio of the steam formed by vaporization of the water injected to the steam formed by the hydrogen combustion, (dilution factor) was plotted against the temperature of the exiting steam and also against the energy release efficiency (ERE). The dilution factor is significant because it is proportional to the amount of energy extracted from the combusted gases to vaporize the water per unit of chamical energy input. The ERE is defined here as the thermal energy of the exiting steam divided by the chemical energy of combustion, and is representative of the degree of combustion completion. The results of the experiments are presented in two plots, the first is a plot of the exiting steam temperature versus the dilution factor and shows the

TABLE II

EXPERIMENTAL AND CALCULATED DATA POINTS

$\dot{M}_{oxygen}$ lb_m/min	$\dot{M}_{hydrogen}$ lb_m/min	$\dot{M}_{water}$ lb_m/min	EXTENSION EXIT TEMP °F	STEAM BULK TEMP °F	STEAM ENTHALPY Btu/lb_m	INPUT ENERGY KW	STEAM OUT ENERGY KW	ENERGY LOST KW	DILUTION FACTOR	ENERGY RELEASE EFF. %
1.08	0.125	2.544	1342	1550	1832	134	118	2.6	2.277	90
1.12	0.120	1.752	1318	1395	1745	129	87	1.0	1.634	68
0.87	0.089	1.752	1187	1550	1832	95	82	2.5	2.203	89
1.15	0.107	1.835	1304	1550	1832	114	90	3.4	1.920	82
1.15	0.107	1.960	1304	1504	1806	114	93	3.4	2.050	84
1.03	0.124	2.544	--	1537	1824	132	117	2.6	2.290	90
0.93	0.109	2.336	1230	1407	1752	117	102	3.4	2.393	90
0.93	0.109	2.544	1230	1377	1735	117	107	3.4	2.612	95
0.93	0.109	2.962	1187	1286	1686	117	116	3.4	3.041	102
0.93	0.109	1.159	1471	1710	1924	117	72	4.8	1.190	66
1.20	0.079	1.476	1180	1361	1726	84	66	2.9	2.090	82
1.20	0.079	1.835	1124	1266	1675	84	75	2.9	2.600	92
0.74	0.083	1.476	1182	1382	1738	89	68	2.9	1.990	79
0.74	0.083	1.902	1162	1320	1704	89	79	2.9	2.560	92
0.74	0.080	1.627	1119	1330	1710	86	70	2.9	2.287	85
0.74	0.080	1.159	1223	1460	1781	86	59	2.9	1.629	71
0.74	0.080	1.835	1167	1287	1687	86	75	2.9	2.580	91

decreasing bulk temperature for increasing dilution factors (see Figure 9). This plot shows three curves for the three different hydrogen injection rates. Ideally the dilution factor should bring the different hydrogen injection rate lines into one line, but the separation of these temperature plots indicates that for increased hydrogen injection rates, greater than expected water injection rates are necessary to reduce the steam temperature. It is possible that for increased water injection rates some of the water may not be vaporizing making necessary larger dilution factors for greater inputs of chemical energy to maintain the same steam temperature. However, with increasing hydrogen injection rates the combustion efficiencies may improve due to better hydrogen and oxygen mixing at the injector. These two suggested phenomena are very important to this study and are discussed with the results of the second plot. The second plot shows the increase in the ERE for increasing dilution factors, and implies that the greater the heat transfer from the combustion region by the water spray the more efficient the combustion reaction. However, if incomplete vaporization of the water were occurring, then by increasing the water injection rate the assumption, that all of the injected water exits as superheated steam would be false. The temperature of the steam exiting the 50-inch long two-inch extension pipe was measured for each experimental run, and the exiting energys corresponding to these temperatures were calculated and then divided by the input chemical energy of combustion, which yields an ERE not accounting for the heat loss from the pipe. Plotting these energy ratios with the ERE on Figure 10, the two plots can then be compared.

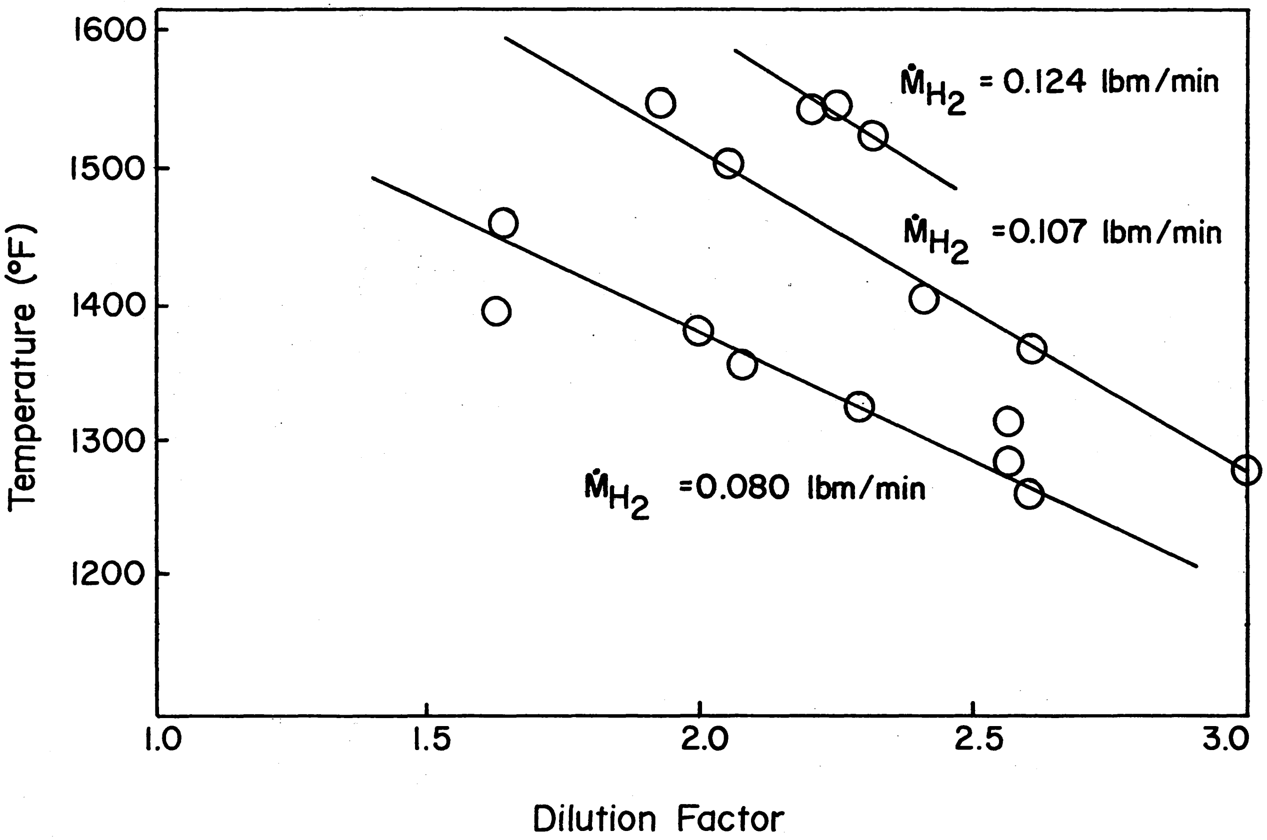

Figure 9. Steam Bulk Temperature at the Exit as a Function of Dilution Factor

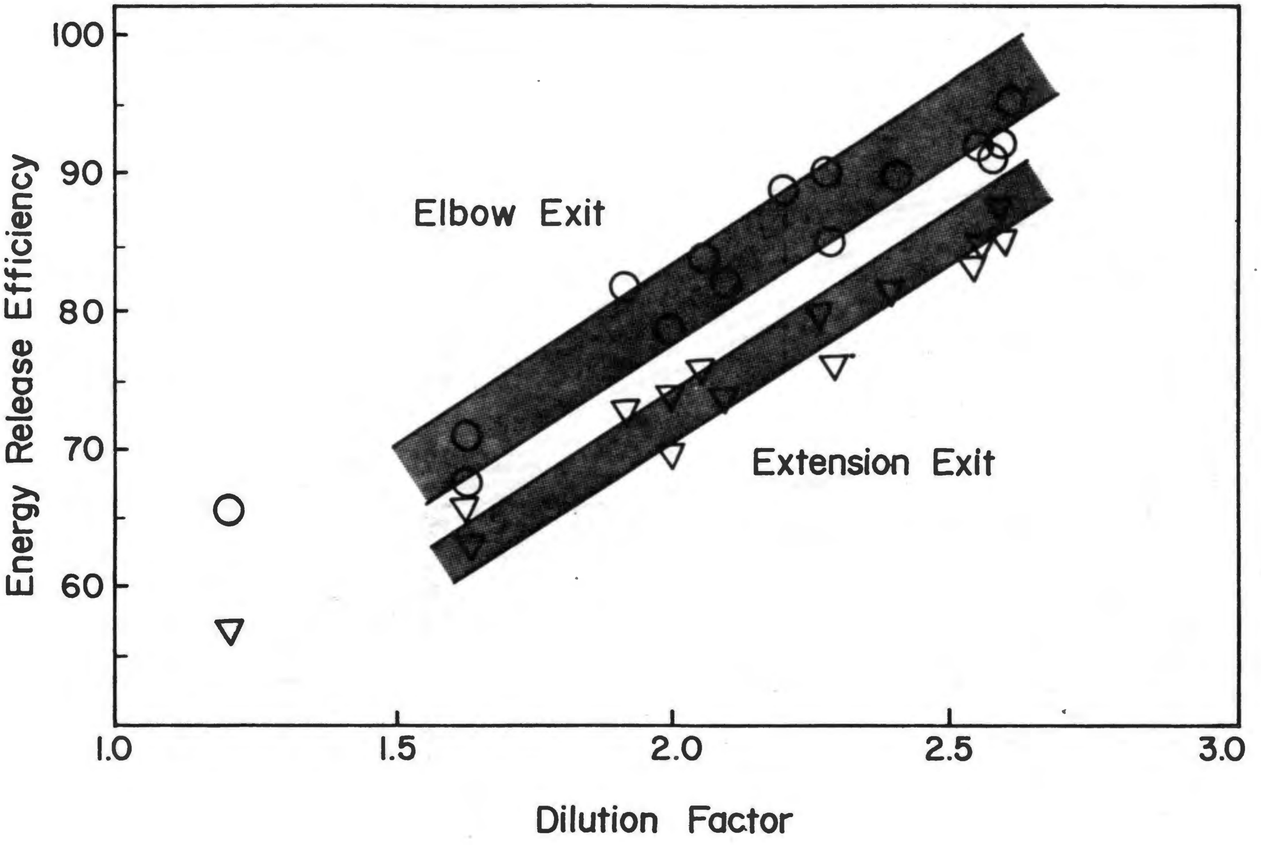

Figure 10. Energy Release Efficiency for the Aphodid Burner as a Function of Dilution Factor

Examining the two plots shows them to be parallel which means that the energy difference between the two temperature probes was constant for increasing dilution factors.

If one suspects incomplete vaporization at the exit of the chamber and assumes that vaporization was occurring in the extension, then for increased water injection rates it should be expected that further vaporization would occur and the two curves of Figure 10 would in fact diverge. It is believed that no liquid exited the extension since no liquid was observed to impinge on targets beyond the exit and bare thermocouples in the flow did not record random droplet inpingement. The average energy difference between the exit of the chamber and the exit of the extension was calculated to be 4.65 kilowatts, and the heat loss from the extension pipe was approximated to be 2.5 kilowatts. This leaves approximately two kilowatts unaccounted for and is less than two percent of the input energy.

The constant increase in ERE for increasing dilution factors, (see Figure 10) is curious in that 100% efficiencies should be approached asymptotically. This phenomenon does not show up in the data points that were determined, but at dilution factors greater than 2.7 quenching of the combustion reaction usually was observed.* Therefore, establishment of this curve in the high efficiency region was not possible. One point was determined at a dilution factor of 3.05, however, the reaction was very unstable and was not considered of value.

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*Quenching of the reaction occurred in several experiments but not at one dilution factor. This is probably due to the different heat transfer rates from the chamber.

In the following Chapter conclusions are stated, with a summary of the advantages of precombustion water injection. An explanation of the physical mechanism which occurs from the precombustion water injection is then presented.

CHAPTER V

CONCLUSIONS AND PROPOSED MECHANISM

The first segment of this investigation was a simple step deemed necessary to actually determine the feasibility of the proposed study of precombustion injection of water into the hydrogen-oxygen flame front. With the attainment of reasonable temperatures (1200 to 1500°F) at the exit of the chamber via crude temperature measurements it was concluded that an experimental investigation should be set up to determine the exit conditions more precisely.

During early phases of experimentation no significant changes in the temperature were noticed as the chamber pressure was varied from one to two atmospheres. Since the upper range of chamber pressures was limited by the gas and water supply system, complication of the controls system did not seem justifiable; and it was decided then that all remaining experiments were to be conducted at atmospheric pressure.

In the next set of experiments the temperature profile at the exit of the chamber was determined, attempting to reveal the extent of water vaporization at the chamber exit. From the temperature profiles no regions at the exit were discovered where liquid water remained in the flow, and visual observation of the exiting flow impinging on targets beyond the exit yielded the same results. From these tests it was believed that the exiting steam was vapor, but also the steam was not at a uniform temperature across the flow section. Therefore, it was concluded that better mixing of the steam was necessary. In continuing investigations it will be necessary to determine the equilibrium steam temperature length and investigate flow mixing schemes such as flow turbulators.

The final phase of experimentation was made to determine the effect of the water injection upon the combustion reaction. The results of an energy balance indicated that the energy release efficiencies increased with increasing dilution factors. Fortunately, as the lower desired steam exit temperatures were approached, the efficiency of the combustion process was increased. However, at high efficiency operation the combustion instability was increased, and for dilution factors in the range of 2.7 to 3.0 quenching of the reaction was noted. At dilution factors less than 2.5 stable operation of the system gave efficiencies of 90 to 70 percent with exit temperatures of 1300 to 1700°F. Dilution factors less than 1.0 allowed the temperature of the system to become very high and destruction of the system was feared, therefore, measurements were not made for steam exit temperatures above 1700°F. Assuming that the efficiencies of approximately 70% recorded at low dilution factors were typical of the dry combustion efficiency for the injection system employed, the increase in efficiency by precombustion water injection for the system poses a major advantage over any water injection system downstream of combustion.

Since the high temperatures of adiabatic combustion were never attained, (in fact temperatures less than 2000°F were maintained) the combustion chamber design is simplified. The results obtained in this investigation illustrate the advantages of the precombustion injection of a finely atomized water spray into an aphodid burner; and in conclusion Table III gives a list of the proposed advantages of the precombustion water injection.

TABLE III

PROPOSED ADVANTAGES OF PNEUMATIC ATOMIZATION
OF PRECOMBUSTION WATER INJECTION INTO
THE APHODID COMBUSTION CHAMBER

1. It yields a larger surface area of water, increasing vaporization rates over simple hydraulic atomizers.
2. It disperses the injected water in a continuous pattern across the chamber.
3. It produces a flow which has initially a radial component from the centerline of the chamber. Thus any escaping fluid droplets tend to impinge against the hot chamber wall, both cooling the wall and vaporizing the droplets.
4. It delays the combustion, allowing more complete mixing of the hydrogen and oxygen and therefore increases combustion efficiency.
5. By holding the maximum combustion temperature below 2400°F dissociation of the products is minimized.
6. The point of injection allows the longest path for vaporization meaning that shorter overall systems will be required for complete vaporization of the water.

Several results and characterizations of the results have been presented. Below is a proposed physical mechanism to describe the precombustion water injection into the hydrogen-oxygen flame front. Several possibilities may exist which explain the increased ERE's, and three are presented; however, one or all may take part in the reaction. These possibilities are:

1. Improved kinetics of reaction for increasing dilution factors
    a. Increased reaction surface
    b. Reaction chains altered
2. Improved mixing of reactants
    a. Delay of the combustion reaction
    b. Increased turbulence with increased collisions
3. Decreased product dissociation

The completed exothermic combination of hydrogen and oxygen is achieved by a mesh of reaction chains. There exists different models as to which simple reactions actually participate, and an example is given below (4).

$$H + O_2 = OH + O$$

$$O + H_2 = OH + O$$

$$H + H_2O = H_2 + OH$$

$$H_2 + O_2 = OH + OH$$

$$H_2 + O_2 = H_2O + O$$

$$O + H_2O = OH + OH$$

Surfaces have been shown to have a pronounced effect on some of the reaction chain radicals participating in these reaction chains (10). With important radicals being tied up by or released by changing the surface area, the combustion may be pushed to improved reaction completion. Therefore, by adding the water spray to the reaction region and increasing the available surface area, the combustion of the hydrogen and oxygen may be enhanced.

Kinetics is important to combustion, but research work with rocket combustors has been concentrated on the injector assembly, attempting to improve mixing of the combustion reactants. By maximizing the mixing of the reactants prior to the combustion region, the escaping reactants can be reduced. It has been shown by investigators that combustion effects impede the mixing rates of hydrogen and oxygen (2). These tests compared radical sampling in cold and hot flows, where it was shown that the mixing rates in the cold flows were impeded by the combustion reaction. Other investigators have noted the quenching of a combustion flame front by fine dust suspensions (3). These investigators propose that the quenching by the dust is due to heat extraction from the flame, lowering the reaction temperature below some critical value. Combustion is perpetuated by the heat conduction back into the reactants, raising their temperature. If this heat transfer is altered by the preinjected water then the reaction is not initiated until an adequate combustion temperature is reached, therefore, delaying combustion. Mixing of the reactants may also be enhanced by the increased turbulence caused by collisions of the gas molecules with the heavier water droplets. It was noted in this investigation that the combustion region moved downstream of the injector for increased water injection into the chamber. Therefore, the precombustion water injection may, by delaying combustion and increasing turbulence allow a more complete mixing of the hydrogen and oxygen, increasing the combustion efficiency.

The third suggested reason for increased combustion efficiencies results from the lower product temperatures achieved with the water injection. That is dissociation of the product steam becomes negligible for temperatures reduced below 2400°F (7). Since temperatures are reduced within this region, dissociation in the products should be minimized.

These mechanisms may all be present but it is believed that the delayed combustion mechanism is primarily responsible for the precombustion water injection's effect on the combustion process and the increase in the energy release efficiency.

CHAPTER VI

RECOMMENDATION FOR FUTURE RESEARCH

Adding water prior to combustion causes many questions to arise. These questions, coupled with system improvement and optimization studies, could yield many research topics. It is believed that of primary interest is the description of the kinetics of reaction of the hydrogen-oxygen water combustion process. Studies might be directed at visual observations of the flame adding combustion tracers. That is, how does the water delay the reaction and how much does the water delay the reaction. To complete such a basic research study advanced equipment capable of sampling flow constituents would be necessary. This instrumentation is common in rocket testing facilities, and mutual testing at such facilities would be advisable.

If steam temperatures less than 1300°F are necessary for input into a turbine, further cooling of the steam will be necessary, either by direct water injection or by indirect contact heat exchangers. Tests then would be necessary to determine the best methods for cooling the steam. There are present desuperheaters available on the market but most require excessive lengths of piping downstream to attain equilibrium temperature. It, therefore, might be more advantageous to remove heat by indirect contact heat exchangers using the extracted heat to increase the temperature of the precombustion injected water facilitating increased amounts of precombustion water injection. With these and other options a feasibility study would involve optimization routines which might point to a proper balancing of steam temperature reduction modes.

The area of atomization and the degree of atomization of the water is important to the heat transfer in the immediate region of combustion. With slightly decreased atomization efficiencies (larger droplets) less heat would be removed from the combustion region leaving droplets in the flow for later vaporization. In the proposed mechanism, there exists a critical maximum heat transfer from the combustion region to maintain stable combustion, with larger droplets initially in the flow larger water rates can be injected without quenching combustion. With larger injection rates more water escapes vaporization in the combustion region and is left in the flow to vaporize downstream of the reaction region. This delay of vaporization allows stable combustion and results in a lower steam exit temperature.

The present investigation should be continued so as to improve knowledge about the exiting conditions. The steam should be condensed and analyzed for hydrogen and oxygen or other radicals possibly formed in the combustion reaction. By condensing the steam the amount of energy extracted will then give a check of the actual steam properties and the total enthalpy. Improved hydrogen and oxygen mass flow rate monitoring is necessary for exact knowledge of energy input into the combustion chamber and for further studies a means whereby the temperature probe can be calibrated in a high temperature gas flow would increase temperature measurement accuracy. An extension of this investigation would be to increase the combustion chamber pressure and develop a control system for maintaining pressure of the system. The hydrogen, oxygen, and water injection rates are very dependent on chamber pressure, and it is believed that much work towards the development of a controls system for a stable balance between mass injection into the chamber and the chamber pressure will be necessary.

Finally, with an improved combustion chamber and measurement system further testing should yield a more detailed analysis of the aphodid power cycle and its applicability to the energy supply system.

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APPENDIX A

THE PROCEDURE FOR ENERGY RELEASE EFFICIENCY CALCULATION

The basic data points coming from an experiment include:

The bulk temperature of the steam at the exit
Pressure and temperature of H_2 and O_2 tanks
Time of experimental run
Water injection rate and
Selected chamber temperatures.

To obtain an efficiency of the combustion-water injection process, the chemical energy of the injected flow was compared to the exiting thermal energy of the steam. The combustion of the injected hydrogen was the total energy available for heat production. The heat of formation of liquid water from the stoichiometric combustion of hydrogen with oxygen was the energy content of the hydrogen. Heat of formation of liquid water at standard conditions is -122,791 Btu/lb_{mole}, for every lb_{mole} of water produced there is a lb_{mole} of hydrogen consumed so hydrogen has an energy content of 122,971 Btu/lb_{mole} or 60,997.0 Btu/lb_m. By knowing the injection mass rate of hydrigen the energy input rate was known. The mass flow rate of hydrogen is found by determining the total hydrogen consumed and dividing then by the elapsed time of the trial, refer to Appendix C. The exiting energy rate of the steam was found from the Bulk steam temperature at the exit of the elbow and the mass flow rate of the steam. The steam mass flow rate was calculated by adding the mass injection rate of the water to the mass rate of steam formed by the hydrogen combustion. This assumed that all of the water injected was vaporized and superheated to the exiting temperature and no mass was accumulated in the chamber. Multiplying the steam mass rate exiting by the enthalpy of the steam, the energy rate leaving the chamber was then calculated. The energy rate loss by the chamber walls was calculated by the method of Appendix B. The energy release efficiency was then found from the equation.

$$\mathrm{ERE} = ((\dot{m} \times \bar{h})_{\mathrm{steam}} + \dot{Q}_{\mathrm{loss}})/(\dot{m} \times 60{,}997\ \mathrm{Btu/lb_m})_{H_2})$$

The following is a sample calculation from experiment number 15, June 7.

Experimental data points:

Exit temperature - 1266°F
Water injection rate - 0.22 gal/min
Hydrogen injection rate - 0.079 $\mathrm{lb_m}$/min
Chamber temperatures
Point A - 950°F
Point B - 714°F
Point C - 860°F

To calculate the mass flow of steam exiting the chamber, the water injection rate was added to the water formation rate from the hydrogen combustion, this assumed mass conservation with no mass storage in the system.

$$\text{Water injection rate} = (0.22\ \mathrm{gal/min})_{H_2O} \times (8.3428\ \mathrm{lb_m/gal})_{H_2O}$$

$$\dot{m} = 1.835\ \mathrm{lb_m/min}$$

$$\text{Water formation rate} = (0.079\ \mathrm{lb_m/min})_{H_2} \times 8.936\ \frac{\mathrm{lb_m}H_2}{\mathrm{lb_m}H_2})$$

$$\dot{m} = 0.706\ \mathrm{lb_m/min}$$

The total steam exiting = 2.54 lb_m/min

The energy rate of the steam exiting was then found from the total enthalpy of the steam.

From the steam tables h = 1675 Btu/lb_m

so the total enthalpy rate is

$\dot{H}$ = 4256 Btu/min or 74.8 kilowatts.

Therefore E_{out} = <u>74.8 kilowatts</u>

To find the input energy rate, multiply the energy content of hydrogen by the hydrogen mass injection rate.

$\dot{m}_{H_2}$ x 60,997 Btu/lb_m = 4850.2 Btu/min

or E_{in} = <u>84.7 kilowatts</u>

To find the energy rate loss from the chamber reference was made to Appendix B. From the three chamber temperatures (A,B,C) associated heat losses were found from Figure 12, Appendix B.

Section 1 - 0.074 kilowatts
Section 2 - 1.60 kilowatts
Section 3 - 1.00 kilowatts
Section 4 - 0.20 kilowatts

The total heat loss rate was then the sum of the above heat losses.

E_{loss} = <u>2.87 kilowatts</u>

The energy release efficiency was then calculated.

ERE = (74.8 + 2.87)/84.7

ERE = <u>91.7%</u>

The dilution factor for this calculation was found by dividing the rate of steam formed from water injection by the rate of steam formed from the combustion of hydrogen.

Dilution factor = (1.835 lb_m/min)/(0.706 lb_m/min)

D_{factor} = <u>2.59</u>

APPENDIX B

HEAT LOSS CALCULATIONS

It was found that temperatures on the outside surface of the chamber were constant around any cross section. However, the temperature varied down the chamber approximately as given by curve 1, Figure 11. To generalize the heat loss calculation and minimize the number of data points for the heat loss calculation, four sections with different constant temperatures were assumed (see curve 2, Figure 11). The temperature at section one was always assumed to be 300°F. The temperature for sections 2, 3, and 4 were measured at the assigned locations of A, B, and C, respectively. All heat loss was assumed to be transferred via free convection and radiation to the environment at 100°F. To facilitate ease of reference the heat loss for each section was calculated for an adequate range of temperatures, then plotted versus the temperature. This plot was then used to approximate the total heat loss from the system (see Figure 12). To calculate the heat loss from the system it was assumed that losses occurred from a horizontal cylinder.

Free Convection: $\dot{Q} = \bar{h}\ A\ (T_{wall} - T_{env.})$

where (14) $\bar{h} = 0.27\ (P/14.7)^{.5} \times (T_{wall} - T_{env.})^{.25}/\text{Diameter}^{.25}$

Radiation: $\dot{Q} = \sigma \, \varepsilon \, A \, (T^4_{wall} - T^4_{env.})$

where (16) $\varepsilon = 0.6$ for sections 1, 2, and 3

$\varepsilon = 0.8$ for section 4

$\sigma = 0.1714 \times 10^{-8}$ Btu/(ft^2,hr,$^\circ$R^4)

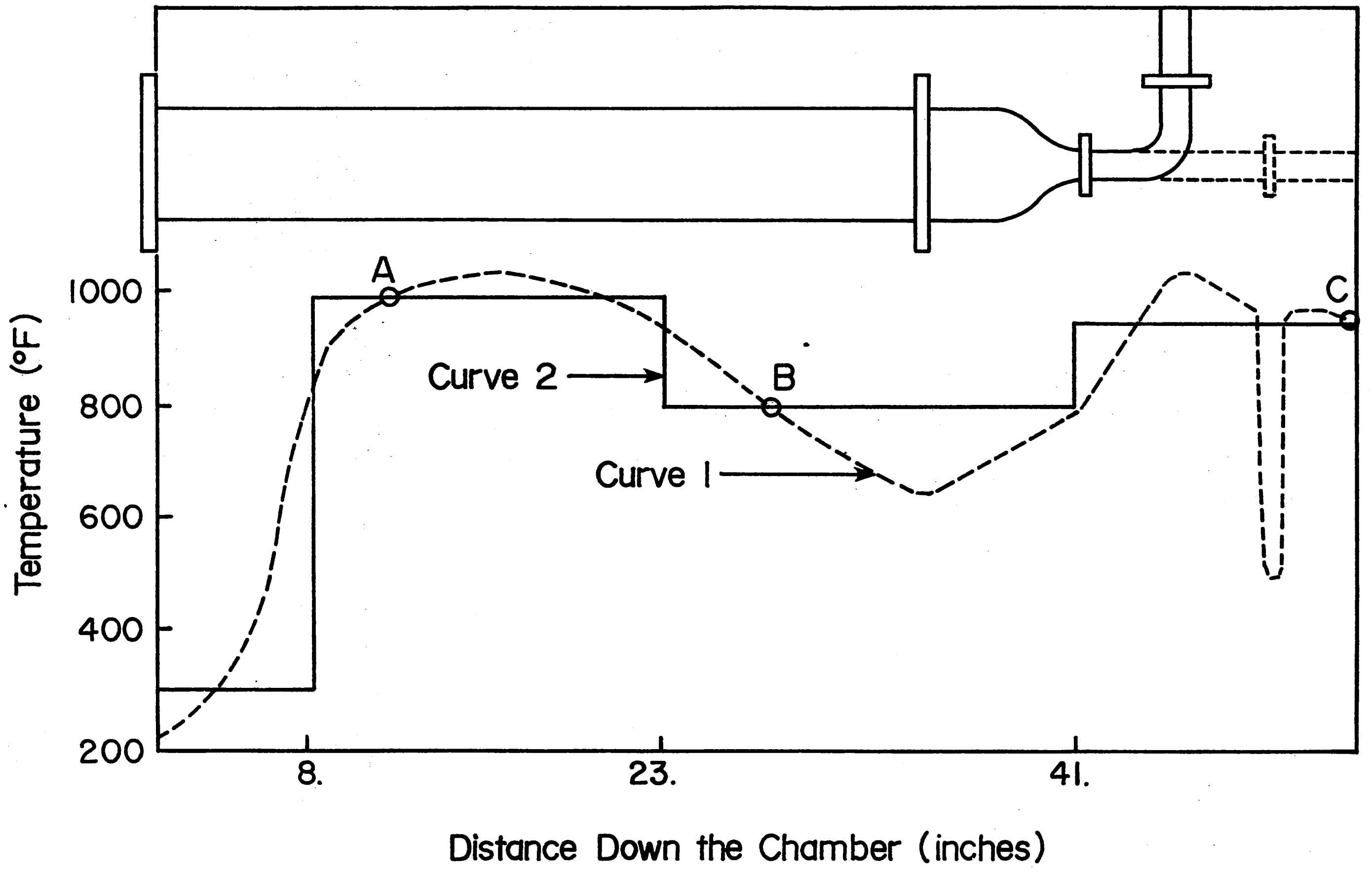


Figure 11. Temperature Variation Down the Chamber

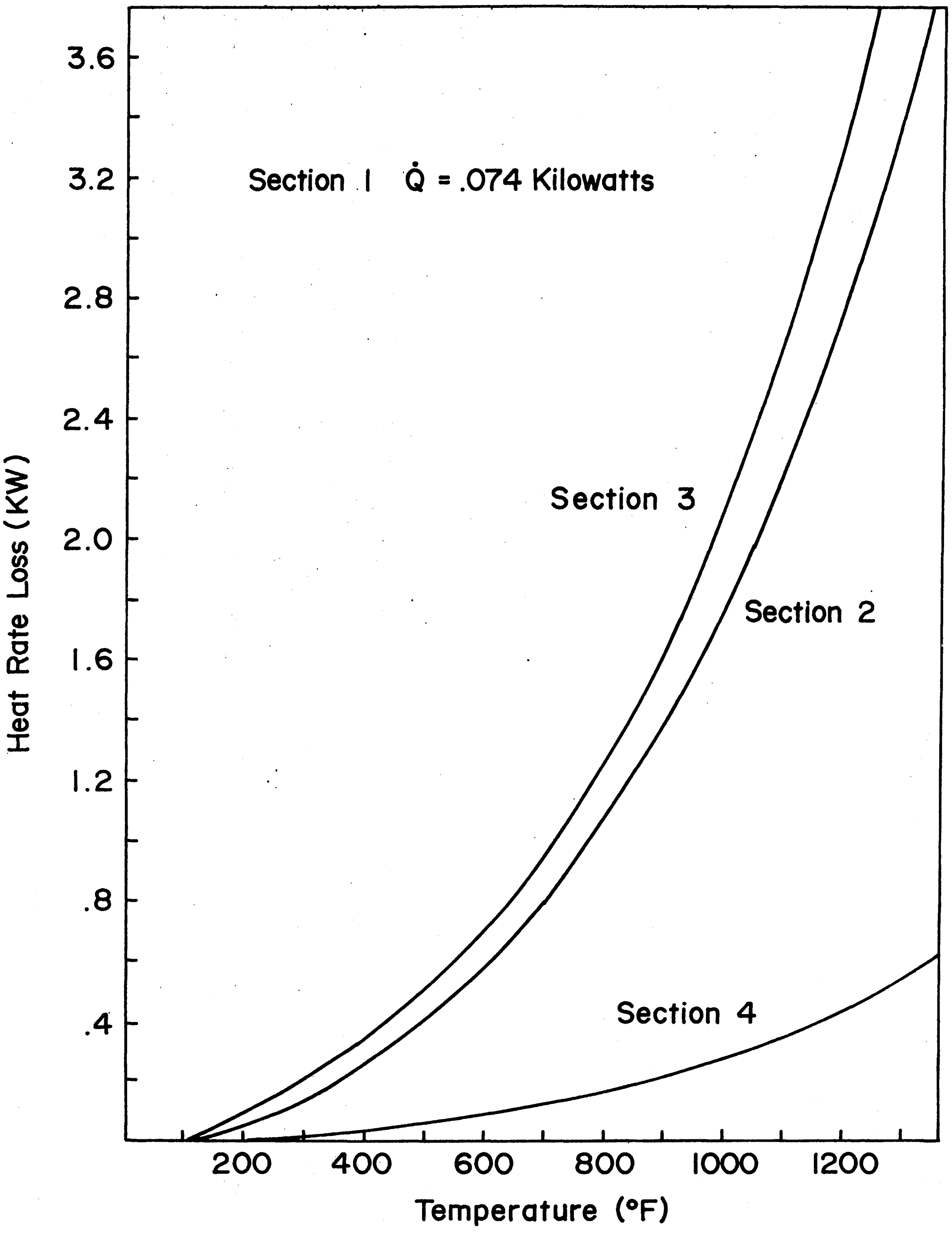


Figure 12. Heat Rate Loss from the Chamber as a Function of the Chamber Temperature

APPENDIX C

H_2 - O_2 MASS FLOW RATE CALCULATION

There exists various types of flowmeters which monitor mass flow rates, but such units are very expensive. The simplest method to measure the mass flow rates of the hydrogen and oxygen was found to be to determine the total mass of the gas in the containers before and after each trial making note of the elapsed time of the trial. Because the weight of the gas was a small fraction of the full containers weight, weighing the bottle could not give accurate mass calculations. Therefore, by monitoring the total pressure and temperature of each cylinder before and af ter a trial the mass of the gas consumed was calculated using the compressibility factor equation.

$$PV = ZmRT.$$

Here V is the tank volume and is constant, R is the gas constant for each gas with

$$R_{O_2} = 48.2 \text{ ft lb}_f/\text{lb}_m {}^\circ R$$

and

$$R_{H_2} = 766.4 \text{ ft lb}_f/\text{lb}_m {}^\circ R$$

The compressibility factor Z is a function of temperature and pressure; therefore, the mass of each gas was found as a function of temperature and pressure. To facilitate ease in determining the mass consumed during each run the mass was plotted versus P/T ratios (see Figure 13). By monitoring the pressure and temperature of each tank, the mass of the gas in the tank was found from the plot.

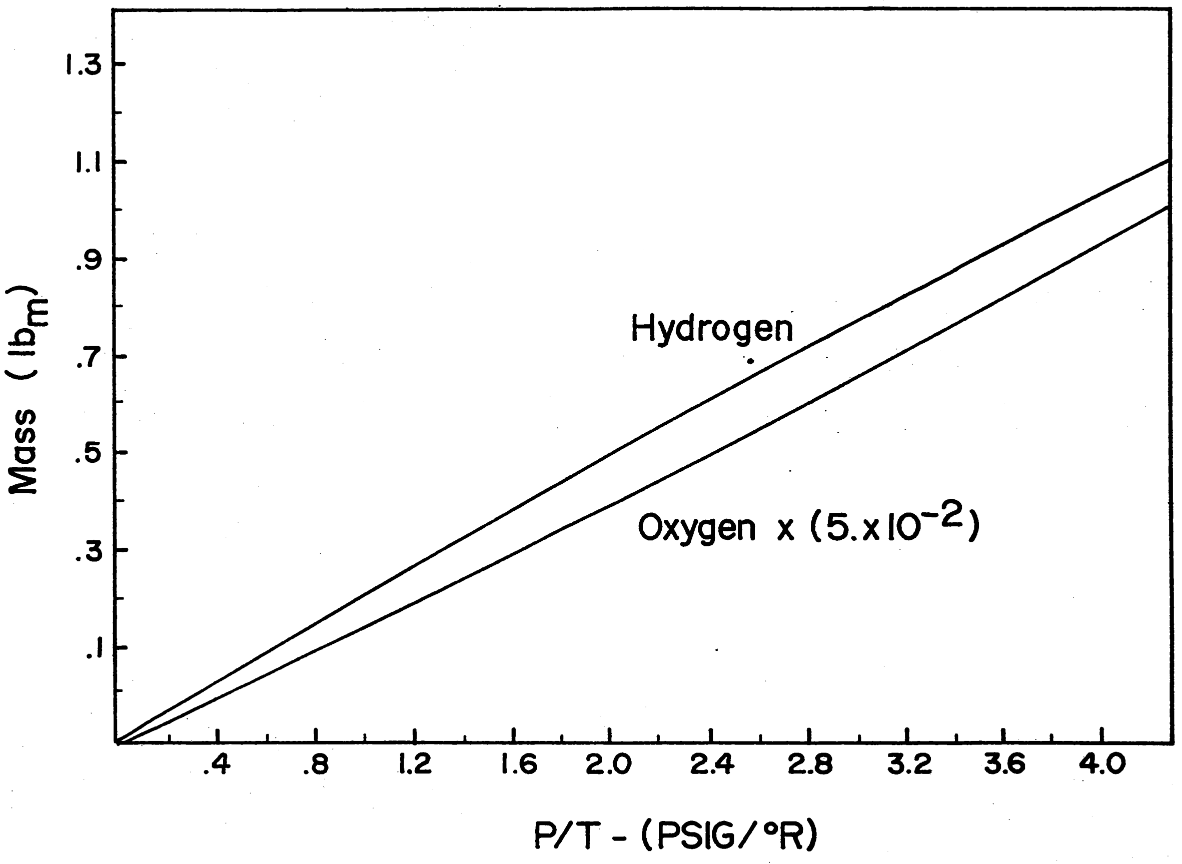


Figure 13. Mass of Hydrogen and Oxygen Gas Remaining in Their High Pressure Cylinder as a Function of the Pressure to Temperature Ratio of the Gas

APPENDIX D

THERMOCOUPLE PROBE CONSTRUCTION

Four basic thermocouple probe designs were used to measure steam temperature in this experimental study; however, their basic construction was similar in that a thermocouple junction must be rigidly held in place in the chamber and that the thermocouple lead wires extending into the chamber must be protected from the steam. The junctions were supported by stainless steel tubing and ceramic insulators while the lead wires were protected by glass tubing, asbestos packing and ceramic insulators placed inside the steel tubing. For initial investigations and simplicity bare thermocouples were inserted into the flow, their construction consisted of the thermocouple wire, 1/4-inch thin walled stainless steel tubing, ceramic and glass insulators using a 1/4-inch compression to 1/4-inch pipe thread adapter to attach the steel tube to the chamber. The thermocouple leads were striped for about 3/4-inch and inserted through the two holed ceramic insulator, the thermocouple junction was then formed by welding the two wires in an argon atmosphere. A piece of four millimeter glass tubing was then cut to the length of the stainless steel tube and slipped over the thermocouple wire butting it against the ceramic insulator. The 1/4-inch stainless steel tube was cut about eight inches long where the actual length depended on the depth in which the probe was to be inserted into the chamber. The wire with the insulators was inserted through the steel tube until the thermocouple junction extended 3/16-inch from the end of the tube (see Figure 14a). To secure the thermocouple junction and wire the tube and seal the tube to high pressure a high temperature epoxy (Armstrong Kit A2/W) was poured into the tube from the tube end opposite the junction.

For added mobility a probe was constructed to be inserted into the flow from the chamber exit. The basic construction of the probe is similar to the probe discussed above in that the thermocouple wire insulation procedure is the same. The probe consists of a two-feet long 1/2-inch stainless steel tube which was inserted into the chamber parallel to the flow. A 3/4-inch piece of tubing was cut one-inch long and attached to one end of the 1/2-inch tube perpendicular to the tube, (see Figure 14b). Two thermocouple wires were inserted into the tube with one thermocouple junction inside the shield and the other junction in front of the shield. The probe assembly was supported by a ring stand and clamp positioned in front of the chamber exit. Measurements from this probe were discussed in Chapter IV.

The probe used to traverse around a cross section was inserted into the chamber via the exit. This probe was used in conjunction with the probe drive discussed in Chapter III and was described there briefly. A piece of 3/8-inch stainless steel tubing was cut two feet in length with the measurement end being "L" shaped, (see Figure 14c). Here a single thermocouple wire was inserted through the tube with the glass tube insulation; the junction was also formed at the end of a two holed ceramic insulator. The thermocouple junction was open to the flow and extended 3/16-inch beyond the steel tube holder. Being open to the flow radiation losses were expected but the thermocouple would also be able to record any water droplets that might exist in the flow.

The above three probes served to qualitatively describe steam temperatures in the chamber but an improved probe was necessary to describe exiting conditions of the steam. The simple probe first discussed was prone to heat losses by stem conduction and the other probes were not feasible for increased pressure measurements since both were introduced into the chamber via the exit. Better shielding from the cooler chamber walls and the hotter combustion region was necessary. It was felt that the probe should be inserted perpendicular to the flow to facilitate increased pressure measurements and allow radial traversing of a chamber cross section. One quarter inch stainless steel tubing was used for the probe construction, the tube was bent to form an "L" which would run parallel to the chamber. The "L" shape allows several inches of the probe stem to be at the same location in the flow as the thermocouple junction, reducing stem conduction losses. The thermocouple wire and glass insulator were inserted through the tube but the junction was embedded in the end of the glass insulator. This was done by melting and sealing the glass tube shut, and while the glass was molten the thermocouple junction was pushed into the glass. With the wire and junction in place, epoxy was again poured into the open end of the tube sealing the probe. The probe was shielded by a concentrically placed 1/2-inch stainless steel tube connected to the probe by a ceramic cylinder wedged between the two tubes (see Figure 15).

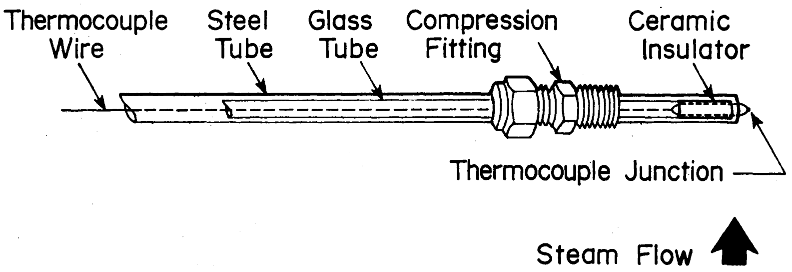


Figure 14a. Unshielded Probe Assembly

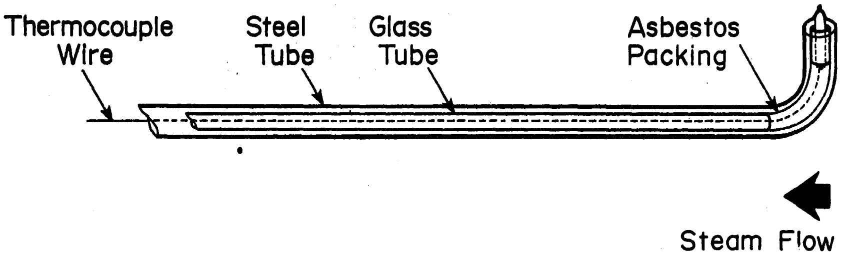


Figure 14b. Angular Traverse Probe Assembly

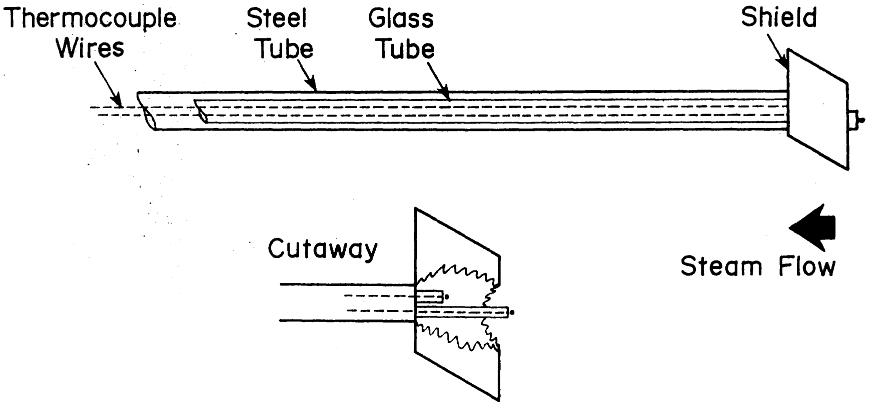
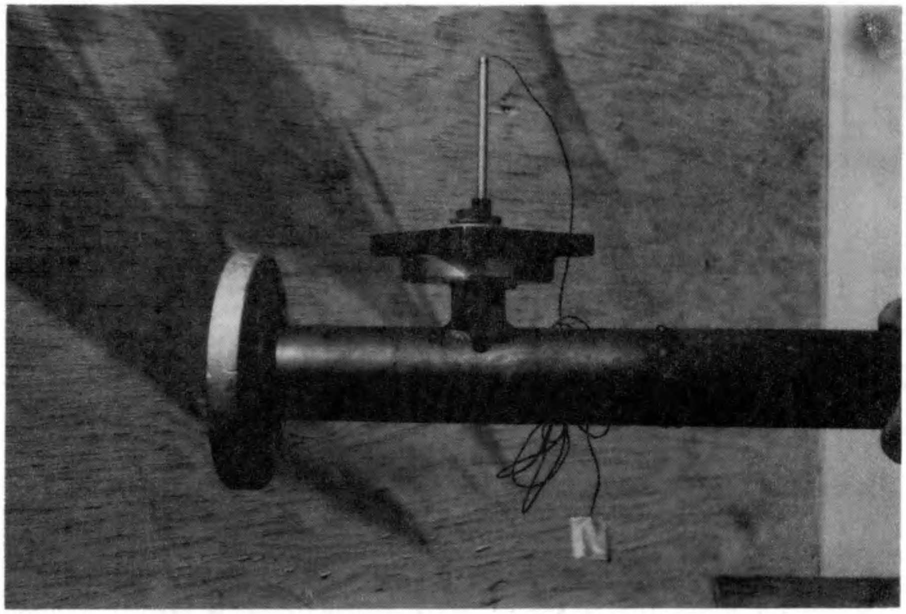


Figure 14c. Stationary Shielded Probe Assembly



Probe in Place at Elbow Exit

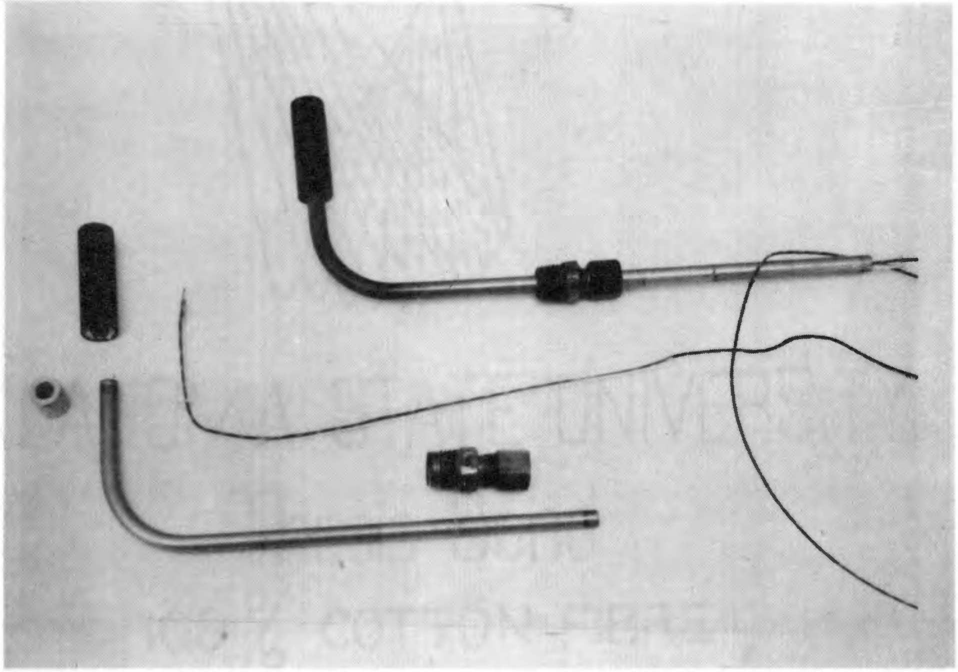


Figure 15. Improved Measurement Probe Assembly

VITA^{2}

Wendell Lee Johnson

Candidate for the Degree of

Master of Science

Thesis: INVESTIGATION OF THE PRECOMBUSTION INJECTION OF A WATER SPRAY INTO THE HYDROGEN OXYGEN FLAME FRONT

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Biographical:

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