QUARTERLY PROGRESS REPORT

PROJECT SQUID

A PROGRAM OF FUNDAMENTAL RESEARCH
ON LIQUID ROCKET AND PULSE JET PROPULSION
FOR THE
BUREAU OF AERONAUTICS AND THE OFFICE OF NAVAL RESEARCH
OF THE
NAVY DEPARTMENT
CONTRACT N6ORI-119, TASK ORDER I

CORNELL AERONAUTICAL LABORATORY
BUFFALO, NEW YORK
1 APRIL 1947

PHASE NO. 1

In connection with pulsating-jet engines: to undertake theoretical and wind-tunnel investigations on flows and losses in diffuser inlets, diffusers, intake valves, exhaust nozzles, and thrust-augmenting ducts for subsonic and supersonic pulsating jets.

SUMMARY

Two-dimensional diffuser models were tested at a Mach number of 1.7 in the Cornell Aeronautical Laboratory Supersonic Wind Tunnel. Striae photographs were made of the shock patterns in these diffusers. A diffuser is now being studied which uses fluctuating back pressure to simulate intermittent combustion.

The effect of spillover on the pressure distribution on the external surfaces of ducted bodies was simulated in wind-tunnel tests of both blunt and sharp wedges.

A study of gas flow in half-open pipes was started and the possibility of representing the conditions by means of electrical or hydrodynamical model experiments is being investigated.

PROGRESS

A two-dimensional Kantrowitz diffuser designed for $M = 1.7$ was tested at this Mach number. A butterfly valve, which can be set to any desired angle with respect to the diffuser axis, or which can be rotated by means of an electric motor drive, was installed at the diffuser outlet. The test setup is shown in Figures 1 and 2. To detect the motion of the normal shock in the diffuser as the valve was turned, a series of striae photographs was made at a speed of 4 microseconds. This motion of the normal shock is shown in Figures 3, 4 and 5.

A two-dimensional model was used to investigate the effect of spillover on external wave drag. This model consists of a single wedge with one blunt and one sharp edge. Either the sharp or blunt edge can be used forward, and the thickness of the blunt edge can be increased. The blunt edge simulates the external shape of a ducted body with steady spillover from the duct entrance. There are static pressure holes in the upper surfaces of the wedge.

Measurements of these static pressures were made at a free-stream Mach number of approximately 1.7. The results of these tests indicate that the effect of steady spillover is to increase the wave drag over most of the external surface, but to decrease it in a narrow region near the lip. Striae observations show that there is a region of intense expansion following the detached shock.

Figure 1. Model Setup for Operating Valve by Hand.

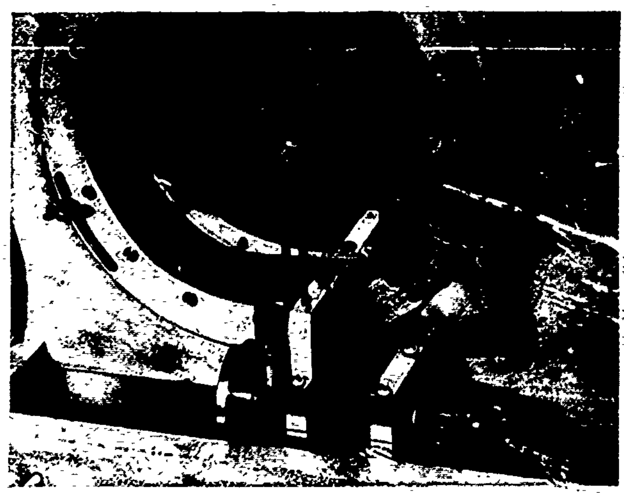

Figure 2. Model Setup for Operating Valve by Motor.

This expansion culminates in a second shock aft of the lip.

The problems of gas flow in a pipe suddenly opened at one end were studied. It was found that the air, which initially is under pressure, expands, and that oscillations are set up in the system. Relations are being derived which show the effect of the shape of the pipe, of the amplitude of oscillations, and of the nature of the gas on the resonance frequency. There is a perfect similarity between the pressure waves in a gas and electric waves along a transmission line for acoustical oscillations, but for large amplitudes the underlying differential equations become nonlinear in a different way. All attempts to develop a satisfactory electrical equivalent circuit have failed for this reason. An attempt is now being made (following a suggestion by Dr. V. Paschkis of Columbia University) to see wheth..r, instead of a continuous solution, a good approximation in steps might not be possible after all.

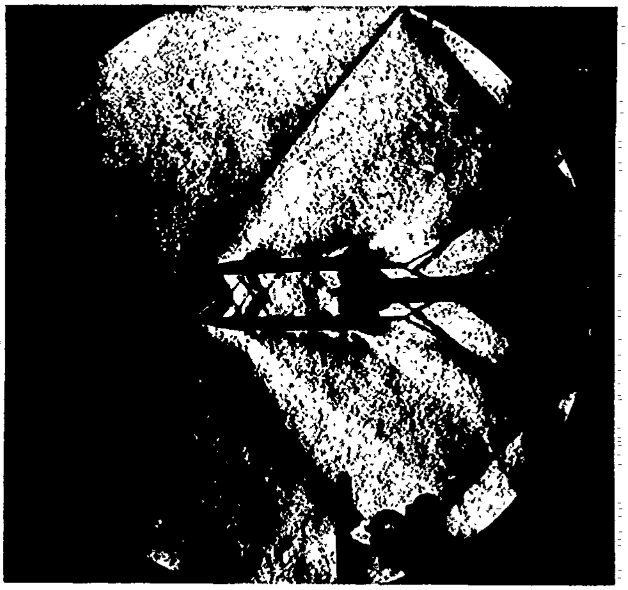

Figure 3. Valve At 0°.

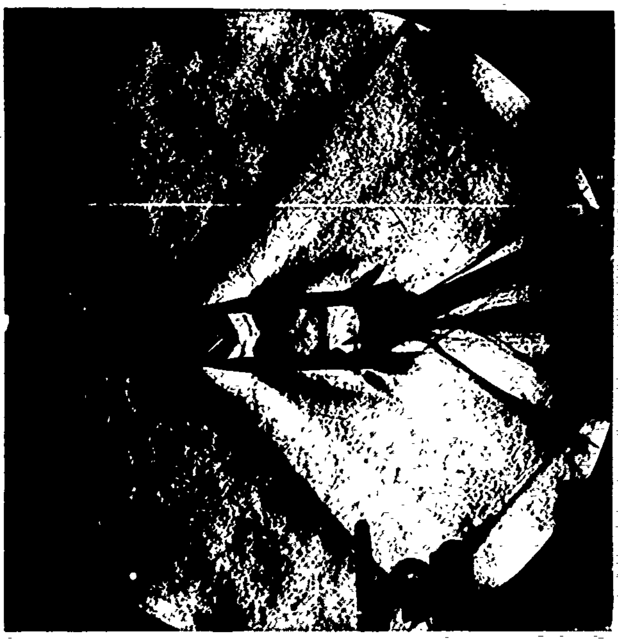

Figure 4. Valve At 21°

Figure 5. Valve At 60°.

Paralleling this study, the possibility is being investigated of using the property of surface gravity waves in open water channels to simulate conditions of a gas in a pulse jet after burning is completed. It appears that this approach should give valuable information on the operation of a pulse jet.

PLANS

Tests of the diffuser with the rotating valve will be continued. An attempt will be made to determine whether a relationship can be established between the amplitude of the pressure fluctuations and the frequency of the pulsations so that the normal shock will not be forced out of the diffuser. The variation of pressure and shock position inside the diffuser will be determined with varying positions of the valve (simulating varying amounts of back pressure). High-speed motion pictures will also be made to ascertain the exact fluctuation of conditions in the diffuser.

Conclusions reached on the hydrodynamical analogy will be tested by comparing experiments of equivalent setups both for pressure waves in gas and surface waves in water. If satisfactory agreement can be obtained, a variety of problems can be investigated by the comparatively simple water analogy. These problems include optimum shape of ducts to obtain maximum thrust, optimum valve operation and the comparative value of different types of valves. If a way can be found, a similar program will be followed on the electrical analogy.

PHASE NO. 2

In connection with pulsating-jet engines: to study the theory of combustion, effect of turbulence on flame propagation and cooling, and to verify and augment existing theories by means of experimental investigation of ignition, combustion, flame holding, flame propagation and cooling.

SUMMARY

The preliminary experiments have been completed to move a spark through a combustion chamber by means of a magnetic field across the electrodes, and a full-scale setup is being designed. The apparatus for studying flame propagation in a steel tube has also been completed and experiments have been started to find the optimum configuration for the ionization gaps. These gaps are used to measure flame velocities. Experiments are being carried out to take high-speed movie films of striae patterns. Successful films up to 1000 frames per second have been taken. General problems on instrumentation are being continuously studied.

Tentative plans have been made for studying the possible catalytic influence of combustion-chamber-wall materials. A description of these plans has been sent to the chairmen of the Pulse Jet and Rocket Panels.

Proving tests have been run to establish the efficiency of a refrigerated probe for sampling combustion gases. While results are encouraging, difficulties have been encountered in obtaining a satisfactory equilibrium mixture for sampling purposes.

PROGRESS

The preliminary experiments with the pyrex-glass combustion chamber indicate that high-speed movies of the flame can be successfully taken up to the maximum speed of the camera (4000 frames per second). With the small magnet used for the first experiments, a spark was moved at a speed of about 10 feet per second. A much stronger permanent magnet has now been ordered and improvements are being made to the combustion-chamber design on the basis of preliminary experiments.

Experimentation with the steel combustion tube has started. The first step is to find the optimum arrangement of the ionization gaps. Their orientation relative to the flame front, in addition to the geometry of the ionization gap itself, are being investigated.

Since the mercury ac arc, normally used for striae observations, is not suitable for taking high-speed movie films because of the resulting periodic variation of light intensity on the film, a dc carbon arc was tried. A film taken at 1000 frames per second was well-exposed. Now, by a simple modification of the optical system, attempts are being made to focus the striae pattern directly on the film (16 mm) of the high-speed movie camera, instead of photographing the screen. It remains to be seen whether elimination of the screen is not more than offset by the reduction of quality of the optical system.

A study was begun on the possible catalytic influence of combustion-chamber-wall materials. It is generally known that combustion takes place very readily on certain solid surfaces. This fact is utilized in surface combustion furnaces in which combustion occurs on the porous surface of refractories. Welsbach mantles in lanterns produce intense brilliance on the surface of the metal oxides used in the mantle. A recent study by Curtiss-Wright developed a catalytic flame holder and igniter in which a platinum surface is used to promote combustion.

The use of such materials in combustion-chamber walls seems of particular interest in propulsion devices where space, weight, and time are at a premium.

The specific objective of this work is to study the catalytic effect of wall materials on the capacity of a combustion chamber and on the completeness of combustion.

It has been previously reported that a water-cooled triple-walled sampling tube of 0.020-inch internal diameter gave indications of justifying the theoretical calculations of its ability to freeze the CO_2 and H_2O dissociation equilibrium. The experiments which have been conducted from January through March have been complicated by the difficulty of obtaining an equilibrium gas mixture for sampling purposes. Numerous experimental setups have been developed and tested to overcome this difficulty.

The experimental trials can be divided roughly into two classes. The first includes those experiments in which a flowing CO_2 system was used; the second includes those in which flames were used as a source of equilibrium products. Using a Zircofrax tube and an Alundum tube sealed with sodium silicate, CO_2 was heated to the order of 3000°F by heating the refractory tubes with an oxy-gas flame. The temperatures were determined with an optical pyrometer. The sample was collected by inserting the sampling tube into the exit end of the refractory tube to the point of closest proximity to the region of maximum temperature.

With the Zircofrax tube, no decomposition of the CO_2 was observed. This could be due to recombination either in the cool portion of the heated tube or in the refrigerated sampling tube itself, since the gas approached and entered at a relatively slow velocity. In order to eliminate the latter possibility, tubes of very small diameter were constructed of Alundum. A higher rate of flow was used and samples were again collected. The amounts of oxygen and carbon monoxide found were in the order of magnitude predicted for the dissociation calculated at the observed temperature. However, small discrepancies indicated that leakage might have occurred through the Alundum walls.

To eliminate this possibility, a platinum tube of 0.020-inch internal diameter was fabricated. It was heated by a 60-cycle alternating current to temperatures just below its softening point (approximately 3100°F). A series of tests were conducted in which the temperature was gradually stepped up. No decomposition of the CO_2 was observed. This may have been due either to the malfunctioning of the sampling tube, or the reassociation of the gases in that portion of the platinum tube which was cooled by the proximity of the sampling tube (approximately 0.25 inch).

Previous investigators like Sand, Nernst and von Wartenberg have used a refinement of this method to determine dissociation constants of water vapor and carbon dioxide. They have pointed out certain design considerations which limit the usefulness of this method.

Through a long tube, heated over an length *ab* to a temperature *t*, the vapors are passed, and, in passing from *a* to *b*, proceed toward dissociation equilibrium. Then over a distance *bc*, which is small compared to *ab*, the gases are cooled to a temperature so low that the equilibrium is frozen. Further, the cross-sectional area of *bc* must be such that the gases are cooled in a minimum of time so that the equilibrium obtained at temperature *t* is not appreciably disturbed. This is usually accomplished by use of a narrow capillary tube. Thus *ab* must be long enough so that equilibrium is attained, and the time of cooling in *bc* must be so short that it is not disturbed. At low temperatures, equilibrium would only be obtained for a very great length. At high temperatures, the disturbance due to the finite time of cooling becomes appreciable.

Thus the authors point out that for any physical setup the geometry of that setup governs and delimits a region corresponding to a temperature range in which the observed dissociation agrees with that theoretically calculated for dissociation. Below this temperature range, equilibrium is not established in the length *ab*, and above this range the disturbance of the equilibrium because of the finite time of cooling is appreciable.

These men have not used temperatures in excess of 1478°K. The fact that they have not worked at high temperatures may indicate that satisfactory sampling tubes can not be made to operate in gas mixtures at such temperatures.

Another approach to the problem was tried. A series of tests was run in which samples of gas were withdrawn from flames produced by various types of burners. Both methane of 99.2 per cent purity and a mixture of natural gas and producer gas of known average composition were used as fuels.

The combination of a natural gas and a producer gas was burned in an oxy-gas torch with oxygen. Samples were withdrawn from the outer cone of the flame. The analysis of the gas withdrawn shows amounts of CO, H_2 and O_2 which correspond to equilibrium at a high temperature, but not, in results so far obtained, at a temperature as high as the calculated flame temperature. In a typical analysis the following results were obtained.

CO_2	39.5%	on dry basis
O_2	3.9	
CO	24.4	
H_2	12.9	
CH_4	2.0%	on dry basis
C_2H_6	0.4	
Inert	16.9	
H_2O	114.2	

From the partial pressures of CO_2 and O_2, it was computed that the amount of decomposition of CO_2 corresponds to the equilibrium amounts at 4160°F. From the partial pressures of H_2O, H_2 and O_2, it was computed that the amount of decomposition of H_2O also corresponds to the equilibrium amounts at 4160°F. The excellent agreement between these temperatures shows that the refrigerated sampling tube affects the two reactions in the same manner. The calculated flame temperature, based on the analysis of the fuel gas and the above analysis of the gas from the flame, is considerably higher than 4160°F. This calculated flame temperature, however, should be corrected for the heat amounts absorbed in decomposition reactions not shown in the analysis, such as decomposition of O_2 and H_2, and formation of CH_2= and OH—. This correction will bring the calculated flame temperature in better agreement with that calculated from the equilibrium amounts of CO, H_2 and O_2. If this agreement can be obtained, either by corrected calculation of flame temperature or by direct measurement of the gas temperature, it will be shown that the refrigerated sampling tube cools the gas rapidly enough to obtain samples containing representative amounts of decomposed CO_2 and H_2O.

In order to simplify the reaction, pure methane was used as a fuel. A metered mixture of methane and air was supplied under pressure to a Meker-type burner. The refrigerated sampling tube was inserted in the flame about 0.25 inch above the inner cones and a sample was withdrawn. It was then possible to calculate the flame temperature from the analytical data, the air-fuel ratio and the hydrogen-carbon balance. The flame temperature could also be calculated from the extent of dissociation based on the analysis. These values could then be compared with the known values determined from the input.

The results of a series of runs are shown in Table 1.

It will be noted that the results in Run 1 are extremely good. However, in this case the analysis for CO was made by absorption in acid cuprous chloride. When similar runs were attempted (3 and 4) using a suspension of cuprous sulfate and beta-napthol, the results were not so well in line. Much higher quantities of carbon monoxide were detected. Although the flame temperature calculated from the analysis agrees very well with the theoretical value calculated from the air-fuel ratio, the value calculated from the apparent dissociation of the CO_2 is much too high. This indicates that the combustion of the methane was incomplete. To check this point, increased air-fuel ratios were used, but incomplete combustions were still obtained (runs 5 and 6).

These tests are, therefore, inconclusive. Since equilibrium was not established in the flame, no accurate check of the efficiency of the sampling tube was obtained. Although there are indications that the tube can stop the re-association of carbon monoxide and oxygen to carbon dioxide, the proof is not rigorous. In Run 1 it is possible that equilibrium actually was established in the flame, but the discrepancy in the carbon dioxide analyses leaves even this in question.

PLANS

A new glass combustion chamber will be built when the new magnet has been tested. This chamber will have flat side walls so that striae patterns, in addition to high-speed movies, can be obtained. When the apparatus has been installed, a study will begin on the effects of various disturbances on flame propagation under controlled conditions of temperature, pressure, and mixture composition. The steel combustion tube will be used to study the effect of various constrictions on flame propagation, and to determine to what extent the high velocities reached are being maintained in the remaining section of the tube.

Experimental work will be started shortly to study the catalytic effect of combustion-chamber-wall materials.

In an attempt to provide a rigorous proof of the efficiency of the tube, gas mixtures will be sampled which have been allowed sufficient time to attain equilibrium. The exact experimental techniques are being detailed. The procedure will probably be to heat carbon dioxide in a static system, rather than in a flowing system as has been previously reported, or to repeat the platinum-tube experiment since that tube has a larger bore than the present sampling tube.

TABLE 1

Run	1	2	3	4	5	6
Fuel	CH_4	CH_4	CH_4	CH_4	CH_4	CH_4
A/F (input)	17.3	14.9	17.0	17.0	21.6	18.2*
A/F (calculated from analysis)	17.3	10.4	14.15	14.12		
Analysis						
CO_2	11.4 vol%	9.15 vol%	5.53 vol%	4.03 vol%	5.8 vol%	7.26 vol%
O_2	9.22 "	7.70 "	10.44 "	12.97 "	9.7 "	9.35 "
CO‡	0.45 "	10.98 "	6.79 "	8.88 "	6.7 "	2.61 "
H_2	0.0 "	0.22 "	0.0 "	1.45 "		
CH_4	0.65 "	0.0 "	1.38 "	0.45 "		
N_2	78.28 "	71.95 "	75.86 "	72.22 "		
Hydrogen/Carbon Balance						
(input)	0.333	0.333	0.333	0.333		
(found)	0.292	0.268	0.294	0.302		
Flame Temperature (Theoretical for (A/F)	3600°F	3600°F approx.	3600°F	3600°F		
Flame Temperature (Calculated from analysis)	3500°F	greater than 4000°F	3600°F	3500°F		
Flame Temperature (calculated for dissociation of CO_2	3600°F	greater than 4000°F	greater than 4000°F	greater than 4000°F		
Comment	Sampling tube operated efficiently	Incomplete combustion inconclusive	Incomplete combustion inconclusive	Incomplete combustion inconclusive	Incomplete combustion inconclusive	Incomplete combustion inconclusive

* Gas velocity 1.6 times slower than in 5.

‡ Cuprous chloride was used to absorb CO in the first run and a suspension of cuprous sulfate and beta-napthol was used in the remainder.

PHASE NO. 3

In connection with pulsating-jet engines: To undertake experimental investigation of temperature-and fatigue-resistant materials for intake valves and coatings, and of fabrication methods and techniques to cover said materials.

SUMMARY

The vibration machine has been constructed and preliminary tests are being run.

Two types of microscope stage furnaces, one heated by induction and the other by a resistance

winding, are being constructed. The Tocco Heat Gun has been selected as a source of induction heat. A revised design of the optical system for the metaloscope permits photographing and visual observation simultaneously.

PROGRESS

The pneumatic-resonant vibration machine has been designed and built. A furnace, shown in Fig. 6, is placed around the specimen.

Figure 6. Resistance Furnace for Metaloscope

Preliminary tests are being conducted to determine operating characteristics of the machine at elevated temperatures. Some difficulty has been encountered in determining specimen size and stress during tests. Maximum testing temperature will be about 2000°F. The furnace is so designed that the specimen will be heated at the area of maximum stress.

Attempts were made to use the Ajax 20kw converter as a source of heat for the microscope furnace. A cylindrical piece of steel of 0.5-inch diameter was heated to approximately 1300°F with 15kw for about two minutes. A simple coupler arrangement was used in which a coil was placed inside one of the existing furnaces and coupled to the heating coil. However, the water-cooled copper leads and the necessity for a close coupling to the furnace coil made the arrangement impractical for use on a metaloscope stage.

The Tocco Heat Gun, a small portable inductor unit about the size of an electric hand drill, has been selected as the source of induction heat. Power is furnished by a 15kw Tocco Jr. and supplied to the gun through 10-foot flexible leads.

An experimental vacuum furnace was constructed by sealing a water-cooled brass plate to a glass petri dish. Glass was selected so that the specimen could heat up inside the vacuum chamber and still not heat the container. However, when vacuum was pulled on this setup, the thin petri dish collapsed. The new design has a ⅛-inch-thick glass plate sealed into the bottom of a brass container. Both top and bottom of this furnace will be water-cooled.

A furnace which has a resistance element as a heat source is also being constructed. This furnace is similar in design to those used by previous investigators in this field. It will be used to check the work that has been done and will be available should induction heating prove impractical. This work has been awaiting the arrival of refractories.

The design of the optical system has been revised so that visual observation and photographing of the specimen can be accomplished simultaneously. This permits controlling the camera while the reactions are being photographed.

Orders have been placed for the following equipment: Tocco Heat Gun, vacuum gauge, potentiometer for measuring temperatures, vacuum pump for evacuating the furnace, resistance windings for the resistance furnace, refractories and cements for construction of furnaces. A formal quotation on the revised optical system has not been received but is expected within a few weeks. Temperature-controlling equipment will not be ordered until further experiments are conducted to determine the type needed.

PLANS

Instrumentation of the vibration machine will be made to permit recording the vibration rate, temperature and specimen amplitude. Sufficient data will be collected to work out the fatigue curve on a temperature basis.

After both a resistance furnace and a furnace for use with the Tocco Heat Gun have been constructed, they will be tested for their ability to hold a vacuum. The resistance furnace will also be tested for heating ability. When this stage is reached, auxiliary equipment will be arranged and tested as it arrives.

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ABSTRACT:

Wind-tunnel tests are being conducted at supersonic speeds on model diffusers to study flow characteristics and pressure losses in pulse-jet engine. Possibility of representing gas flow conditions by electrical or hydrodynamical experiments is discussed. Work is progressing on investigations of spark propagations in combustion chamber and on studies of catalytic effect on combustion chamber wall materials. Vibration machine and two types of microscope stage furnaces are being constructed for research on temperature and fatigue-resistant materials.

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