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
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INTRODUCTION

During the first quarter of 1947, the staff of Project Squid at New York University was increased, with a corresponding increase in the number of parts of Phases which are being actively worked on. At the same time new plants and equipment facilities, which had been expected for a long time, materialized, so that the physical background of much of the future work is now determined. Not among the least of these acquisitions are the test spaces and facilities to be at Reaction Motors, Inc., near Lake Denmark, N. J., which are projected for use in connection with the main experimental work on pulsejets and liquid fuel rockets. Thus, physically, Project Squid at New York University was characterized by a period of expansion.

Technically, progress continued apace, mainly in Phase I, having to do with flame propagation and combustion studies, and in Phase IV, dealing with instrumentation. Work on the other phases, chiefly because of the aforementioned expansion, is rapidly gaining momentum.

Specifically, in connection with the plant and equipment growth, the following items should be noted. The thermomechanics laboratory associated with the West Hall offices and laboratories at University Heights has been in use for a month as a small jet testing laboratory. In this laboratory will also be located the supersonic blowdown tunnel, which utilizes a series of air bottles pressurized to 3000 psi by an Ingersoll-Rand four-stage compressor which has been received from the Navy. Two trailers have been acquired; one is being fitted out for use as a portable mount for the Merlin engine-supercharger blower for stationary flame studies at Lake Denmark, and the other is a Mobile Electronics Laboratory kindly loaned to us by Dr. Paul Fye, Director of the Underwater Explosion Research Laboratory at Woods Hole, Massachusetts, and with the cooperation of the Bureau of Ordnance, Navy Department.

The enthusiastic cooperation of Reaction Motors, Inc., officials has enabled plans to be executed for immediate tests of the JB-2 pulsejet engine, work on which began on 31 March. At first, the installations and work will be temporary and preliminary. More permanent facilities, shops, laboratories, and test stands are being planned in detail, specifically for stationary flame studies (Phase I) and pulsejet studies (Phases III and IV).

PHASE NO. 1

In connection with pulsating jet engines: to undertake theoretical and experimental investigations of (1) flame motions with controlled initial turbulence, (2) stationary flames with controlled turbulence, (3) suitable theoretical models based on the above observations, and (4) statistical mechanics of non-uniform gases. (The main objective in this phase is to determine the character of, and parameters for, flames in a combustible medium in which turbulent or eddy motion analogous to that in pulsating jet motors is produced under controlled conditions. Analysis of high speed movies of flame motions in Buzz-bomb motors indicates that effective flame speeds of the order of 200 feet/sec relative to the gas do arise, for reasons which require study).

SUMMARY

The experimental work on combustion and flame propagation studies proceeded rapidly with the indirect verification of the fact that the high flame speeds in a moving-flame tube, due to the presence of a turbulence making grid, were not due solely to gross mass motion of the burning gases. These moving flame studies were then oriented toward obtaining information which would lead to the values of certain fundamental parameters needed in the development of the pulsejet theory and the theory of flame propagation in turbulent media. Stationary burner flame experiments were also carried out in the investigation of the effect of turbulence on flame propagation, with the introduction of one or two interesting techniques. The setting up of a stationary flame tube at the Lake Denmark site is expected to aid these investigations greatly.

The main theoretical work on this phase was concerned with the development of a physical description of the propagation of a flame moving down a tube. This theory makes use of certain empirically observed relations, such as the velocity-time curve to evaluate some fundamental parameters which occur. The longer range theoretical work on non-uniform gases proceeded mainly in the direction of more explicit formulation of the mathematical statement of the problem.

EXPERIMENTAL

Moving Flame Experiments.—The moving flame studies have been carried out in two pyrex flame tubes, one of which was four feet long, the other, which was introduced more recently, is eight feet long. In the four-foot flame tube, more observations were made on the flame motion through a two-foot sleeve of wet tissue paper which was added at the open end. The velocities in this sleeve remained very high, corroborating the preliminary observation reported in the semi-annual report that, despite the great reduction in flow speed of the gas which must occur in the shattered sleeve, the flame velocity relative to the tube drops only gradually.

A series of experiments have been carried out in the four-foot tube and the eight-foot tube to obtain reproducible flame velocity-time curves with and without grids near the igniters to produce turbulence or swirling. In the four-foot tube, there was no significant difference observed between two different types of igniter. At first, in the eight-foot tube, anomalies in the velocity occurred, so that in some experiments the flame actually appeared to reverse its motion. This reversal appears to have been traced to reflection of a compression wave from the floor at the open end of the vertical tube. When the tube end was elevated 33 inches above the floor, this phenomena disappeared and has not been observed since.

Shadowgrams have been attempted using a Mercury arc (operated on AC) as a light source and more satisfactorily with a Zirconium light. In both cases, the pattern of the pyrex tube obscured any flame shadows.

Stationary Flame.—An intensified program of investigation of turbulent diffusion coefficients in burner flames and their effect on flame propagation is under way. A Meker burner has been remodelled so that air and fuel flow into the burner can be measured. Calibration of flow meters for this use have been made. Apparatus for studying the controlled flame is being set up so that temperature measurements and sodium diffusion measurements may be conveniently made at various points in the flame. The local average velocity of the gas near the point at which the turbulence angle is being measured is simply obtained by suddenly withdrawing a sodium bead on a wire from the flame and taking motion pictures of the boundary of the incandescent vapor as it flows upward with the gas.

A Merlin engine now at New York University is being rebuilt so that it drives its own supercharger as a blower. This unit will be mounted on a trailer and taken to Lake Denmark and used to supply air for a stationary flame tube.

Shock Ignition Experiments.—The attempts to obtain ignition with the shock tube were unsuccessful due to the necessity for higher temperatures throughout the entire tube. This meant that the whole set-up has had to be redesigned and a much more elaborate apparatus constructed. The apparatus is nearing completion. It is hoped that this study will lead to an understanding of the phenomena of reignition in pulsejets.

THEORETICAL

Combustion in Flame Tubes.—Using one-dimensionalized thermo-aerodynamical equations, calculations have been made of pressures, temperatures, and flame front positions versus time in moving-flame tubes, in terms of the parameters: average *rate of release of energy* per unit mass in the burning gas, average *velocity,* and *acceleration,* of the flame front with respect to the gas. Values of these parameters will be chosen to fit data on the four-foot and eight-foot pyrex flame tubes.

This theoretical formulation has been extended to include a definite zone of burning (about 2 or 3 feet wide in the 8-foot tube). This characteristic may be included in the theory by assuming that each layer of gas burns for a finite time, less than the time taken by the flame front to travel the length of the tube.

NON-UNIFORM GASES

Effort on the theory of non-uniform gases in systems with chemical reactions has been concentrated on describing the *behavior* of systems in an appropriate phase-space, and in non-Maxwellian equilibrium. Some equations have been derived but, due to their complexity, analytic solutions seem feasible only under very special conditions.

FUTURE PLANS

More work is to be done on obtaining reproducible velocity time curves in the moving-flame tube; experiments on turbulence in the stationary burner flame and on the new shock tube will continue. Theoretical work on non-uniform gases is to proceed along the lines indicated, and calculations on the flame tube will be made.

PHASE NO. 2

In connection with liquid rockets and pulsating jet engines: to study (1) measurement of temperature dependence of conductivity and heat capacity of steels and other materials, (2) *adiabatic* calorimetry and metallography, (3) characteristics of heat transfer between hot flowing gases and walls, using measurements of gas velocity and temperature by radiation and thermocouple devices, (4) calculation of temperature changes in jet and rocket walls.

SUMMARY

The experimental study of the specific heat of steel at high rates of change of temperature is proceeding slowly; no quantitative results have yet been obtained. Theoretical work on non-linear heat conduction has been mainly an extension of previous results reported in the semi-annual report. Future work will continue along these lines.

EXPERIMENTAL

The apparatus for measurement of specific heats of metals undergoing rapid changes in temperature has been completed. A tiny thermocouple has been welded to a steel bar which is surrounded by a nitrogenous atmosphere, and which is heated rapidly by a current supplied by storage batteries. The change in temperature versus time, as well as the power input versus time is recorded on an associated oscilloscope. So far, only preliminary photographs have been taken of the temperature-time curves. It is expected to be able to infer from these measurements whether the anomalous changes in specific heats, which occur at particular temperatures under static conditions, also occur under rapidly changing circumstances, as in a rocket wall.

THEORETICAL

A general analytical method for solving problems in heat flow, in particular in wedges and tetrahedra, has been developed and is expected to be of use in connection with wall temperature measurements in jet engines. An investigation has begun of the types of boundary conditions which can be treated with the previously developed particular solutions of the non-linear heat conduction equation. Sample numerical calculations have also been made for heat flow in a standard steel plate.

FUTURE PLANS

Quantitative results concerning the variation of specific heat with temperature rate will be obtained. Also more controlled experiments are planned in which the temperature will be held to a small range around a high average temperature, while the effect of rapid rates of change of temperature are studied. Theoretical work on the non-linear heat flow equation will continue.

PHASE NO. 3

In connection with liquid rockets and pulsating jet engines: (1) to observe flame and particle motion, pressures, temperatures, densities and effects of turbulence in pulsating and rocket jet devices; (2) to study water stream analogues for gas motions in pulsating jets and rockets in order to determine characteristics of simple theoretical models, and (3) to use the above for theoretical treatments of the internal ballistics of jet devices on the basis of justified simple models.

SUMMARY

Observations of flame motions in the combustion chamber and tail pipe of small transparent-walled pulsejets were made; the back flow corresponding to the initiation of each cycle was easily discernible. Tests were run of the Mark I pulsejet, which has a combustion chamber and tail pipe adjustable in length; this jet has resonated for short periods and will be of use in indi-

cating the effect of varying several fundamental parameters, as well as in preliminary pressure instrumentation tests. In the immediate future, similar observations and studies are to be made of the JB-2 pulsejet engine at Lake Denmark.

EXPERIMENTAL

Transparent-walled Pulsejets.—Several streak photographic observations of the flame motion in transparent-walled pulsejets, which utilize a Minijet valve bank and fuel injection system, were made. These photographs appear as a sequence of traces, each made by a knot of flame travelling through the combustion chamber and down the tailpipe during each cycle. Each trace has ordinarily a "kink" in it (sometimes two if proper resonance has not been achieved). These kinks indicate that the motion of the flame is momentarily reversed as the gas reverses its flow and recompresses the fresh mixture in the combustion chamber. Some burning appears to be present in the combustion chamber at all times, which flares up as the fresh mixture is compressed by the back flow, and a new knot of flame shoots down the tube. The frequency of occurrence of these knots of flame agrees with the frequency (250 cps) usually quoted for the Minijet. The fact that there is continuous burning in the combustion chamber, instead of intermittent burning is possibly due to the short period of the Minijet cycle as compared to the time needed for combustion.

Adjustable Pulsejet.—Preliminary tests have been made of a pulsejet, designated as Mark I in previous reports. The lengths of the combustion chamber and tailpipe of this jet can be varied over a combined range from 4 to 6 feet. The preliminary trials were to establish the range of conditions under which the jet could be made to resonate; thus far, runs of only a few seconds duration have been made, but it has been observed that it is possible to obtain resonance at several settings of the tailpipe and combustion chamber lengths. When operating satisfactorily, average thrust, internal pressure, and fuel flow measurements will also be taken. In addition, this jet will be used to perfect pressure gage instrumentation for use with the JB-2 engine.

JB-2 Engine.—The JB-2 buzz bomb and engine have been transported to a test site at Reaction Motors, Inc. Pressure, temperature, flame and gas velocity and density measurements, will be made on the engine and on modifications of it, with and without ram air. For the present, tests are being made to determine starting and stopping characteristics and techniques. When this work has gained momentum, it will constitute a major phase of the Squid program at New York University, since results will be used to check and advance an existing theory of the Pulsejet.

Test Stands.—A thrust stand has been constructed to measure average thrusts exerted by the Mark I jet. A rotating arm miniature jet testing stand is in process of construction.

THEORETICAL

A report on a pre-compressing pulsejet has been kindly received by Mr. L. B. Edelman who had been concerned previously with relevant experimental work. His suggestions are being incorporated in a final review of the report which will be submitted to the Administrative Group of Squid for publication.

FUTURE PLANS

Studies of the Mark I jet are to continue, and observations and studies are to be made of the JB-2 engine at Lake Denmark.

PHASE NO. 4

In connection with liquid rockets and pulsating jet engines: to develop instruments for recording transient thrust and pressures, temperatures and densities of hot oscillating gases, and gas velocities.

SUMMARY

Progress in instrumentation during the first quarter was marked by the completion and initial testing of a variety of gauges and techniques. A great deal of necessary allied electronic equipment was acquired or constructed during this time.

Pressure Pickups, Amplifiers and Calibration.—Several different types of pressure pickups have been investigated as to their suitability for use in measuring transient pressures in pulsejets and flame tubes. Some types have already been eliminated.

A Cox crystal gauge was used to obtain preliminary estimates of pressures near the igniter in a moving-flame tube. Poor frequency response made the results doubtful.

Two tourmaline piezo-electric crystal pressure pickups were kindly furnished us by the Cambridge-Thermionic Corp. through the courtesy of Dr. A. Arons of Stevens Institute. An amplifier was built for use with these pickups which would have a good low-frequency linear response. This set-up was calibrated at several sensitivities; pressure measurements made with the gauge in the moving-flame tube indicated more adequate thermal insulation than the existing wax coating was needed in order to make more reliable long-time pressure records. Thus the tourmaline gauge in its present form is not practicable for pulsejet use, but it will be used on the moving flame tubes for short time records.

A water-cooled adapter has been built for use with both condenser type and magnetostriction type pickups. This will be mounted in the wall of the Mark I jet and the pressure gauges screwed into it—pressure being transmitted through a set of holes in the adapter to the sensitive face.

Several condenser gauge pickups have been built and tested. An FM circuit for use with these gauges was constructed and showed a good sensitivity. It is being modified to see if a greater output can be obtained for a given noise and microphonic level. The idea is to modulate a high frequency (50MC) oscillator having a small tuning capacity of which the gauge is a fairly large proportion. This will make the frequency shift greater for a given pressure. Then the signal is mixed with another oscillator and lowered to 10MC, the frequency required by the discriminator. The frequency *shift* is now a larger percentage of the carrier frequency. This unit, oscillator and cathode follower, to overcome line impedance problems, will be mounted on a cylindrical housing which screws onto the back of the condenser gauge. All parts will be buried in wax to avoid vibration.

A magnetostriction gauge has been constructed and operates successfully after the removal of an iron thermocouple from the nickel core where it was installed to check the water-cooling system. Since this type of gauge is sensitive to time rates of change of pressure, an integrating amplifier was built for use with the gauge. This unit integrates accurately down to 5 cycles per second. Experiments are being conducted to determine if the output of the integrating unit can be used with the tourmaline gauge amplifier and cathode ray tube.

It is necessary to calibrate the pressure gauges accurately under conditions which simulate those to be encountered in practice. For this purpose, a pressure gauge calibrator, consisting of a pressure chamber in which pressures varying periodically with the time can be produced, has been designed and is now out for bid.

Temperature Measurement Devices and Allied Equipment.—A photocell circuit for measuring the temperature of a tungsten ribbon lamp, has been completed. Calibration with an optical pyrometer will follow. The tungsten ribbon lamp itself is to furnish the background spectrum in the sodium "D" line reversal method of measurement of the temperature of the stationary burner flame and turbulence experiments.

A new high resolution spectroscope has been designed and is under construction. This, after delivery in April, will be employed in the sodium "D" line reversal method, and in the "two line" method of temperature measurement which employs potassium emission line, as well.

An electronic photometer, employing a photomultiplier tube, is to be used to measure the transient temperatures of the flaming regions in the pulsejets. This instrument is being calibrated at present against a thick sodium flame the temperature of which in turn will be determined by the sodium "D" reversal method. A satisfactory burner for the sodium flame has been developed from an ordinary welding and cutting torch. This enables the flow of gas and oxygen to be conveniently controlled with a consequent control on the flame temperature from 1800° C. to 2200° C.

Work is proceeding on the design and construction of a new highly-filtered, electron stabilized, power supply for the photomultiplier tube. An electronic DC to AC inverter of the type described in the OSRD Report 5868 has been constructed and is now being tested. This will eliminate the difficulties attendant upon the use of DC amplifiers for the photomultiplier output voltage.

Flame-coloring techniques.—In order to observe the flame temperatures in a pulsejet, or flame tube, it is hoped to be able to color the flames with some sodium or potassium compound and then employ the electronic photometer. Several unsuccessful attempts have been made to color a blow torch flame with sodium naphthanate—unsuccessful mainly because of high carbonation. Future work will include actual tests in glass-walled jets. It is hoped to receive a potassium naphthanate solution from Nuodex Co. as promised by Mr. Minich, Vice President. This may make it possible to use the "two line" system for determination of the temperatures.

Fluid Velocity Measurements.—It is hoped that it will be possible to measure the mass flow of gases in a pulsejet by means of radioactive tracer technique in which a pulse of radioactive material is injected into the engine and its progress observed thereafter. The use of Iodine 131, half life 8 days, is contemplated. However, inquiries at Oak Ridge as to its availabilty have not yet been answered.

The same method of measurement of gas velocity in the pulsejet tests or in the moving flame experiments is contemplated with the use of a pulse of sodium vapor instead of a radioactive element.

A study of hot-wire anemometry for measuring average fuel rates has begun.

FUTURE PLANS

The oscillographic equipment in the Woods Hole Mobile Laboratory is being studied and repaired. New oscillographic recording units are being built. It is hoped to test the pressure instrumentation on the Mark I jet, and try the transient temperature photometer with the transparent walled jet.

PHASE NO. 5

In connection with liquid rockets and pulsating jet engines: to study drag characteristics of pulsating jet and other devices under conditions of non-steady or of supersonic flow, using firing range photography, wind tunnel measurements and theoretical investigations.

SUMMARY

A theoretical analysis of non-steady flow, including aspirator effects, around a pulsejet tube has begun. This problem is being attacked by a step-by-step procedure, working from an extremely idealized case and gradually adding the complicating features of the real situation. Experimental work on artificially pulsed flow in pulsejet tubes and on flow through reed valves will begin as soon as sufficient personnel is acquired to handle this task.

THEORETICAL

The preliminary mode of attack on the non-steady flow problem consists in attempting to combine a set of sources, sinks, dipoles, and other elements, in the proper configuration to build up a three dimensional potential flow pattern in which the outline of the pulsejet tube would be one of the streamlines. Studies are for the moment limited to non-compressible non-viscous fluids; they will be extended to compressible real fluids involving pulsating elements with the ultimate aim of bringing out the flow and drag characteristics of pulsejet devices.

FUTURE PLANS

Theoretical work on the non-steady flow is to continue, with calculations being made on potential flow around a pulsejet. Experimental work on flow through reed valves is to begin.

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ABSTRACT

Flame studies were made to obtain information useful in determining fundamental parameters needed in development of flame propagation theory for both engine designs. Work is progressing on studies of specific heat of steel at high temperature change rates and of nonlinear heat conduction. Tests were run on Mark I pulse jet to determine effect of varying fundamental parameters. Pressure, temperature, and fluid velocity measurement instruments have been constructed and are being tested. Analysis of nonsteady flow around pulse jet tube has begun.
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