BIBLIOGRAPHY OF BOOKS AND PUBLISHED REPORTS ON GAS TURBINES, JET PROPULSION, AND ROCKET POWER PLANTS

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Bibliography of Books and Published Reports on Gas Turbines, Jet Propulsion, and Rocket Power Plants

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Preface

The purpose of this Circular is to present references to published sources of information on gas turbines and jet propulsion, classified so that the reader may select with ease articles of specific interest. For convenience, the references are grouped according to subject matter. To aid in the use of the bibliography, there is included a brief introduction on the classification and rating of jet engines. The introduction also discusses the scope and arrangement of the bibliography.

E. U. Condon, *Director.*

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INTRODUCTION

Classification of Recent Power Plants

A prevalent error among beginning students in jet propulsion is that some sort of push on surrounding air is required for propulsion. The presence of air around the unit offers a resistance, known as drag, to its forward motion. Air also has important effects upon the jet after it has left the unit. This action alters the shape of the jet and the time in which it is brought to rest relative to the surrounding air, but has no significant effect upon the thrust developed by the jet engine.

The thrust produced by a jet engine is simply the rate of change of momentum of the material entering and leaving the engine. To produce a change in momentum, the working medium is heated by chemical reaction known as combustion. Such heating causes the working medium to increase in volume, and produces the desired increase in velocity and momentum. By the third law of motion, the unit must undergo a change in momentum which is equal in magnitude but opposite in direction to that of the working medium.

Because rockets carry not only fuel, but also some other substance which reacts with it to produce a large volume of hot gas, the *rocket power plant* is in a class by itself. The rocket is distinguished by its self-sufficiency, and it is the only type of power plant capable of operating outside the earth's atmosphere. Its jet normally has a higher temperature and velocity than that of other jet engines.

The *gas-turbine* unit is a power plant consisting essentially of an air compressor, a combustion chamber in which the temperature and velocity of the air are increased greatly by burning fuel, and a turbine driven by the hot gas in much the same fashion as steam turbines are driven by heated water vapor. In the gas turbine the compressor and combustion chamber replace the boiler of a steam plant and are much smaller and lighter. The steam plant requires relatively pure water, while the gas turbine requires no water at all. However the gas turbine requires an efficient air compressor and much power is required to drive this compressor. The corresponding compression in the steam plant is accomplished within the boiler by heating the steam. The steam plant can operate on coal, while the application of solid fuels in gas turbines is not fully developed. The steam plant can be started by merely firing up the boiler, while the gas turbine must be started by other means, since there can be no combustion until the compressor is in operation and the compressor does not rotate until power is being developed by the turbine.

The *turbo-jet engine* is a gas-turbine unit in which the turbine develops only enough power to drive the air compressor. The forward thrust of the turbo-jet engine is derived from the high-velocity jet which emerges from the turbine. It is obvious that the primary application of the turbo-jet engine is as a power plant for aircraft.

If the turbine of a gas-turbine unit is designed to develop more power than that required to run the air compressor, which can be done by adding more turbine stages, the excess power developed by the multi-stage turbine can be utilized to drive an electric generator, propeller, or any other chosen machine. For flight application in which the turbine drives a propeller, the engine is usually called a *turbo-prop* or a *prop-jet engine*. Naturally the jet emerging from the turbine of such an engine is also utilized for its contribution to the forward thrust, though it has a lower velocity, and hence contributes less to the thrust than the jet from a turbo-jet.

It has been pointed out that gas-turbine units have compressors and turbines. The *ram-jet engine* operates upon the same principle of propulsion, but has neither a mechanical compressor nor turbine. The ram jet derives its name from the fact that it picks up its air by virtue of its forward motion, which is commonly called its ram. Obviously combustion cannot be started in a ram jet at rest, so that such a device must be launched by rockets or from an aircraft before it can become self-propulsive. The ram jet is sometimes called an athodyd, a word created from various letters appearing in the expression *aero-thermodynamic* duct, which was used formerly in referring to this device.

Although the ram jet has no mechanical compressor, this does not mean that the air in its combustion chamber is at the same pressure as the air through which the device is moving. Actually the air entering the ram-jet engine is compressed without the use of any moving parts by passage through a device called a diffuser. The diffuser has a smaller opening at its front than at its rear, so that the velocity of the air is decreased as it passes along the duct having a gradually increasing cross section. In this process part of the velocity head of the entering air is converted into pressure head in passing through the diffuser. In the combustion chamber which normally follows the diffuser, the pressure is therefore higher by an amount depending upon the characteristics of the diffuser and upon the forward velocity of the device. A properly designed diffuser accomplishes this transformation of velocity head into pressure head with high efficiency.

In general both the efficiency and the power output of a gas turbine can be increased by raising the temperature of the gases entering the turbine. The ability of the turbine blades to with-stand high temperatures, while subjected to the enormous stresses which accompany rotation at high speeds, now limits the maximum permissible operating temperature to a value more than 1,500°F below that which can be obtained by burning gasoline in air. The temperature of the gas entering the turbine is kept within the permissible range by using an excess of air, usually about four times the amount actually required to burn the fuel completely. Hence the gas emerging from the turbine still contains much oxygen which can be used for additional combustion, if desired.

The fact that this oxygen is present in the jet leaving the turbine of a turbo-jet engine has made possible the development of a device known as a *tail-pipe burner* or *thrust augmenter,* for application when sudden bursts of power are required. This type of thrust augmenter is thus essentially a combustion chamber of the ram-jet type installed in the tail pipe of a turbo-jet engine, so that extra fuel may be burned in the gases after they emerge from the turbine and before they leave the tail pipe. By this means the thrust can be increased materially above that of the normal jet. Since much more fuel is required per unit of additional thrust resulting from the augmenter than per unit thrust from the engine operating normally, the thrust augmenter must be considered as a device to be used only for emergencies.

The exhaust gases from reciprocating engines can be directed rearward in the form of jets which produce forward thrust. This process also is called thrust augmentation, and there are still other types of thrust augmenters which need not be considered here.

The type of engine employed in the German V-1 robot bomb is referred to variously as the *intermittent or pulse jet,* the resonance jet and the reso-jet. Like the ram jet it has neither mechanical compressor nor turbine. It usually has valves at the front which open to admit air, then they are closed by the explosion which follows each admission of fresh air. The adjectives intermittent and pulse have been applied since the combustion occurs as a succession of separate and distinct explosions. After each explosion in a pulse jet, the hot air escapes through the rear at high velocity and causes the pressure in the combustion chamber to fall below that of the atmosphere. When this condition is attained, atmospheric air opens the valves and rushes into the combustion chamber. Thus the pulse jet will operate while stationary, once a single explosion is set off in the combustion chamber. However, when the pulse jet is moving forward, ordinary ram also adds to the quantity of air entering through the valves, so that greater thrust can be developed when the engine is moving forward.

In all jet engines the ignition can be shut off once combustion is started. Since there are intermittent explosions in the pulse jet, it might be thought that a continuous or a timed spark would be required. However this is not the case ordinarily, since, after the first explosion, successive charges are ignited by contact with hot gas or hot metal parts.

The frequency of the explosions in a pulse jet is determined by the dimensions of the unit, which acts somewhat like an organ pipe. The theory of this type of power plant is more complicated and less completely understood than that of other types of jet engine.

Rating of Jet Engines

In rating power plants which do not utilize jets for propulsion, the concepts of power and efficiency have been found most useful, primarily because these characteristics of a given engine do not vary greatly with flight velocity. This is not true for a jet engine, for which the power is the product of thrust and forward velocity, provided that the velocity has resulted solely from the action of the jet engine being considered. Thus if a jet engine is to be rated on a power basis, great care must be exercised in specifying the operating conditions, particularly the flight velocity.

On the other hand, the thrust or force produced by a jet is much less dependent upon the operating conditions than is the power, and the thrust is therefore a more useful characteristic of the jet engine. As an example, consider the operation of a reciprocating engine and of a jet engine on a test stand. The former develops power which must be absorbed and which can be measured by means of torquemeter, brake, or dynamometer. The jet engine requires no such power absorber, since no power is developed. However a forward thrust, which can be perceived and measured readily, is developed by the jet and in this instance is called the *static thrust* to indicate that it is developed when the engine is at rest with respect to the earth and its atmosphere.

If it is felt desirable, for comparative purposes, to express the rating of a jet engine in terms of power, this can be done if both the thrust and velocity are known, but only when the engine being rated is solely responsible for all the velocity which has been attained. Under these circumstances the power is the product of thrust and velocity, and is usually designated as *thrust power* Thrust power may be expressed in foot pounds per second, and if a large unit such as 1 horsepower=550 ft-lb/sec is used, then the expression *thrust horsepower* is applied.

It is meaningless to say that a particular jet engine is a 1.000-hp engine, and it is also meaningless to say that this engine develops 1,000 lb of thrust. However if the engine develops 1,000 lb of thrust when it is the sole source of thrust in an aircraft which has attained a forward velocity of 550 ft/sec in level flight, it is perfectly definite to say that the engine develops 1,000 lb of thrust at 550 ft/sec . The thrust power under these conditions is $1000 \times 550 = 550{,}000$ ft-lb/sec, and the thrust horsepower is $550{,}000/550 = 1000$. Only at a velocity of 550 ft/sec are the thrust in lb and the thrust horsepower equal numerically.

In the turbo-jet engine the power developed by the turbine is always equal to the power required to drive the compressor and accessories. This turbine power can be rated in the same way as that of more familiar types of turbines. The power of the turbine is several times the thrust power of the jet, but is not available for any purpose except driving the compressor and accessories.

In the prop-jet engine the turbine develops more power than is required to drive the compressor, and the excess is used to drive a propeller. The power developed at the propeller shaft can be rated in the usual way in terms of shaft horsepower. Added to this shaft power is the thrust power of the jet, which again varies with forward velocity. Hence the rating of a hypothetical prop-jet engine might be as follows: 2,000 shaft hp at 10,000 rpm, plus 300-lb static thrust at sea level.

It is even more difficult to apply the concept of efficiency than of power to jet engines. Actually the numerical value of efficiency depends upon the system of reference, and there has been no general agreement as to the most useful definition. It is probably better for the uninitiated to omit considerations of efficiency and to think in terms of more definite terms such as specific fuel consumption, specific impulse, and ratio of weight to thrust.

The expression *specific fuel consumption* is used somewhat loosely to mean one of the following: (a) Pounds of fuel consumed per pound of thrust per hour, which for a turbo-jet engine, might be 1.3 lb/lb hr; (b) Pounds of fuel consumed per pound of thrust per second, which, for a ram jet at sea level, might be 0.001 lb/lb sec at 1,500 mph and 0.005 lb/lb sec at 300 mph for the same engine; and (c) Pounds of fuel consumed per thrust horsepower hour, which, for the turbo-jet engine mentioned in (a), would be 1.3 lb/thrust hp at 375 mph. Hence caution must be exercised in comparing existing numerical values of specific fuel consumption.

Specific impulse is the thrust obtained per unit weight of fuel consumed per unit time. Both specific fuel consumption and specific impulse, when applied to rockets, include as fuel consumed the total weight of fuel and oxidant (for example, alcohol and liquid oxygen).

The ratio of the weight of the power plant to the thrust which it develops is significant only when the operating conditions under which the thrust is developed are stated. For most turbo-jet engines at sea level the ratio is in the range 0.3 to 0.6.

In the literature on jet propulsion, frequent use is made of the term *Mach number*, which is simply the ratio of the velocity under consideration to the velocity of sound in gas at the same temperature. For example if a ram jet is flying at 1,500 mph through air in which the velocity of sound is 750 mph, the unit is said to be traveling at a Mach number of two.

Scope and Arrangement of the Bibliography

The topical subdivisions and the periods covered are clearly shown in the table of contents. Each subdivision is arranged chronologically and, within the chronological sections, alphabetically by author. "Anonymous" articles appear at the end of each chronological section. References to periodicals prior to 1940 are not included because the development of practical power plants has taken place primarily since that date. Since the gas turbine and the jet engine may, in the future, utilize energy from nuclear fission, some references in this field are included.

The journal abbreviations used are those employed in Chemical Abstracts. Volume numbers are in bold-faced type, and the date of issue is given in cases where page numbers do not run consecutively throughout a given volume. A number of references are made to unpublished papers presented before various societies. These are designated by the abbreviations M.P. or Pre. and, in some instances, copies may be purchased from the headquarters of the society concerned.

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