Московский государственный технический университет

Имени Н.Э.Баумана

Т.И. Кульбакова, А.Г. Котина

ОБУЧЕНИЕ ЧТЕНИЮ

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ПО СПЕЦИАЛЬНОСТИ

«РАКЕТНЫЕ ДВИГАТЕЛИ»

Учебно-методическое пособие

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Аннотация

Учебно-методическое пособие авторов Кульбаковой Т.И., Котиной А.Г. «Обучение чтению литературы на английском языке по специальности «Ракетные двигатели»: состоит из трех модульных блоков и трех дополнительных текстов. В каждый модульный блок включены три технических текста, взятые из оригинальной научно-технической литературы на английском языке, словари, включающие активную лексику (прежде всего терминологию) и лексико-грамматические упражнения на развитие и закрепление навыков понимания, осмысления и перевода оригинальных публикаций по изучаемой тематике, а также умения устного профессионального общения.

Для студентов старших курсов, обучающихся по специальности «Ракетные двигатели».

ПРЕДИСЛОВИЕ

Учебно-методическое пособие, состоящее из трех модульных блоков и дополнительных текстов, содержит оригинальные тексты, взятые из английской научно-технической литературы. Работа имеет практикоориентированную направленность, в пособие входят разнообразные лексико-грамматические упражнения, на отработку конструкций, характерных для языка научно-технической литературы, а также упражнения, направленные на развитие коммуникации с зарубежными коллегами; словари, содержащие активную лексику и специальную терминологию. Коммуникативные задания, имеющиеся в каждом модуле, помогут студентам готовить презентации, выступать с сообщениями, участвовать в обсуждениях.

Материал, представленный в пособии, может использоваться студентами как во время аудиторных занятий под руководством преподавателя, так и для самостоятельной работы.

Пособие предназначено для студентов старших курсов МГТУ им. Н.Э. Баумана, обучающихся по специальности «Ракетные двигатели».

Unit 1

1.Read and learn the following words and word combinations:

configuration - структура, конструкция, расположение, компоновка

nozzle -сопло, форсунка

propellant - ракетное топливо

thrust - тяга, сила тяги

mass flow rate - удельный массовый расход, массовая скорость потока

mass ratio - отношение масс, относительный массовый расход (в потоке)

degradation - старение материала, ухудшение качества поверхности

turbine -турбина

throat - горловина, соединительная часть

evaporation - испарение

cryogenics -физика низкихтемператур, криогенная техника

hypergolic propellant - самовоспламеняющееся топливо

swirl injector - вихревая форсунка

orifice - отверстие

plumbing - система труб

coaxial injector - форсунка с коаксиальным впрыском

annular aperture - кольцевая апертура, диафрагма

cross section - поперечное сечение

igniter - воспламенитель

motive power - движущая сила

2. Give the synonyms.

restriction, plumbing, issue, contraction, pipeline, problem, ensure, fulfil, enable, guarantee, implement, allow.

3. Translate the following word combinations into Russian.

Majority of large liquid propellant engine systems, important consideration, fluid flow laws, combustion chamber design, low specific impulse, hypergolic propellant combinations, high thrust engines, low thrust engines, hypersonic airbreathing propulsion system task.

4. Find English equivalents of the following phrases.

Двигатели малой тяги, еще один недостаток, газ под высоким давлением, прочные стенки, топливо подается в, прогорание

a further penalty, thermal degradation, strong walls, the propellant is fed to, low-thrust engines, high-pressure gas

5. Read and translate Text 1A, answer the questions.

1.What does the liquid propellant rocket engine system consist of? 2. How is the propellant fed into the combustion chamber? 3. Where is thrust developed?

Text 1 A. THE BASIC CONFIGURATION OF THE LIQUID PROPELLANT ENGINE

A liquid propellant rocket engine system comprises the combustion chamber, nozzle, and propellant tanks, together with the means to deliver the propellants to the combustion chamber.

In the simplest system, the propellant is fed to the combustion chamber by static pressure in the tanks. High-pressure gas is introduced to the tank, or is generated by evaporation of the propellant, and this forces the fuel and oxidiser into the combustion chamber. The thrust of the engine depends on the combustion chamber pressure and, of course, on the mass flow rate. It is difficult to deliver a high flow rate at high pressure using static tank pressure alone, so this system is limited to low-thrust engines for vehicle upper stages. There is a further penalty, because the tanks need to have strong walls to resist the high static pressure, and this reduces the mass ratio. The majority of large liquid propellant engine systems use some kind of turbo-pump to deliver propellants to the combustion chamber. The most common makes use of hot gas, generated by burning some of the propellant, to drive the turbine.

Since high combustion temperature is needed for high thrust, cooling is an important consideration in order to avoid thermal degradation of the combustion chamber and nozzle. The design of combustion chambers and nozzles has to take this into account. In addition, safe ignition and smooth burning of the propellants is vital to the correct performance of the rocket engine.

6. Translate the sentences into Russian paying attention to Infinitive.

1. Energia was equipped with a side-mounted cylindrical cargo carrier that could be configured as a payload to be delivered to the Moon or Mars. 2. So if the weight of the object to be delivered to higher orbit is one unit, then the mass of the system in LEO times the orbital altitude mass ratio is the total mass of the system required to change altitude. 3. Even with this information, there is much more to be learned from exploring the Moon and understanding its geology and structure. 4. The danger exists of an accident, such as that of the Challenger's, in which the conventional launcher could explode, damaging the reactor to be orbited and spreading fissile material from the damaged reactor stored in the payload bay either in the atmosphere or on the ground. 5. Following the launch of Sputnik by the Soviet Union, President Eisenhower’s administration elicited proposals to launch a satellite into orbit. 6. We know the questions to ask about underlying materials and structures and about samples when they can be obtained from the surface of Earth’s sister planet. 7. At the same time, the Australian launch range was abandoned in favor of a new launch center to be constructed in French Guiana. 8. Unfortunately, the lessons to be learned from the Europa 1 failures were ignored. 9. This decision provided a substantial growth potential for European satellites and demonstrated a determination to design the Ariane launcher for an extended lifetime.

7. Read and translate Text 1B, discuss the questions:

1. What are the functions of the injector? 2. What does the choice of the injector location depend on? 3. What is necessary to provide efficient injection?

Text 1B. THE COMBUSTION CHAMBER AND NOZZLE (PART 1)

The combustion chamber and the nozzle form the main part of the engine, wherein the thrust is developed. The combustion chamber comprises the injector through which the propellants enter, the vaporisation, mixing, and combustion zones, and the restriction leading to the nozzle. The throat is properly part of the nozzle. The combustion chamber has to be designed so that the propellants vaporise and mix efficiently, and so that the combustion is smooth. It must also withstand the high temperature and pressure of combustion, and in some cases cooling of the chamber walls is arranged. The combustion chamber joins smoothly on its inner surface to the nozzle, and the restriction in the combustion chamber and the nozzle together form the contraction-expansion or de Laval nozzle. The shape is defined by the thermodynamic and fluid flow laws together with the design requirements.

Injection. The injector has to fulfil three functions: it should ensure that the fuel and oxidiser enter the chamber in a fine spray, so that evaporation is fast; it should enable rapid mixing of the fuel and oxidiser, in the liquid or gaseous phase; and it should deliver the propellants to the chamber at high pressure, with a high flow rate. The specific injector design has to take into account the nature of the propellants.

For cryogenic propellants such as liquid oxygen and liquid hydrogen, evaporation into the gaseous phase is necessary before ignition and combustion. In this case a fine spray of each component is needed. The spray breaks up into small droplets which evaporate, and mixing then occurs between parallel streams of oxygen and hydrogen. For hypergolic or selfigniting propellants such as nitrogen tetroxide and UDMH, the two components, which react as liquids at room temperature, should come into contact early, and impinging sprays or jets of the two liquids are arranged. In some cases pre-mixing of the propellants in the liquid form is needed, and here the swirl injector is used, in which the propellants are introduced together into a mixing tube. They enter the chamber pre-mixed, and are exposed to the heat of combustion. In all cases, the heat of the gases undergoing combustion is used to evaporate the propellant droplets. The heat is transferred to the droplets by radiation, and conduction through the gas. The propellant passing through the combustion chamber has a low velocity, and does not speed up until it reaches the nozzle.

The requirement for a fine spray, together with a high flow rate, is contradictory, and can be realised only by making up the injector of many hundreds of separate fine orifices. Good mixing requires that adjacent jets consist of fuel and oxidiser. Thus, the hundreds of orifices have to be fed by complex plumbing, with the piping for two components interwoven. The design of the injector is a major issue of combustion chamber design.

Types of Injector. The simplest type of injector is rather like a shower head, except that adjacent holes inject fuel and oxidant so that the propellants can mix. Improved mixing can be achieved with the use of a coaxial injector. Here each orifice has the fuel injected through an annular aperture which surrounds the circular oxidant aperture, and this is repeated many times to cover the area of the injector.

The above injectors are used for propellants which react in the vapour phase. The fine sprays quickly form tiny droplets, which also evaporate quickly. The first is designed to make sure that propellants mix as early as possible, while still in the liquid phase, and is useful for hypergolic propellant combinations. In the second form, jets of the same propellant impinge on one another. This is useful where fine holes are not suitable. The cross section of the jets can be larger, while the impinging streams cause the jets to break up into droplets.

The injector can be located across the back of the combustion chamber, or it can be located around the cylindrical wall of the rear end of the combustion chamber. The choice depends on convenience of plumbing, and the location of the igniter, where used. For example, the HM7-B cryogenic engine, used to power the third stage of Ariane 4, uses a frontal injector unit with 90 coaxial injector sets which feed the liquid oxygen and liquid hydrogen into the combustion chamber at a pressure of 35 bar. In contrast, the Viking engine used to power the first stage of Ariane 4 uses 216 parallel injector pairs set in six rows around the wall of the combustion chamber, and these feed the hypergolic propellants UMDH and nitrogen tetroxide into the chamber. The number of injectors controls the flow rate and for high thrust engines many more are used. For the Vulcan engine, used as the single motive power for the Ariane 5 main stage, 516 coaxial injectors are used, delivering liquid hydrogen and liquid oxygen at 100 bar. This engine generates more than 1 mega-Newton of thrust.

8. Translate the sentences paying attention to Complex Subject.

1.China is likely to develop a strong manned space programme. 2. Wan Hu is said to have attached 47 rockets to a bamboo chair, with the purpose of ascending into heaven. 3. Powers much above 100 kW are unlikely to be achievable with the current technology. 4. The graphite itself appears to have suffered cracking and rupture once the protective surface had been eroded away. 5. Water seems to be present near the south pole. 6. In general there seems to be an increasing demand for heavy launchers, and consequent pressure to increase the capability. 7. Thus in effect, all sense of time will seem to vanish for beings that reach the speed of light.

9. Read and translate Text 1C, discuss the pyrotechnic igniters and the electrical spark igniters. Make a brief summary in English. *Useful phrases: The text describes (considers)… . First we need to identify/ clarify/ pinpoint the problem. I'd like to stress/ highlight/ emphasize the following points… . In addition/ moreover/ furthermore, there are other interesting facts we should take look at. That covers just about everything I wanted to say about… . In conclusion I'd like to… .*

Text 1 C. THE COMBUSTION CHAMBER AND NOZZLE. IGNITION (PART 2)

Secure and positive ignition of the engine is essential in respect of both safety and controllability. The majority of engines are used only once during a mission, but the ability to restart is vital to manned missions, and contributes greatly to the flexibility of modern launch vehicles. A typical requirement is to restart the upper-stage engine after an orbital or sub-orbital coast phase, which enables the correct perigee of a transfer orbit to be selected, for example, irrespective of the launch site. The restart capability is therefore becoming a more common requirement.

For single-use engines, including all solid propellant engines, starting is usually accomplished by means of a pyrotechnic device. The device is set off by means of an electric current, which heats a wire set in the pyrotechnic material. The material ignites, and a shower of sparks and hot gas from the chemical reaction ignites the gaseous or solid propellant mixture. Pyrotechnic igniters are safe and reliable. They have redundant electrical heaters and connections, and similar devices have a long history, as single-use actuators, for many applications in space. For this reason, they are often the preferred method of starting rockets. They are clearly one-shot devices, and cannot be used for restarting a rocket engine.

An electrical spark igniter, analogous to a sparking plug is generally used to ignite LH2/LO2 engines, which in principle provides the possibility of a restart. However, there is a difficulty in that the electric spark releases less energy than a pyrotechnic device, and there is also the possibility of fouling during the first period of operation of the engine, which may then put the restart at risk. Much design effort has been put into reusable igniters, and this will continue as restart capability becomes more desirable. For a single use, the Space Shuttle main engine has electric ignition for both the main combustion chamber and for the turbo-pump gas generators. In this case the spark is continuous for the period during which the igniter is switched on, and the system is contained in a small tube which forms part of the injector. The gaseous hydrogen and oxygen in the tube ignite first, and then the flame spreads to the rest of the chamber. By confining the initial gas volume to that in the tube, the risk of the flame being quenched by a large volume of cool gas is reduced. There is sufficient heat in the flame, once established in the tube, to prevent quenching.

For a secure restart capability on manned missions, hypergolic propellants must be used. These have the property that they ignite on mixing, and so starting the engine is simply a matter of starting the flow of propellants into the combustion chamber. This process is used for all manned flight critical engines. It was used for the Apollo lunar transfer vehicle, and is used for the de-orbiting of the Space Shuttle. The most common combination of propellants is nitrogen tetroxide and UDMH. As mentioned before, these are liquid at room temperature and can be stored safely on board for a long time, with no special precautions. The disadvantage of these propellants is their rather low specific impulse, which is a little more than half of that achievable with liquid hydrogen and liquid oxygen. Safe and secure restartable engines using more powerful propellants would be a major advance, but these are yet to be produced.

Restartable engines are preferred for upper stages, particularly for injecting spacecraft into elliptical transfer orbits. The use of this facility means that the argument of perigee can be selected correctly, independent of the launch site and time of launch. The higher exhaust velocity of cryogenic propellants combined with such a facility would convey a much greater advantage. The starting sequence for cryogenic engines is complicated, and will be dealt with after the propellant supply and distribution have been considered. Before this, the steering of rocket vehicles using thrust vector control will be discussed.

10. Translate the sentences paying attention to Complex Object.

1. This conclusion led France to propose the development of an engine of this type, based on the project commenced in 1980, to the European Space Agency. 2. Because this parameter has such a great influence on disk design, it is normal to hear structural engineers talk in terms of allowable wheel speed. 3. We assume the flow to be one-dimensional. 4. "I heard a whistle and a roar that grew louder and louder, and felt the giant craft begin to shake all over and slowly, very slowly break away from the launch pad." 5. This practice minimizes the influence of velocity-coupled energy waves and allows the influence of pressure-coupled waves to be more clearly recognized. 6. Atmospheric dynamicists often find it more convenient to treat the rotational pole as the North Pole. 7. In the future, we might expect surface-force compensation systems (so-called ''drag-free'' satellites) to be employed, so that the satellite orbits are entirely unaffected by nongravitational forces.

11. Translate the sentences paying attention to different meanings of "since".

1. The temperature drop through the turbine is now greater than the temperature rise through the compressor since the turbine drives the fan in addition to the compressor. 2. Since Dr. Gaubatz made his presentation, MIR has deorbited and crashed into the Pacific Ocean and the International Space Station

(ISS) has replaced it in 55-degrees inclination orbit. 3. Since the first warning may be the arrival of the radiation, so the entire crew may be required to be in a safe house. 4. However, the landing speeds do increase with takeoff mass ratio, since the operational empty weight of the vehicle increases with mass ratio. 6. Since 1970 the availability of materials has changed, so not all of the materials identified in the reference are available today.

12. Prepare presentations on the following subjects: "The Basic Configuration of the Liquid Propellant Engine" and" The Combustion Chamber and Nozzle Ignition".

UNIT 2

1. Read and learn the following words and word combinations

pitch angle - угол начального конуса (ЗК)
rocket firing- запуск ракеты
attitude measurement system- система пространственной ориентации (положение ракеты в воздухе)
steerable exhaust stream- управляемый поток выхлопных газов
gyroscope- гиросоп
divert *(v)*- отклоняться
yaw- отклонение от направления движения
gimballed engine- карданный двигатель
solid booster- стартовый двигатель, ракетоноситель
roll (n)- качка, воздействие крена
dead-weight - собственный вес конструкции
turbomachinery- турбины
high-thrust engine- двигатель большой тяги
bleeding off - отвод, выпуск
branch line - отводная линия

2. Translate the following word combinations into Russian:

on-board computers, attitude measurement system, flexible nozzle joint, exhaust stream, turbo-pump and propellant distribution system, roll errors, attitude error, difficult engineering problem, large solid-fuelled boosters, extreme conditions, electromechanical actuators, steerable exhaust stream, go off course, bring the rocket back on course.

3. Read and translate Text 2A, answer the questions:

1. How is thrust of the rocket engine developed? 2. Why is it necessary to conrole the trust vector? 3. How does the rocket behave after firing? 4. What measurements and what corrections should be made to keep the thrust vector parallel to the rocket axis? 5. What is made to correct errors in pitch and jaw?

Text 2A. THRUST VECTOR CONTROL

As we have seen, the thrust of the rocket engine is developed mostly on the exhaust nozzle, and is transferred to the vehicle itself through the mounting struts of the rocket engine. In effect, the rocket vehicle is being accelerated by a force applied at its lower extremity. This is a very unstable dynamical system, and a brief look at the history of rocketry shows that failure to control the thrust vector has been a major cause of loss. Indeed the development of modern control systems and on-board computers has significantly contributed to the success of the space programme.

Control systems and their theory are beyond the scope of this book, but some useful ideas emerge from simple considerations. Consider any portion of the rocket's trajectory: the early part in which the ascent is vertical, the flight at constant pitch angle, or any controlled path while the rocket is firing. The requirement is to keep the thrust vector parallel to the rocket axis, unless the pitch angle is being changed. To keep the thrust vector parallel to the axis there must be an attitude measurement system, a computer to calculate the attitude error and the necessary correction, and a steerable exhaust stream to bring the rocket back on course. The earliest control system used gyroscopes (the A4 rocket), and these are still used, in a more sophisticated form, to generate the error signal. The A4 gyroscopes used a direct electrical connection to the rocket engine. When the rocket went off course, the relative motion of the gyroscope was transferred electromagnetically to the engine to generate a corrective transverse thrust.

The A4 used four graphite vanes, set in the exhaust stream of the single rocket engine to divert the thrust vector, in order to correct errors in pitch and yaw. This was the first successful use of thrust vector control and was an essential step in the development of the modern rocket vehicle. The vanes, being set in the hypersonic exhaust stream, generated shocks, which reduced the thrust. The benefit of a simple and robust thrust vector control far outweighed the loss of thrust. An uncontrollable rocket is useless as a vehicle.

Many modern engines have either a gimballed mounting for the whole engine, or a flexible nozzle joint so that the nozzle itself can be moved. The latter is often used on solid boosters. Use of a gimballed engine requires that the propellant supply lines are to some extent flexible. These flexible joints are usually in the lines from the tanks to the turbo-pump inlets; the turbo-pump and propellant distribution system are all mounted on the engine itself, to avoid flexible joints operating at high pressures. If there is more than one motor to a stage, then separate control of the motors can be used to correct roll errors as well as those in pitch and yaw. If there is only a single motor then roll must be controlled by separate small rocket motors mounted, typically, on the side of the vehicle and directed tangentially.

4. Complete the text using the following words: *control, engineering achievement, flows, reduced, be steered, failure, deflection.*

The Japanese Mu rocket is solid fuelled, and has a fixed nozzle. For thrust vector control, cold liquid is injected into the exhaust stream through a ring of injectors set around the throat of the nozzle. Transverse thrust is generated by injecting liquid at the side toward which the rocket axis should be tilted. The liquid _______ down the inside of the nozzle, and cools the exhaust stream as it evaporates. The pressure at that side of the nozzle is thereby _______, and the stream diverts towards the cooler gas. By carefully selecting which injectors are opened, accurate _______ of the thrust vector can be achieved without resorting to a flexible joint on the nozzle.

This difficult engineering problem has had to be solved for the large solid-fuelled boosters employed on the Space Shuttle and Ariane 5. Here the thrust is so great that _______ to steer the booster thrust vector would render the vehicle uncontrollable. At the same time it is not possible by the use of cooling techniques to generate sufficient transverse thrust. The flexible joints on the Space Shuttle and Ariane 5 boosters are a major _______. They allow the whole thrust of the boosters to be steered, and at the same time they survive the heat and pressure existing at the entrance to the nozzle.

Because the thrust of the engine is so high, only a very small _______ of the stream or nozzle is needed. On the other hand, the mechanism for deflection has to deal with large forces, extreme conditions, or both. Gimballed engines can _______ by hydraulic or gas-powered pistons attached to the nozzle, and if the thrust is not too large then electromechanical actuators can also be used.

5. Translate the sentences into Russian paying attention to Participle.

1. Delays with the Shuttle, due to technical difficulties, discouraged satellite operators, obliging them to seek other launch possibilities. 2. People trying to walk radially outward on a spinning carousel will feel a surprising force pushing them sideways, parallel to the circumference. 3. These propulsion systems can offer major advantages when applied to existing rocket launchers. 4. The hot gases then drive an expansion turbine to drive the turbopump before being introduced into the combustion chamber. 5. Bones are living tissue, constantly being strengthened by calcium extracted from the blood and destroyed by returning calcium to the blood. 6. Current vehicles still being launched at Complex 17 include both Delta 2 and Delta 3 vehicles. 7. The so called ‘‘planetary nebulae’’ - the remnants of the outer layers of red giant stars, having exhausted their

thermonuclear fuel, become unstable and eject most of their mass into interstellar space. 8. Soon, having transferred to the Central Scientific and Research Institute of Machine Building, he began work to use this principle to develop a plasma thruster.

6. Read and translate Text 2B, give a brief summary taking advantage of the words and word combinations below.

to be reliable over the life of the engine, to work under extreme conditions, maximum efficiency, propellants, thin-walled tanks, to be of paramount importance.

Text 2B. LIQUID PROPELLANT DISTRIBUTION SYSTEMS

The most commonly used distribution system employs turbo-pumps to deliver the propellants to the injectors at high pressure and flow rate. The turbo-pumps are driven by hot gas, generated in a separate combustion chamber or gas generator. This basic idea has many variants which seek to confer improvements in efficiency, but here we shall examine only the basic concept, leaving variants until later in this chapter.

There are a number of design problems to be overcome. Above all, such pumps have to be reliable over the life of the engine, and they have to work under extreme conditions and at maximum efficiency. The mass of turbo-machinery is part of the dead weight of the rocket and limits the achievable mass ratio. The total mass of a rocket engine seems small compared with that of the vehicle and propellant at lift-off. However, once the propellant is exhausted, the rocket engine mass becomes a significant part of the total dry mass. There is therefore a strong incentive to reduce the mass of the engine as far as possible, and this has an affect on the design of the turbo-pumps.

The propellants will be of different densities, and the mixture ratio is generally quite far from 50 : 50, so the pump for each component has to be individually sized. Changes in mixture ratio during flight, or minor adjustments to keep the ratio constant, require the pumps to be controllable individually. The propellants may be corrosive or cryogenic, or they may have other properties not compatible with simple engineering: for example, hydrogen leaks very easily through gaskets and seals. Mass limitations prevent the use of redundant delivery systems, and so reliability is of paramount importance.

The propellant tanks should be thin-walled to reduce dead weight, but have to bestiff to transmit the thrust up the rocket without the need for additional structure. The propellants also have to be delivered to the turbo-pump at quite a high pressure to prevent cavitation. For both of these reasons it is convenient to pressurise the propellant tanks to 5-10 bar, although this is far too small to deliver the propellant to the combustion chamber of a high-thrust engine. Sometimes this pressure is provided by a separate compressed gas supply-generally helium or nitrogen-stored on board, or one of the propellants is converted to gaseous form by the heat of the combustion chamber and used to pressurise the tanks. This pressure can also be supplied by bleeding off into the propellant tanks some of the gas used to drive the turbines. The temperature of this gas needs to be kept low, so some cooling may be needed before introduction to the tanks.

The gas generator which provides the high-pressure gas to drive the pumps is a miniature combustion chamber, burning part of the propellant supply. It needs a separate igniter, and it has to be supplied with propellant, usually by a branch line from the turbo-pump itself. The propellant burned in the gas generator represents a loss of thrust, and is included in the mass ratio. The mass decreases as a result of the gas generator operation, but no thrust is produced. Some of this loss can be recovered by exhausting the gas, after it has driven the turbine, through a proper miniature nozzle in order to develop some additional thrust. The natural temperature of the burning propellant in the gas generator would be close to that in the main combustion chamber, rather too high for the turbine blades. Sometimes water is injected into the gas generator to reduce the temperature of the emerging gas, or a very fuel-rich mixture is used, which achieves the same result. A fuel-rich mixture is also less corrosive.

Basically, the former measure requires a water tank on board, and the latter implies a waste of propellant; both reduce the efficiency of the rocket. Some rocket engines with turbo-pumps make use of propellant evaporated in the cooling of the combustion chamber to drive the pump. This saves the mass of the gas generator, but generally results in a lower inlet pressure, and is suitable for low thrust engines. For modern high-thrust engines, the inlet pressure needs to be of the order of 50 bar, and this requires a gas generator powered turbo-pump.

Turbines are most efficient when the hot gas inlet and exhaust pressures are very similar. When used for electricity generation or on ships, for example, many stages are used with different sized turbines, each with a small pressure drop to make the most efficient use of the energy. If the turbine exhaust of a rocket turbine were to go directly to the ambient, then the pressure ratio would be too large, and the efficiency would be low. This can be overcome by utilising a multi-stage turbine, but the extra stages add weight. It is therefore necessary to reach a compromise. An important variant of the gas generator system is the staged combustion system. The exhaust from the turbine enters the combustion chamber, instead of the ambient. This has two advantages: the pressure ratio for the turbine is more compatible with high efficiency, and the remaining energy in the turbine exhaust contributes to the main combustion chamber energy and ultimately to thrust.

Where the exhaust from the turbines is used directly to generate thrust the efficiency is low, because the temperature at the nozzle inlet is much lower than that in the main combustion chamber. As we have seen, the exhaust velocity depends on the square root of the combustion chamber temperature. If the exhaust from the turbines is allowed to enter the combustion chamber, the residual heat contained in the gases contributes to the heating of the combustion products in the chamber. This provides a way of using the waste heat that is thermodynamically much more efficient. Engines which do this in general produce a higher exhaust velocity for a given thrust.While turbo-pumps driven by gas generators are widely used, there are other methods of providing the hot gas that can save in complexity by making use of the gas created by regenerative cooling. Here the propellant, often liquid hydrogen, is passed through the cooling channels of the combustion chamber and nozzle, emerging as a hot gas, which is then diverted to drive the turbine. In some cases, there is only one turbine and the oxidant pump is driven by a gear chain.

In others, there are two turbines, in series, with the hot hydrogen emerging from one turbine and flowing to the second. The exhaust is sometimes then diverted into the combustion chamber to recover any remaining heat. This system, because of its simplicity, was used on early engines, and is now being specified again for upper- stage engines to reduce the cost and mass associated with a separate gas generator. This system is sometimes described as the topping cycle or expander cycle, and has many variants.

7. Translate the sentences into Russian paying attention to Independent Participle Construction.

1. The receiving antenna was finally installed at the Data Center in 1998, the delay being due to the commercialization of the program. 2. Luna 14 was making measurements of the micrometeorite and plasma environment, its radio tracking being used to study the structure of the lunar gravity field. 3. With more electric propulsion systems flying than ever before, the choice of proven electric propulsion thruster types is becoming larger. 5. The engine operates as a ramjet with the afterburner acting as the ramjet's burner. 6. The velocity of sound is equal to the propagation speed of an elastic pressure wave within the medium, sound being an infinitesimal pressure wave. 7. Obviously, both the apogee and perigee points change in position, the rate of change being a function of the satellite altitude and plane inclination angle. 8. Solid propellant rocket motors being built in approximately 35 different countries today, the technology is well understood and disseminated.

8. Translate the sentances paying attention to translation of "rather than".

1. The detonation wave does the compression and heating rather than a mechanical pump. 2. For space activities to change, there has to develop a similar customer base requiring hundreds of flights per year, rather than eight to twelve. 3. Since the ascent to orbit with a two-stage vehicle is in two segments, the lower-speed, lower-altitude segment might use a hydrocarbon fuel rather than hydrogen. 4. As the speed increases, the engine performance becomes characterized by energy conservation rather than by combustion: energy conservation is far more important than chemistry.

9. Read and translate Text 2C, discuss the questions.

1. When does the cavitation generally occur? What processes are taking place during the cavitation? 2. Why is the cavitation a seriouse problem for rocket engine turbo-pumps? 3. How can the cavitation be avoided and what measures should be taken?

Text 2 C. CAVITATION.

This is a well-known problem which occurs when a liquid is in contact with a rapidly moving vane on, for instance, a ship's propeller. The pressure in the liquid at the retreating surface of the vane is reduced, and it can be low enough to allow local boiling to take place. Bubbles of vapour are produced, and they then collapse when they enter a region of normal pressure. The tiny shock waves produced damage the surface of the vane. Severe cavitation can produce significant quantities of vapour at the inlet of the turbo-pump. This very quickly reduces the efficiency of liquid transfer as the rotation speed increases and larger regions of vapour appear.

For rocket engine turbo-pumps the rotation speed is very high indeed-10,000- 30,000 rpm is typical-and the liquids are quite likely to be cryogenic. These are ideal conditions for cavitation to take place. Damage to the vane surface may not be too serious for a single-use pump, but if a significant amount of vapour forms then the turbo-pump will 'race' due to the reduced load and damage the bearings and other components. The flow rate of propellant will also suddenly decrease, with a consequent drop in thrust, which in most cases would lead to disaster. This is therefore a very serious problem.

To avoid cavitation, the pressure at the inlet to the pump must be kept high enough to prevent local evaporation of the liquid. This can be realised in several ways. Static pressure in the propellant tanks may be sufficient, and the acceleration of the rocket can generate additional pressure at the pump inlet, if the propellant is reasonably dense and the supply lines are axial and sufficiently long. This is unlikely to be the case with liquid hydrogen, which has a specific gravity of 0.071. Where other measures cannot succeed, and particularly where the pump speeds are very high, a two-stage pump is required. The low-pressure pump-often called an impeller-simply has the task of raising the inlet pressure at the main pump to an acceptable level of, say 10-20 bar. It can therefore be rather simple in design. If it is mounted directly at the inlet and on the same shaft as the main pump, it may not be possible to avoid cavitation at the impeller blades if the shaft speed is very high. Some improvement can be realised by correct shaping of the impeller blades, although they may need to be driven by a gear train. The Space Shuttle main engine uses separate low-pressure turbo-pumps driven by a small fraction of the propellant flow, diverted from the outlets of the high-pressure pumps. This allows the low and high-pressure pumps to be individually optimised.

Pogo. This humorously named phenomenon is nevertheless a serious problem. The pressure at the inlet to the combustion chamber should be constant for a steady flow of propellant to the combustion chamber and hence a steady thrust. As mentioned above, the acceleration of the rocket raises the pressure at the pump inlet, and it is possible to develop a feedback loop between the instantaneous thrust and the pump inlet pressure. If this happens, then a small natural fluctuation in thrust will result in a fluctuation in flow rate to the combustion chamber. The fluctuation will make itself felt, with a slight delay (the time taken for the propellant to flow from the pump to the chamber), as a further fluctuation in thrust. This, in turn, changes the inlet pressure at the pump, which causes another thrust fluctuation, and so on. The time delay is usually in the 10-ms region, and the reinforcement mechanism can result in the build-up of an oscillation in thrust with a period of about 100 Hz. This is very damaging to the rocket and the payload, as a small fluctuation in a mega-Newton of thrust is a large force. For this reason, pogo correction systems are fitted to liquid-propellant rocket engines.

The basic principle is to introduce some capacitance to the system in order to smooth out fluctuations in inlet pressure. A small sealed volume is connected to the propellant line, adjacent to the combustion chamber inlet, and is filled with propellant. It is pressurised using gas from the tank pressurisation system. If the line pressure falls momentarily, additional propellant is very quickly injected from the storage volume, to raise the pressure to its original value. If the pressure rises then some of the excess propellant flows into the sealed volume, again restoring the line pressure to normal. It is usually only necessary to fit pogo correction to one propellant line, which in most cases is the oxidant line. This system can be passive, or it can be actively controlled, to deal with, for example, the much greater pressure fluctuations which occur when an engine is shut down or is started. In such cases the pogo correction system can also protect the turbine from cavitation. For a single-use engine, damage to the turbines at shut-down is of no consequence, but for a reusable engine a turbine damaged due to 'racing' in a heavily cavitated fluid is a serious matter.

10. Give a brief summary of Text 2C. The words to help you:

local boiling, bubbles of vapour, tiny shock waves, efficiency of liquid transfer, ideal conditions for cavitation, turbo-pump will 'race', flow rate of propellant, drop in thrust, dense propelant, supply lines, specific gravity.

11. Translate the sentences payig attention to Gerund.

1. Prolonged exposure to weightlessness itself can result in deconditioning many of the body's systems. 2. It was equally important for them to be able to obtain images anyplace on the globe without their rivals knowing about it. 3. After leaving the expansion turbine, the hydrogen is introduced into the ramjet combustion chamber. 4. When discussing propulsion, hypersonic flight or atmospheric entry, the question of cooling is always prominent: cooling implies discarding the rejected energy. 5. This is why we are relatively certain of the total mass of the asteroids, even without having counted all of the small ones. 6. Each of these missiles had substantial deficiencies that prevented them from being used in real combat conditions. 7. Two additional launch vehicles, the Zenit-2 and Zenit-3SL, were developed without using military prototypes. 8. Constructing a silo launcher would have required a large amount of time, so most test launches of this missile were done from a hastily constructed aboveground launch facility.

12. Translate the sentences paying attention to translation of "in terms of".

1. In terms of mass ratio to orbital speed and of oxidizer to fuel ratio, the authors examined six principal propulsion categories with hydrogen as fuel. 2. The pulse detonation rocket is essentially equivalent to the rocket in terms of weight ratio to orbital velocity. 3. In fact the airbreathing launcher is more efficient than Concorde in terms of fuel use. 4. To attempt a Neptune mission with chemical propellants in trans-Mars trip times is impossible in terms of the requirements. 5. Note that this criterion depends on the system of units one uses: it is not cast in terms of numbers such as Mach or Reynolds. 6. In terms of our current best space propulsion systems, it takes over one year to travel to our planetary neighbor, Mars.

13. Prepare presentations on the following subjects: “Thrust Vector Control”, “Liquid Propellant Distribution System” and “Cavitation”.

UNIT 3

1. Read and learn the following words and word combinations:

filmcooling – пленочное охлаждение

storablepropellant – топливо длительного хранения

refractory – огнеупорный, жаропрочный

lend itself to – быть подходящим для, служить для

increment – увеличение, наращивание

pressure-fed – с вытеснительной подачей (топлива)

actuator – привод, силовой привод

dissipate – рассеивать

purge – продувать, прочищать

expandercycle – цикл с фазовым переходом

bulkhead – перегородка, шпангоут

expansion ratio – степень расширения

incorporate – объединять, включать

vent – выпускать, сбрасывать, отводить

2. Translate the following word combinations into Russian:

melting point, film cooling, structural strength, cryogenic propellants, further complications, complicated structure, operating temperature and pressure, to retain its structural strength at this high temperature, to generate a little additional thrust, the advantage to be gained is significant.

3. Replace the prepositional phrases by word combinations:

For example: efficiency of cooling - cooling efficiency.

cooling of the combustion chamber and nozzle, evaporation of the liquid film, extraction of energy, performance of the rocket, total burn time of the engine.

4. Translate the sentences paying special attention to "that and those" in different functions.

1. Considerable attention was then paid during that year to improving the cost levels and analyzing the operating costs announced for the Space Shuttle and those observed for the early stages of the Ariane operational phase. 2. Since most of them have orbits that are roughly similar to those of the planets (low inclination and eccentricity), they have sometimes been called minor planets. 3. It is the blunt leading edges and nose plus the winged configuration that reduces their lift-to-drag ratio. 4. Hypergolic propellants are those that spontaneously ignite on contact with each other. 5. That vast difference in outlook between the aircraft manufacturers and the ballistic missile manufacturers remains today. 6. One of the serious impediments to commercial operations is that there is only one launch site available per launcher. 7. It is only through detailed component energy balancing, coupled with unsteady detonation analysis and loss modeling that accurate estimates of the PDE/PDRE performance may be obtained. 8. However, it must be said that this particular status quo is comfortable, and profitable, for the telecommunications and launcher companies. 9. It is this third and last stage that is responsible for bulk flow momentum change, and therefore for the rocket thrust.

5. Translate the sentences paying special attention to "because - because of".

1. Earth time and ship time are different, but it is Earth time we must be concerned with, because that is the time in which the project team is living. 2. There is in fact an important consequence with respect to changing velocity, because velocity is a vector. 3. Because of the vacancy created in the electron shell, there is the transition of one of the shell electrons to that vacancy, accompanied by the emission of X-rays. 4. Because there are no aerodynamic forces in space, any motion initiated will continue until it is negated by a counter propulsion force of equal magnitude and opposite direction. 5. Because of the

mass ratio to orbit, these are generally vertical takeoff and horizontal landing vehicles.

6. Read and translate Text 3A, answer the questions:

1. What is the simplest method of cooling of liquid rocket engines? 2. What cooling temperatures does the film cooling method work best with? 3. What does the use of film cooing in rocket engines result in? 4. What is called damp cooling and what can it be used for? 5. What is regenerative cooling and in what type of engines is it used? 6. How is the smooth flow of propellants through the walls of an engine provided?

Text 3A. COOLING OF LIQUID-FUELLED ROCKET ENGINES

Before considering examples of actual rocket engines it is convenient to consider the cooling of the combustion chamber and nozzle. High combustion temperature produces a high exhaust velocity. A typical temperature is 3,000 K, but the melting point of most metals is below 2,000 K and so the combustion chamber and nozzle must be cooled. This is done by allowing part of the cool unburnt propellant to carry away the heat conducted and radiated to the walls of the chamber and nozzle. This can be done in a number of ways.

Technically, the simplest method is film cooling. Part of the liquid propellant is caused to flow along the inside surface of the combustion chamber and down the inside surface of the nozzle. The evaporation of this liquid film has a certain cooling effect, and results in a layer of cool gas between the wall and the hot gases passing from the chamber and through the nozzle. The cooling film is introduced through part of the injector next to the wall. This type of cooling works best with lower combustion temperatures such as are encountered in storable propellant engines. The Ariane 4Viking engine uses film cooling, which results in the simplest configuration of the combustion chamber and nozzle. In this engine the injector is mounted on the cylindrical wall of the chamber rather than at the end, and it is therefore simple to inject part of the UDMH parallel to the wall. This method is suitable for cooling the combustion chamber and throat, because the efficiency of cooling decreases with distance from the injector. The nozzle is less well cooled and may glow red hot, cooling by radiation. The use of a refractory cobalt alloy enables the nozzle to retain its structural strength at this high temperature.

Cryogenic propellants, liquid hydrogen and liquid oxygen generate much higher combustion temperatures, and the cold liquid lends itself to efficient cooling. In such cases the walls of the combustion chamber and the nozzle are made hollow, and one of the propellants-usually hydrogen-is passed through the cavity. This cools the chamber and nozzle walls effectively, at the expense of additional complication and cost in construction. The gas resulting from the waste heat carried away from the walls can be used in various ways. The simplest approach is to exhaust the gas through many small nozzles round the rim of the main nozzle, to generate a little additional thrust. This is called dump cooling, and it can be used to cool the long nozzle of an engine designed for use in a vacuum, where it may be inconvenient to pipe the gas back into the top of the engine. As mentioned above, the gas may also be used to drive the turbine or to pressurise the propellant tanks. The most efficient way of using this gas is to feed it back into the combustion chamber and burn it to contribute to the main thrust. This has two advantages: the chemical energy of the gas-part of the propellant load of the rocket is not wasted, and the waste heat conducted and radiated out of the combustion chamber is returned to the main combustion. This latter point is very important. Fundamental thermodynamics tells us that extraction of energy from a hot gas depends on the temperature difference between the source and the sink. After cooling the walls, the temperature of the propellant is far below that in the combustion chamber, so not much energy or thrust can be extracted from it. On the other hand, if it is passed into the combustion chamber and heated to the combustion temperature, then much more of the energy acquired during cooling is released. This technique is called regenerative cooling, and results in the most efficient engines. Of course, it leads to further complications and results in a heavier engine, and as always there must be a correct balance between extra thrust and extra weight.

If hot spots on the chamber and nozzle walls are to be avoided, the propellant must be in contact with the wall everywhere, and the flow must be smooth and continuous. Moreover, there is a large quantity of heat to carry away. Most engines therefore have the nozzle and lower part of the combustion chamber made from metal tubes welded together, wall to wall, to form a continuous surface. The propellant flows through this multiplicity of tubes freely and is, at the same time, constrained to cover the entire inner wall. In some cases the tubes are parallel to the axis of the thrust chamber, and in others a spiral form is used to produce a longer flow path. The two may be combined, with the spiral form being used on the nozzle and the axial form of the combustion chamber. The design of such a complicated structure is very demanding both on the materials and on the function. The operating temperature and pressure are very high, and any interruption of the flow during operation would be fatal. Nevertheless the advantage to be gained in terms of exhaust velocity is significant. The Saturn V engine developed an exhaust velocity of around 4,200 ms-1, while the SSME develops a velocity of 4,550 m s-1.

As mentioned above, these apparently small gains have a major impact on the performance of the rocket, in terms of payload and achievable velocity increment.

7. Translate the sentences into Russian paying attention to Conditional Sentences.

1. If the astronaut were to turn around and walk along the rim in the direction opposite to the spin, the Coriolis force would be upward and the apparent weight of the astronaut would be reduced. 2. If we wanted the spacecraft to reach Pluto in one year, its average speed would have to be 614,100ft/ sec (187.2 km/sec). 3. In those test, the flight weight engine would have had an installed thrust-to-weight ratio of 22, had it been installed in an aircraft. 4. If a commercial

hypersonic transport version of the first stage was contemplated, then the propulsion system would have to be changed to a cruise-focused system, replacing the acceleration-focused system of the launcher. 5. The increasing human presence in space calls for newer and newer support and rescue capabilities that would make space an easier' and safer frontier. 6. The propellant storage would accommodate about 100 tons of propellant or up to five propellant tanker payloads. 7. Were this to happen, reactor walls would melt, plasma would cool too much and too fast (quench), and fusion would stop.

8. Read and translate Text 3B, give a brief summary.

Text 3B EXAMPLES OF ROCKET ENGINE PROPELLANT FLOW (PART 1)

For most modern launchers, gas-pressure-fed systems are not sufficiently powerful for use in first or second stages. This is just a matter of the required thrust, as pressure-fed systems cannot deliver propellant at a very high flow rate without prohibitively high tank pressures. Pressure-fed systems are advantageous for upper stages, because the reduction in weight helps to produce a high mass ratio, and the thrust and propellant flow requirements are less demanding. Before considering examples of gas generator and turbo-pump systems, a modern pressure-fed system used on the Ariane 5 upper stage will be described.

The Aestus engine on Ariane 5. This is the restartable engine used on the upper stage of the Ariane 5 rocket. The propellants are hypergolic: monomethyl-hydrazine (MMH) and nitrogen tetroxide. Both of these are liquid at normal temperature and pressure (NTP) and can be stored safely. Ignition of the rocket results simply from the chemical reaction that occurs spontaneously when the propellants meet in the combustion chamber.

There is a single combustion chamber gimballed to allow ±60 of thrust vector control through two actuators. The nozzle is bell-shaped with an expansion ratio of 30 to develop an exhaust velocity of 3,240 m s-1 in vacuo; as an upper stage, it operates only in vacuo. Regenerative cooling is employed for the combustion chamber walls and the inboard part of the nozzle, for which the MMH is used. It flows from the tank into the lower part of the hollow walls, and having extracted heat it enters the combustion chamber through the injector. This is a multi-element coaxial injector with which the swirl technique is used to mix the MMH with the nitrogen tetroxide. While the combustion chamber and the inboard part of the nozzle are regeneratively cooled the nozzle extension is not; it is allowed to glow red- hot in use, dissipating heat by radiation.

There are two fuel tanks and two oxidiser tanks. The fuel (MMH) tanks are spherical, while the oxidiser tanks are slightly elongated, reflecting the differing volumes of fuel and oxidant. The oxidant-fuel ratio is 2.05. Both types of tank are made of aluminium alloy. The spherical shape uses the minimum volume of aluminium to contain the propellant, and also produces the minimum wall thickness to safely contain a given pressure. Thus the propellant tanks are optimised for a pressure delivery system. This can be employed for an upper stage in which the quantity of propellant is relatively modest, but the huge amounts of propellant needed for the first stage cannot be contained in spherical tanks. This approach for an upper stage also minimises the length, and hence the structural mass required. The tanks are pressurised with helium from a pair of high-pressure tanks; the gas pressure being moderated by a reducing valve to around 18 bar to pressurise the propellant tanks. The propellant is delivered to the engine at 17.8 bar, and the combustion chamber it self operates at 11 bar. There is a considerable pressure reduction across the injector. The passive anti-pogo system is fitted to the oxidant line.

Before the engine is started, the system is purged with helium to remove propellant residues from test firings. The oxidiser valve is then opened, followed, after a short delay, by the fuel valve. The full thrust of 29 kilo-Newton is developed 0.3 seconds after the start signal. Shutdown is initiated by closing the MMH valve, followed shortly by the closure of the oxidiser valve. The engine is then purged with helium to prepare it for the restart. The total burn time of the engine is 1,100 seconds, and the vacuum exhaust velocity is 3,240 m s-1. This engine has been used successfully for the upper stage of Ariane 5 since 1999. The restart capability has been demonstrated for an improved range of orbit options. A pump-fed version has been tested for higher thrust applications.

9. Complete the text using the following words:

is driven, be adapted, heritage, properties, cooling channels, combustion products, delivers.

The RL 10 engine. This engine, still a workhorse of the United States programme, has a _______ going back to the earliest liquid hydrogen-liquid oxygen engines designed in the United States; the first RL 10 was built in 1959. A pair of RL 10s power the Centaur upper stage, used on Atlas and Titan launchers. In its latest manifestation, the RL 10A-4-1, it has a vacuum thrust of 99 kN, weighs only 168 kg, and develops an exhaust velocity of 4,510 m/s. It is the archetypal upper-stage engine, optimised for vacuum use. It uses the expander cycle, with hydrogen heated in the _______ of the combustion chamber and upper nozzle powering the turbine of the liquid hydrogen pump, before entering the combustion chamber as gas. The liquid- oxygen pump _______ by a gear chain, from the hydrogen turbine; it _______ oxygen, as a liquid, to the injector. The engine is re-startable, giving a greater range of potential orbits.

The RL 10 engine has recently been considered as a potential chemical engine for Mars exploration, because it can _______ to run using methane, instead of hydrogen, with the liquid oxygen. It is thought possible to produce methane on Mars from the carbon dioxide in the atmosphere, and this could be used for a return journey. Methane has other useful _______ in that it is easy to store and has a high density as a liquid. It may therefore be the propellant of choice for long chemically propelled voyages. The exhaust velocity is of course smaller because of the presence of carbon dioxide in the_______; values as high as 3,700 m/s are predicted.

10. Translate the sentences paying attention to "both" and its combinations.

1. An airbreathing launcher has the potential to reduce the mass ratio to orbit by one-half. It is clear that results in a significantly smaller launcher, both in weight and size. 2. Both the United States and Russia have experimented with magnetic refrigerators to condense the vaporized propellants back to liquids and return them to the storage tanks. 3. Both the operational example and the demonstrator example have the same ICI value as the previous rocket case. 4. From both sources, the combustor length for maximum energy efficiency is 0.40 meters. 5. The lift loading lines have the same value in both operational areas. 6. The other great debate was single-stage-to-orbit versus two-stage-to-orbit. Both have advantages and disadvantages depending on operational concept and geographical location.

11. Read and translate Text 3C, discuss the questions:

1. What is the SSME intended to? 2. Where are the propellants stored and how are they delivered to the combustion chamber? 3. What is the most important aspect of the SSME design? 4. Describe the paths of the liquid hydrogen.

Text 3 C. EXAMPLES OF ROCKET ENGINE PROPELLANT FLOW (PART 2)

The Space Shuttle main engine. The SSME uses the same cryogenic propellants as the Ariane engines, but is different in concept. It is intended to be reused many times, and to be highly efficient. It uses the staged combustion system to drive the turbo-pumps, and has full regenerative cooling. The vacuum exhaust velocity is 4,550 m s-1, and the thrust is controllable from 67% to 109% of nominal.

The propellants are stored in the external tank. The hydrogen tank is pressurised by gas from the regenerative cooling of the combustion chamber, and the oxygen tank by gas resulting from regenerative cooling of the oxidiser gas generator. The propellants are delivered to the combustion chamber by separate turbo-pumps, with individual gas generators. These are called 'pre-burners' because the exhaust from the turbo-pumps passes to the combustion chamber for further burning. The propellants are raised from tank pressure to combustion chamber pressure in two stages, using separate low-pressure and high-pressure turbo-pumps.

The most important aspect of the SSME design, for our purposes, is the fact that all the exhaust from the fuel delivery system passes into the combustion chamber so that all the energy stored in the exhaust contributes to the thrust. This recovery of energy is much more efficient if enabled at high temperature in the combustion chamber than by venting the gas at the turbine exhaust temperature as in, for example, the Vulcain engine. Since the propellant flow is rather complicated, we shall examine each propellant system in turn.

The unique aspect of the SSME is that nearly all of the hydrogen from the fuel tank passes through the pre-burners or gas generators, and only a small fraction passes directly to the main combustion chamber after driving the low-pressure fuel pump; as the exhaust from the pre-burners will eventually enter the combustion chamber, this does not matter. It has the further advantage that a fuel-rich mixture- to keep the pre-burner exhaust temperature low enough for the turbine blades-is automatically achieved.

Liquid hydrogen arrives at the inlet of the low-pressure pump at the static pressure of about 2 bar. The pump raises this to 18 bar. It is powered by hot hydrogen gas emerging from the cooling channels in the combustion chamber. The liquid hydrogen is then pressurised to 440 bar by the high-pressure turbo-pump. It then follows three separate paths. Part of the flow enters the cooling channels in the combustion chamber and emerges as hot gas, which is routed to the low-pressure fuel pump turbine to drive it. Emerging (now cool) from the turbine some of it goes to pressurise the fuel tank, and the rest cools the hot gas manifold before entering the combustion chamber. The second path passes through the cooling channels of the nozzle before joining the third path, which routes most of the hydrogen to both of the pre-burners.

The exhaust from the pre-burners is effectively hydrogen-rich steam, at quite a high temperature (850 K). This is the fuel supply for the main combustion chamber. Consequently the hydrogen "injector" is handling hot gas rather than cold liquid, and is called the "hot gas manifold". This takes the exhaust from both turbo-pumps and feeds it into the combustion chamber, where it burns with the liquid oxygen, to generate a thrust of 2 MN.

All of the liquid hydrogen is routed through the chamber or nozzle cooling channels, and afterwards becomes gaseous. In contrast, most of the oxygen remains in the liquid state right up to the combustion chamber injector. The static pressure in the oxygen tank is higher than in the hydrogen tank-about 6 bar-and the low- pressure oxygen turbo-pump raises this pressure to about 30 bar for the inlet to the high-pressure oxygen turbo-pump. After this turbo-pump the pressure of the liquid oxygen is 300 bar. The flow now divides into four separate paths. The first path carries some of the liquid oxygen to the low-pressure turbo-pump to drive the turbine, and on leaving the turbine it re-enters the main flow to the high-pressure turbo-pump. In the second path the liquid oxygen cools the high-pressure pre-burner and is converted into gas, which is used to pressurise the main oxygen tank and the pogo corrector. The third path carries most of the oxygen to the main combustion chamber injector. The fourth and final path takes liquid oxygen to an additional turbo-pump attached to the main pump shaft, which boosts the pressure to 500 bar for injection into the two pre-burners. This oxygen is burned with part of the hydrogen and forms the hot steam in the pre-burner exhaust, which then enters the combustion chamber. These routes can be followed in Plate 4. The thrust and the mixture ratio are controlled by the fuel and oxidant pre-burner valves which regulate the flow of oxygen to the pre-burners, and hence the turbine speed. Since the mixture is fuel rich, it is only necessary to vary the oxygen flow to the pre-burners to control the speed.

As with all highly developed devices the SSME seems complicated in its propellant distribution. The main aim is, however, simple: to run each element of the system at its maximum efficiency, and then convert all the energy released from the burnt propellants into thrust, at a high exhaust velocity. In previous chapters we have seen that high exhaust velocity is the ultimate determinant of the success of a rocket as a launcher.

12. Prepare presentations on the following subjects: "Cooling of Liquid-Fuelled Rocket Engines" and "Rocket Engines".

Supplementary Texts

Text 1.

The Ariane Viking engines. This series of rocket engines is used to power the first and second stages of the Ariane 4launch vehicle. There are three variants. The short nozzle version-Viking 5C-is used in groups of four to power the first stage; the Viking 6-more or less identical to the 4C-is used for the strap-on boosters; and the Viking 4B powers the second stage and has a long nozzle to produce greater efficiency at high altitude. There is little difference in the propellant delivery systems.

The Viking engine uses the storable hypergolic propellants nitrogen tetroxide and UDMH25 (unsymmetrical dimethyl hydrazine with a 25% admixture of hydrazine hydrate). There is no ignition system because the propellants ignite on contact, which, as mentioned before, is convenient for restartable engines and is also a very reliable system even when the engine is not restartable. In addition to the tanks of propellant, water is also carried to act as a combustion coolant, and high-pressure nitrogen to operate the valves. (High flow rates demand large-diameter pipes and large valves, which are difficult to operate purely electrically). There are two valves to control the flow of the individual propellants to the turbo-pump. This is a single turbine, developing 2,500 kW at 10,000 rpm and driving two pumps on the same shaft; the different flow rates are accommodated by having different sized pumps. A separate pump, driven through a reduction gear, distributes the water. Part of the propellant flow (about 0.5%) is diverted to the gas generator, where the propellants react to produce the hot gas which powers the turbine. Water is injected to cool the combustion products. The hot gases pass to the turbine and then to the turbine exhaust, which is nozzle shaped to add to the thrust. Part of the hot gas is diverted to pressurise the propellant tanks. This static pressure is quite high-about 6 bar- and is enough to prevent cavitation at the pump blades with these room - temperature liquids.

The thrust is stabilised by two control loops. One controls the temperature of the hot gases from the gas generator by varying the amount of injected water, and the other uses the combustion chamber pressure to control the flow of propellant into the gas generator and thus the turbo-pump speed. In this way the thrust is kept constant. A third balancing system controls the relative pressures of the two propellants at the injector to keep the mixture ratio correct. The pogo corrector is a small cylindrical chamber surrounding the main oxidiser pipe and linked to it by small holes; it is pressurised from the nitrogen supply used to operate the valves. The combustion chamber and nozzle are cooled with a film of UDMH from the lower part of the injector. The 5C develops 678 kN of thrust at sea level, with an exhaust velocity of 2,780 m s-1. The high altitude 4B variant develops 805 kN of thrust with a higher exhaust velocity of 2,950 m s-1.

This engine has been used successfully for the upper stage of Ariane 5 since 1999. The restart capability has been demonstrated for an improved range of orbit options. A pump-fed version has been tested for higher thrust applications.

Text 2.

The Ariane HM7 B engine. The HM7 B liquid hydrogen-liquid oxygen engine is used to power the third stage of the Ariane 4series of launchers and a version is presently used as a cryogenic upper stage for the Ariane 5 while the Vinci engine is being developed. The schematic is shown in Plate 3. It uses a single gas generator and turbine driving two pumps on different shafts. The high-speed pump driven directly by the turbine at 60,000 rpm delivers the liquid hydrogen at 55 bar, while the low speed pump driven through a gear chain at 13,000 rpm delivers the liquid oxygen. The static pressure in the gas lines is raised by coaxial impellers to a level sufficient to prevent cavitation The gas from the turbine is exhausted through a shaped nozzle to generate additional thrust. The nozzle throat and combustion chamber are cooled regeneratively by passing most of the hydrogen through 128 axial tubes forming the wall, before it enters the combustion chamber itself. The rest of the nozzle is dump cooled by routing a fraction of the hydrogen through 242 spiral tubes and then through micro-nozzles at the end of the main nozzle. The gas generator is fed a hydrogen rich mixture, which keeps the temperature down and reduces oxidation of the turbine blades. The gas generation rate-and therefore the propellant flow rate-is stabilised by controlling the oxygen flow into the gas generator. The valves which control the flow of propellant are operated by helium at high pressure, switched by electro- magnetic valves. A pogo corrector is fitted to the liquid oxygen line, pressurised by helium.

A particular requirement of cryogenic engines is to purge the system before ignition, and to deal with the boil-off of the cryogenic propellants. Neither liquid oxygen nor liquid hydrogen can remain liquid under achievable pressures, and so the tanks have to vent continuously to the atmosphere until a few minutes before launch. The need for purging is twofold. Firstly, all the components-the valves, pumps and combustion chambers-need to be brought down to the temperature of the propellants to avoid localised boiling of the cryogen. This would generate back pressure and interrupt flow. Secondly, the entire system must be freed of atmospheric gases which would freeze and block the system on coming into contact with the cryogenic liquids. For this reason, purging valves are provided to enable a free flow of cold gas from the boiling cryogens through the system before the main valves are opened.The pre-launch sequence includes the chilling and purging of the system. The gas generator is then started-in this case by a pyrotechnic igniter. When the turbines are delivering full power, the main propellant valves are opened and the main combustion chamber is started by another pyrotechnic igniter.

The Vinci cryogenic upper-stage engine for Ariane 5. Further increase in the payload mass to geostationary transfer orbit (GTO) with the Ariane 5 makes use of a cryogenic upper stage, to replace the Aestus storable propellant engine. This engine, called Vinci will power the upper stage from 2006. For an upper stage, mass ratio is very important, and the system does not use a gas generator to power the turbo-pumps, instead the turbines are driven by hot hydrogen emerging from the cooling channels of the combustion chamber and upper nozzle. This expander cycle can be used when the propellant delivery rates and chamber pressure are not too high. The two turbines are connected, in series, on the hot hydrogen line, the gas being routed first to the hydrogen turbine. On emerging from the oxygen turbine, the gas enters the combustion chamber; all the hydrogen follows this route while the oxygen is delivered in liquid form to the combustion chamber straight from the turbo-pump. The exhaust velocity is 4,650 m/s, thanks to this efficient regenerative cooling and an expansion ratio of 240 (achieved by a deployable nozzle extension). The thrust is 180 kN. These values are to be compared with the thrust of the Aestus, 29 kN, and its exhaust velocity, 3,240 m/s. This is an example of the modern trend to reduce the complexity of rocket engines, and to address all the factors that make the vehicle efficient. This engine only weighs 550 kg, which helps to keep the mass ratio of the upper stage high.

Text 3

The Ariane 5 Vulcain cryogenic engine. The Vulcain cryogenic engine used for the main propulsion stage of Ariane 5 develops 1.13 MN of thrust and operates at 110 bar combustion chamber pressure. It is similar to the HM7 B in design, but uses full regenerative cooling of the combustion chamber and nozzle. The single gas generator drives two separate turbo-pumps, with nozzle exhausts. The propellants enter through 516 coaxial injectors and generate an exhaust velocity of 4,300 m s-1.

The propellants are stored in a cylindrical tank 24 metres long, which also provides the main structural element of the stage. Combining the functions of fuel tank and rocket structure reduces the dead weight. The 25.5 tonnes of liquid hydrogen occupies most of the volume of the tank, the 130 tonnes of oxygen being stored in the upper portion, separated by a hemispherical bulkhead. The density of liquid oxygen is much higher than that of liquid hydrogen. The hydrogen tank is pressurised by gaseous hydrogen produced by the regenerative cooling circuit- that is, heated by the combustion chamber. The oxygen tank is pressurised by helium stored in a spherical tank containing 140 kg of liquid helium. The helium is heated by the turbo-pump exhaust. A separate gaseous helium supply is used to operate the propellant valves and the pogo corrector, and to pressurise the liquid helium tank. This is stored in separate spherical tanks.

The gas generator and the combustion chamber are both fitted with pyrotechnic igniters. A separate solid propellant cartridge provides the gas pressure to start the turbo-pumps. The hydrogen and oxygen then enter the gas generator and the combustion chamber and are ignited. The engine is started 8 seconds before firing the boosters. This allows it to be checked out before the irrevocable booster ignition. The engine is stopped by closing the propellant valves.

The Vulcain 2 engine specified for Ariane 5 launchers after 2002, to give an additional tonne of payload into GTO, is an updated version of the Vulcain engine used before 2002. The new engine incorporates a number of improvements, the most notable being an increase of 10% in the mass of propellant available, as a result of changing the fuel-oxidiser ratio of the engine in favour of more oxygen; the ratio was changed from 5.3 to 6.15. Because of the higher density of liquid oxygen, this can be accomplished without increasing the total volume of the propellant tanks. More oxygen increases both the mass ratio and the thrust. Normally, this would be expected to decrease the exhaust velocity because the mean molecular weight of the exhaust increases, however other improvements mitigate this effect and in fact the exhaust velocity is some 30 m/s faster. The exhaust velocity is maintained by a higher expansion ratio-60 compared with 45. The cooling of the longer nozzle is accomplished by outing the turbo-pump exhaust into the nozzle extension to create a film of cooler gas, protecting the walls from the hot exhaust. The quantity of oxygen carried is increased by 23% and a re-designed two-stage turbo-pump for the oxygen line gives a 40% higher delivery rate. This combined with an increase in throat area gives a higher thrust of 1,350 kN, compared with 1,140 kN for the Vulcain.

The RS 68 engine. From 1990 onwards the United States has been developing the Evolved Expendable Launch Vehicle, a complementary vehicle to the Shuttle. The Delta family of launchers is one manifestation of this programme, and amongst its technological innovations has been the RS 68 engine, claimed to be the first new large rocket engine to be developed in the United States since the SSME (Space Shuttle Main Engine). Its main features, compared with the SSME, are its simplicity and low cost. The number of separate components has been reduced by 80%, compared with the SSME, and the amount of manual manufacture has been cut to the minimum, most components being made by digitally controlled machines. The RS 68 has now been flight qualified on launches of the Delta IV vehicle. It is the United States counterpart to the Vulcain 2 engine on Ariane 5. The vacuum thrust is about twice that of the SSME, being 3.13 MN, while the exhaust velocity is relatively low for a liquid hydrogen-liquid oxygen engine, at 4,100 m/s. This is because of the low expansion ratio; this engine is intended to operate on the main stage of the Delta IV, and so is not optimised for vacuum. The sea-level thrust is relatively high at 2.89 MN, reflecting its purpose as an all-altitude booster. The weight of the engine is 6.6 tonnes, heavier than the SSME, but the thrust-to-weight ratio is about the same. Like the SSME, it can be throttled from 100% down to 60%. An engine of this thrust needs to make use of the gas generator-turbo-pump propellant delivery system to provide the necessary mass flow rates, and this contributes to the lower exhaust velocity; the hydrogen emerging from the turbo-pump exhaust is used for the roll-control thrusters of the Delta vehicle. Fundamentally, this is a low-cost expendable engine designed to provide high thrust for a heavy launcher.

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