PRODUCTION OF POWER

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Contents

Summary

In order to produce power a rotating machine is required. For large scale power production the turbine is the only feasible machine. It is driven by a fluid containing energy which is transferred to the turbine blades and then to the turbine shaft as mechanical energy. This can readily be converted into electrical energy in a generator.

Turbines may be driven by a range of different fluids but, for all large applications, it is water, steam or air. Hydro turbines make use of the potential energy of water directly and do not require any heat input to a thermodynamic cycle. Steam turbines are by far the most common turbines used for power generation and make use of the thermal energy in steam. Gas turbines similarly use the thermal energy in a hot gas which is basically hot air produced directly by the combustion of fuel. Wind turbines use the kinetic energy of air in motion but are severely limited in output by the low concentration of the energy.

All turbines must produce electrical energy as it is required by the consumer. This means that turbines are required to be flexible and responsive in their operation. Neither electrical nor thermal energy can be stored on a significant scale so all plants operating on a thermodynamic cycle must follow the load demand in their electrical output. This is neither always possible nor desirable so hydro turbines deriving their power from the stored potential energy of water are a valuable asset. This can be taken a step further in the concept of pumped storage. Here reversible pump-turbines use surplus electricity to pump water to an elevated storage reservoir. In times of high demand or rapidly increasing demand this energy can be recovered by running the machines as turbines and putting the electricity back into the grid system.

An important aspect of all thermodynamic cycles is that only part of the heat put into the cycle can be converted into work. The remainder must be rejected to the environment. In the case of gas turbines this heat rejection is simply via the hot exhaust gases. In steam turbines however the exhaust steam is condensed by cooling water for reuse in the cycle. It is the cooling water that carries away the rejected heat. Where no large bodies of cooling water are available, cooling towers must be employed. Most

rely on partial evaporation to promote cooling but dry systems have been developed for dry regions.

1. Introduction

1.1 Prime Movers

Large scale production of work is required to produce electrical power in sufficient quantities to meet the demand for electricity. The direct production of electricity by other means such as chemical or photoelectric is insignificant in the context of power production. Various machines have been devised to produce work from suitable sources of energy which are usually fluids with a high degree of potential or thermal energy. These are generally known as *prime movers* and have many applications beyond the power industry such as manufacturing and transport. Prime movers generally fall into two major groups namely *reciprocating engines* and *turbomachines*.

Reciprocating engines include internal combustion engines and steam engines. Both operate on a closed cycle with the high energy working fluid trapped in a cylinder. Expansion of the gas or vapor drives a piston which in turn, turns a crankshaft and produces continuous rotational motion. In the closed cycle, the fluid system boundary is made to move under the influence of the fluid pressure and, in so doing, produces work W by way of a certain force F due to pressure p being applied to a given area A which it moves over a certain distance L.

$$W = F\,L$$
$$W = p\,A\,L \qquad (1)$$

In a reciprocating engine there are a number of strokes per unit time so the power output P can be expressed in terms of the number of power strokes N per second.

$$P = p\,L\,A\,N \qquad (2)$$

In a reciprocating engine L is the stroke, p the average pressure, A the area of the piston and N is determined from the number of power strokes per engine revolution per cylinder and the number of cylinders. The above parameters depend upon the geometric design of the engine and upon the particular thermodynamic cycle employed. Different internal combustion engines have different modes of combustion and this influences the average or mean pressure in the cylinder.

Turbomachines include turbines which produce work as well as compressors and pumps which require work. Steam turbines, gas turbines and hydro turbines all fall into the former category. They operate on an open cycle with the high energy working fluid passing through the machine continuously. There is a decrease in pressure as the fluid passes through the machine and the energy in the fluid is transferred to the blades in the turbine which in turn drive a shaft and produce continuous rotational motion. Energy in the fluid is thus transferred to the rotating components. Theoretically the amount of work produced is equal to the difference between the initial and final energies of the fluid. In a hydroturbine the work output per unit mass w_{out} is equal to the difference in elevations z between the water level above and below the turbine multiplied by the gravitational acceleration g. This represents the potential energy of the water.

$$w_{\text{out}} = g\left(z_1 - z_2\right) \tag{3}$$

In a steam turbine the work output per unit mass w_{out} is equal to the difference in enthalpies h between the inlet and outlet. Enthalpy is a combination of the thermal energy and the pressure energy of the steam.

$$w_{\text{out}} = h_1 - h_2 \tag{4}$$

In a gas turbine the work output per unit mass w_{out} is equal to the difference in temperature T between the inlet and outlet multiplied by its specific heat at constant pressure c_{p}. This is equivalent to the enthalpy change of the gas.

$$w_{\text{out}} = c_{\text{p}}\left(T_1 - T_2\right) \tag{5}$$

Turbines are very versatile and produce high outputs from relatively small machines. The rotary motion of turbomachines allows for high speeds and smooth running. This is a severe limiting factor in reciprocating engines which cannot be made in large sizes due to the excessive forces produced by heavy reciprocating parts.

1.2. Scope of Topic

Having identified turbines as the dominant method of producing power in power plants, this topic is concerned primarily with turbines and their applications.

Power Plant Technology covered the more theoretical aspects of thermal power plants and dealt with thermodynamic cycles, heat transport and material considerations. These are all aspects where there is the potential for generic improvement to increase plant efficiency and reliability. This topic covers various aspects of power generation particularly those where there is likely to be future development, for example, improved overall cycle efficiency by the use of combined cycle plants. It follows on from *Production of Steam* which was concerned with the generation of steam for use in large prime movers such as steam turbines. This topic is concerned primarily with the use of this steam to produce power but does recognize that the use of hot gas in a gas turbine is also a significant contributor.

As clarification, the individual articles within this topic cover the most important aspects of power generation. Only current technology for large scale power generation is considered. The main reason for this approach is that thermal power plants are very capital intensive and have long operating lives. This makes the industry conservative with regard to unproven innovations and technological evolution is slow. It is possible that some plants will still be running half a century after commissioning. Reference to current technology will therefore be appropriate for many years to come. Nevertheless there are many new developments and possibilities for adopting other technologies. These will be outlined in this introductory topic. Naturally it is impossible to predict which way technology will develop but indications are that the thrust will be towards the implementation of combined cycles to obtain better overall thermal efficiencies and towards life extension and repowering of existing turbine installations.

1.3. Current Trends

There are two distinct aspects driving changes in power plant technology. One is environmental considerations and the other is financing of new installations.

With regard to the environment there has, in recent years, been an effort to reduce the emissions from fossil fuel fired plants. This can be done by appropriate selection of fuel, using an alternative fuel or burning the fuel in a different manner. Since the demand for electricity is ever increasing it follows that there is some penalty in decommissioning an existing plant. It is possible in certain cases to repower the plant with an alternative fuel or an alternative method of steam production so that the existing steam turbine can be kept in operation.

The aspect of financing is related to reduced economic growth and reduced government spending on large scale projects. Generally private enterprise is less willing to invest in projects with a low return and a long pay-back period. There is thus an incentive to retain existing plants in operation. The financial implications of extending the life of an existing plant are often more favorable than those of building an entirely new plant as a replacement.

It should be noted in this context that well maintained and carefully operated steam turbines are capable of running far beyond their design life. Furthermore the efficiency of turbines has reached a plateau so that new turbines do not necessarily have a better efficiency than those that have just reached the end of their originally projected life.

2. Turbine Fundamentals

2.1. Thermodynamic Cycle

In all thermodynamic cycles heat is received by the working fluid from a heat source at an elevated temperature and rejected to a heat sink at a temperature close to ambient conditions. For a working fluid to operate in this manner it must inevitably be at a higher pressure when receiving heat and at a lower pressure when rejecting heat. The working fluid is pumped to the higher pressure before receiving heat and expands to the lower pressure before rejecting heat. It is evident that the higher the pressure and higher the temperature of the working fluid before expansion the greater its energy and the greater the amount of work that can be produced when it expands to a lower pressure. All turbines operate as the part of a thermodynamic cycle where expansion of the working fluid occurs. Ideally this expansion is without any heat or frictional losses. Without heat transfer between the fluid and its surroundings, the expansion is adiabatic and, without frictional losses, it is thermodynamically reversible. A reversible adiabatic process is, by definition, an isentropic process. Idealistic thermodynamic cycles such as the Rankine cycle for steam cycles and the Brayton cycle for gas cycles are based on this assumption of isentropic expansion in the turbine as well as isentropic compression in the pump or compressor.

2.2. Internal Efficiency

In real turbines the working fluid passes through the turbine at high velocities. This results in fluid friction between the working fluid and the turbine components. Any fluid friction in turn results in slight heating of the fluid so that it does not leave the turbine at as low a temperature as it would have, had there been no fluid friction. Since the amount of work done by the working fluid in the turbine depends upon the temperature and pressure difference between the inlet and the outlet, it follows that an increased outlet temperature results in less work being produced. A comparison of this actual work produced with the ideal work that could be produced by an isentropic process gives an indication of the internal or isentropic efficiency of the turbine. This can be expressed mathematically as follows where η_{internal} is the internal efficiency.

$$\eta_{\text{internal}} = actual\ work / ideal\ work \tag{6}$$

Considering the fluid properties, work can be expressed in terms of the temperature difference ΔT and the specific heat at constant pressure c_{p}. Thus the internal efficiency is given by

$$\eta_{\text{internal}} = \left(c_{\text{p}}\,\Delta T\right)_{\text{actual}} \Big/ \left(c_{\text{p}}\,\Delta T\right)_{\text{ideal}} \tag{7}$$

This equation may be simplified when applied to gas turbines as the difference in specific heat c_{p} for the two expansions is usually negligible. This gives the following expression for internal efficiency.

$$\eta_{\text{internal}} = \Delta T_{\text{actual}} / \Delta T_{\text{ideal}} \tag{8}$$

The original equation may also be simplified when applied to steam turbines. In steam turbines however some steam condenses so latent heat is involved and specific heat cannot be used. However, enthalpy h can be used instead since the following definition applies to specific heat at constant pressure.

$$\Delta h = c_{\text{p}}\,\Delta T \tag{9}$$

This gives the following relationship for internal efficiency.

$$\eta_{\text{internal}} = \Delta h_{\text{actual}} / \Delta h_{\text{ideal}} \tag{10}$$

This actually applies to both steam turbines and gas turbines but is commonly used only on steam turbines.

2.3. Momentum Principles

When a fast moving fluid is made to change direction, this is a change in the velocity vector relative to the original velocity vector even if the magnitude of the velocity has not changed. The greater the angle through which the fluid is turned from its original direction the greater the change in the velocity vector. Also, when a fluid is accelerated or decelerated, while continuing in the same direction, there is a change in velocity in that direction. In both cases a force must be applied to the fluid to make it change its velocity with reference to the original direction. Conversely a fluid which changes direction will impart a force on whatever object is making it change direction. An equation derived from Newton's Second Law of Motion can be used to demonstrate that the force F in the original direction of motion is related to the mass flow rate M of the fluid and the change in velocity ΔV in the same direction.

$$F = M\,\Delta V \qquad (11)$$

It is evident that high mass flow rates and large changes in velocity will develop large forces. If the object on which the force is applied by the fluid can move Δx in the same direction as that of the force F then work W is produced.

$$W = F\,\Delta x \qquad (12)$$

If the object moves at a certain velocity V_B then, by dividing both sides of the equation by a time interval Δt, a rate of doing work or power P is obtained.

$$P = F\,V_\mathrm{B} \qquad (13)$$

This principle applies to all turbines. The working fluid is accelerated in a fixed nozzle and then made to change direction in moving blades. The force F applied to the moving blades, which are attached to a rotating disc and move at a certain velocity V_B, generates power P in the shaft on which the disc is fitted. The power output then, based on momentum principles, is given by the following equation:

$$P = M\,\Delta V\,V_\mathrm{B} \qquad (14)$$

Most turbines have multiple stages consisting of fixed nozzles and moving blades. The rows of moving blades are mounted on discs on the same shaft so the general flow of the working fluid is in an axial direction with reference to the shaft and passes through the blades of each disc sequentially.

This means that the direction of fluid flow and blade motion are not the same and components of the fluid velocities in the direction of blade motion must be incorporated into the equations.

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Biographical Sketch

Robin Chaplin obtained a B.Sc. and M.Sc. in mechanical engineering from University of Cape Town in 1965 and 1968 respectively. Between these two periods of study he spent two years gaining experience in the operation and maintenance of coal fired power plants in South Africa. He subsequently spent a further year gaining experience on research and prototype nuclear reactors in South Africa and the United Kingdom and obtained M.Sc. in nuclear engineering from Imperial College of London University in 1971. On returning and taking up a position in the head office of Eskom he spent some twelve years initially in project management and then as head of steam turbine specialists. During this period he was involved with the construction of Ruacana Hydro Power Station in Namibia and Koeberg Nuclear Power Station in South Africa being responsible for the underground mechanical equipment and civil structures and for the mechanical balance-of-plant equipment at the respective plants. Continuing his interests in power plant modeling and simulation he obtained a Ph.D. in mechanical engineering from Queen's University in Canada in 1986 and was subsequently appointed as Chair in Power Plant Engineering at the University of New Brunswick. Here he teaches thermodynamics and fluid mechanics and specialized courses in nuclear and power plant engineering in the Department of Chemical Engineering. An important function is involvement in the plant operator and shift supervisor training programs at Point Lepreau Nuclear Generating Station. This includes the development of material and the teaching of courses in both nuclear and non-nuclear aspects of the program.