POWER PLANT TECHNOLOGY

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Contents

Summary

In order to generate electricity using a source of heat it is necessary to employ a thermodynamic cycle with a working fluid. The working fluid receives heat from the heat source and rejects part of it to a heat sink while producing work. The First Law of Thermodynamics requires that energy be conserved and that the work and heat rejected be equal in quantity to the heat supplied. The second Law of Thermodynamics requires that a certain amount of heat be rejected for the cycle to produce work. For an idealistic situation the amount rejected depends upon the temperatures of the heat source and heat sink. Since not all the heat entering the thermodynamic cycle can be converted into work, any such cycle can only have a certain maximum efficiency defined as work output divided by heat input.

The working fluid of a thermodynamic cycle circulates around or through the system while receiving or rejecting heat and doing work. Usually a common fluid such as

water-steam or air-gas is employed although other fluids are sometimes used for special applications. Generally the working fluid receives heat at a high pressure, does work while expanding and rejects heat at a low pressure. In a water-steam cycle there is a change of phase associated with the absorption and rejection of heat which occurs during boiling and condensation respectively. Steam at high pressure expands in a turbine to produce work. In an open air-gas cycle, hot gas at a high pressure expands in a turbine to produce work while in a closed cycle, it expands in a cylinder to drive a piston. All cycles require that the working fluid be pumped or compressed to the required pressure before receiving heat. This requires that some of the work output be directed back into the cycle to sustain it.

Various modifications to the basic cycles have been adopted to suit certain applications and to improve thermodynamic efficiency. Combined cycles actually make use of two thermodynamic cycles with the heat rejected from one cycle being the heat source of the other. Thus improved efficiency can be obtained which is an important factor when using costly fuels.

While proper selection of the fuel and the thermodynamic cycle ensures good plant efficiency, proper selection of materials of construction is required to ensure good plant reliability. This is important for the overall economy of operation. Generally carbon steel is used for most structural and system components but special alloys and other materials are used where resistance to stress, temperature and corrosion is required. With high temperature working fluids, especially water-steam, corrosion can cause weakening and wastage of materials. This can be minimized by appropriate chemical treatment of the working fluid to inhibit corrosion. Water chemistry is therefore an important aspect in steam power plant operation.

1. Technological Decisions

1.1 Scope of Topic

In the planning, construction, operation and maintenance of power plants, certain technological decisions must be made. As background, some fundamental requirements and environmental considerations are outlined to indicate the scope of such decisions. However a certain depth of knowledge is required in making appropriate decisions. Generally management decisions are based on cost or, to be more correct, least cost. This does not necessarily guarantee a good decision because of the technological implications. On the other hand a good technical decision may have unsatisfactory financial implications. The technical and financial aspects both have to be taken into account.

In the construction of new plant or installation of new equipment, a specification setting out the minimum technical requirements is generally drawn up and the contract awarded to the bidder with the lowest cost. With maintenance there are certain technical requirements with regard to degree of wear or maximum running hours and the maintenance is scheduled for a period with the lowest cost penalty for lost production. However, when considering alternative technologies for similar purposes there may be unknown technical factors or hidden costs which make the selection of one or the other difficult. This is especially true for new technological developments for which there is no existing operational experience. Because of the high capital cost of power plant equipment there is generally a high degree of conservatism in the management of power utilities. Thus technical recommendations must be well founded and supported by extensive scientific knowledge and engineering experience.

This and related chapters, deals with the scientific basis applicable to power plants while *Production of Steam* and *Production of Power* cover the engineering constraints related to the design and operation of large commercial power plants.

1.2 Scientific Knowledge

To fully understand the concept of plant thermal efficiency, for example, a basic knowledge of thermodynamic cycles is required. This indicates that temperatures in the cycle are a key parameter and that one should strive for the highest peak temperature in the cycle for optimum efficiency. Furthermore there is a maximum theoretical efficiency which is considerably less that 100 % due to the fact that the lowest temperature in the cycle cannot be less than that of the environment.

This topic gives an overview of the basic scientific knowledge associated with power plants while the individual articles within the topic address certain important aspects, such as heat transfer and fluid flow, which is important as a basis to the understanding of the engineering constraints covered in the latter topics. Although nuclear energy is addressed in a separate theme, an article on nuclear theory is included to complement the article on combustion theory as both nuclear and fossil fuels provide the necessary heat to drive thermal power plants.

1.3 Engineering Experience

Returning to the concept of efficiency it was noted that the highest thermodynamic cycle temperature will give the best efficiency. There are however certain engineering constraints to the use of high temperatures. Structural materials weaken and deform at temperatures beyond certain maximum values thus imposing a limit on the operating temperature and hence the plant thermal efficiency. Comparing a small steam turbine and an industrial gas turbine of similar capacity, for example, it is found that the gas turbine can receive gas at a higher temperature than that of the steam entering the steam turbine. Such temperature constraints which ultimately impact the plant thermal efficiency are explained, along with many other engineering limitations, in the later topics.

Ultimately a combination of engineering experience and scientific knowledge can provide a sound basis for technological decisions which have to be weighed against their financial implications. The purpose of this theme, *Thermal Power Plants*, is to provide a suitable background of knowledge and experience for the reader to recognize some of the complexities of modern thermal power plants. Before embarking on the technicalities however some fundamental requirements for power plants and certain environmental considerations should be reviewed.

2. Fundamental Requirements

2.1 Common Principles

Whether purchasing a motor vehicle, an aircraft or a power plant, the same basic principles apply. It must meet the intended purpose and provide good service. Furthermore it must be properly financed and economical to operate. It must also comply with various regulations regarding human safety and environmental impact. Some of these common principles related to certain aspects are outlined below. Naturally the greater the investment the greater the consideration given to the individual aspects.

2.2 Capital Cost

Capital cost is often seen to be the most important aspect. Finance for the purchase must be obtained and the expenditure justified. Usually there are constraints regarding the maximum expenditure and a lower cost item is perceived more favorably. Often, provided similar items meet the required technical specification, a very small difference in cost will determine whether to purchase the item from one vendor or another. In the case of a power plant, which will take many years to build, a small difference in cost can escalate considerably before the payment is actually made in full. Capital cost, however, is not necessarily a measure of the ultimate lifetime cost of operation as there are many other costs to be taken into account. Also different models or types have very different capital costs for same capacity. This is certainly the case in motor vehicles and follows through to power plants where nuclear, hydro and fossil fueled plants have widely ranging costs per megawatt of installed capacity.

2.3 Fuel Cost

The cost of fuel is a very important consideration as it is the one cost that is directly and immediately reflected in the product. Most other costs are not nearly as clearly defined. Capital costs, although fixed, are repaid over a period of time which is not based on operating hours. Maintenance costs which are usually based on running hours are not necessarily fixed. Fuel however is purchased and almost immediately used at a certain efficiency to product of a given value. In a fossil fueled power plant the chemical energy in the fuel is converted to electrical energy at an efficiency determined by the design of the plant. The cost of the fuel therefore becomes a known fraction of the cost of electricity. Power utilities thus preferentially operate those plants which have high efficiencies and low fuel costs so as to minimize the fraction of fuel cost in the overall cost of producing electricity. Similarly some airlines operate only very high fuel efficiency aircraft to minimize the fraction of the total flying cost that is related to fuel. For motor vehicles the cost of using the vehicle is often related to the cost of fuel even though this may be only about a quarter of the overall lifetime operating costs.

2.4 Efficiency

Following from fuel costs is efficiency. The two go hand in hand as part of the cost of the product and the cost of the fuel are linked by the efficiency of the process. There is, however, also a link between capital cost and efficiency. In many energy conversion processes, efficiency can be increased by improved technology which invariably results in increased capital cost. In a thermal power plant, efficiency can be increased by, for example, increasing the upper temperature of the thermodynamic cycle. This requires the use of exotic and expensive heat resistant materials which increase the cost of the plant. Whether this is a desirable route to follow depends upon the fuel cost. For a plant with a higher fuel cost there is justification for a higher capital cost to improve the efficiency and hence to lower the fuel cost fraction of the final product. Naturally the increase in the capital cost fraction should not be greater than the reduction in the fuel cost fraction.

In this context it should be noted that nuclear fueled plants generally have high capital costs and low fuel costs and moderate thermal efficiencies. Fossil fueled plants on the other hand have lower capital costs and higher fuel costs and hence a greater incentive for higher efficiencies. There are technical reasons for the differences in efficiency but nuclear plants are able to operate economically at lower thermal efficiencies because of the generally lower fuel costs. Combined cycle gas turbine plants generally have even lower capital costs and higher fuel costs but their inherent high cycle efficiency makes them attractive in certain applications.

This leads to the question of load scheduling. Generally plants with low fuel costs are scheduled to operate for long periods as base load plants and those with high fuel costs for short periods as peak load plants. This tends to balance the repayment of capital costs. Plants with high capital costs thus tend to run longer hours than those with low capital costs so the capital cost fraction appearing in the final product cost is more equitable. The converse, though, is a more logical way of viewing it. Plants operating for short periods should not have too high a capital cost as there are insufficient running hours over their lifetimes to recover excessive costs.

2.5 Availability

From the above it follows that power plants do not have to operate continuously. In fact, with the daily variation in demand, some plants only have to operate when there is a peak demand for power. It is important, however, that, when required to operate, the plant can produce the power required, that is, it is available for service when needed. The same applies to aircraft and motor vehicles. Even if required for only short periods there must be the assurance they will start and run as expected.

Equipment that stands idle for a period of time has the advantage of being checked and maintained regularly when in a shutdown condition but is also prone to startup failures when required for service. Generally equipment that does not suffer thermal transients on startup is less prone to problems arising from short periods of operation. Hydro turbines, for example, may be operated through many startup and shutdown cycles without significant adverse effects.

2.6 Reliability

Reliability is similar to availability but is related to the condition of the equipment when in operation. Once running, it should continue to operate without failure for a predetermined period. This is particularly evident in aircraft where a failure in flight can have disastrous consequences. For a power plant, a failure of a key component may require an immediate shutdown of the turbine generator. The consequent loss of electrical generating capacity requires immediate replacement with alternative more expensive sources of electrical power. There is thus an economic penalty arising from a loss in reliability.

2.7 Unplanned Maintenance

Associated with both availability and reliability is maintenance. A loss of either availability or reliability inevitably results in a maintenance cost in addition to the cost of providing alternative more expensive power. This maintenance cost ultimately becomes part of the overall lifetime cost of operation. Furthermore, the loss of electrical generation for a period ultimately gives a higher overall lifetime cost per unit of electricity generated.

2.8 Planned Maintenance

All plants, aircraft and vehicles require regular servicing after a period of operation. This invariably requires the equipment to be out of service for an extended period which may require the use of alternative equipment. Power plants are generally part of a system that has a variable annual power demand so that they may be taken out of service for several weeks at a time for major maintenance. This is an important factor in the case of those nuclear plants which require off-load refueling on an annual basis. The planning of this routine maintenance is important and is usually scheduled for periods when the system power demand is low.

Not all planned maintenance can be done during the low load periods when there is surplus generating capacity due to the availability of human resources and some routine maintenance has to be done on an ongoing basis throughout the year when a plant can be taken out of service for a short period.

2.9 Maintenance Costs

The overall costs associated with both planned and unplanned maintenance have to be factored into the overall lifetime cost of the plant. There are thus three major components associated with this overall lifetime cost namely: capital cost, fuel cost and maintenance cost. The last is related to availability and reliability and is not easy to predict prior to the plant going into operation. Sound experience in plant operations and maintenance, however, can allow for a critical assessment of a proposed design. Appropriate modifications can ensure better availability and reliability and easier planned maintenance. Such modifications invariably increase the capital cost but, if savings in maintenance costs over the lifetime of the plant are greater than the increase in the capital cost portion over the same period, the modifications are desirable.

3. Environmental Considerations

3.1 General Scope

When a power plant is built and operated it must comply with certain requirements and regulations which are externally imposed and generally not related to the above considerations of efficiency and economy. They are generally related to the health and safety of both the plant staff and the general public. From the time of the first power plants their scope has been progressively extended from the well-being of the plant operator to that of the most remote citizen. Initially there was only concern for the physical safety of the plant operators working on systems containing high pressure steam produced from high temperature gases. More recently concern has been extended to the general public living far away from the plant but in the same atmosphere as that to which the plant discharges its effluent.

3.2 Plant Safety

All power plants are built in accordance with a variety of codes and standards. These ensure a certain quality of material and workmanship and also a certain level of safety. Although failures of equipment may result in severe damage to the plant, safety to personnel tends to be the governing factor when instituting safety regulations. This means that, with regard to certain aspects of the plant, the level of safety required for personnel protection is greater than that required for equipment reliability. There is thus a cost associated with safety beyond that which is required for optimum economical operation. To ensure that plants do provide adequate safety for the operating staff, therefore, some legislation is generally required to ensure compliance with appropriate safety measures.

In most countries therefore, there are building and manufacturing codes to ensure integrity of equipment and a safe working environment. Such codes range from pressure vessel design to the design and layout of stairs and walkways. Once in operation other codes ensure that proper procedures are followed for a range of operations from the periodic testing of pressure vessels to the proper isolation of electrical equipment during maintenance.

Although most safety procedures are legislated by a government body, most plants have additional standing instructions for personnel to follow when carrying out certain operations. These tend to be for the protection of the plant and to ensure good long term reliability. Machine startup procedures for example can prevent inappropriate actions and consequent damage to the equipment. Such procedures are related to safety as any failure poses some risk to the operating staff.

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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.