ТЕПЛОЭНЕРГЕТИКА

(Сборник текстов)

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INTRODUCTION

At the beginning of the nineteenth century, the stagecoach and the saddle horse were still the means of travel on land. Freight was transported on land in wagons drawn by horses or oxen.

On water barges were also drawn by horses. The water wheel had been in use for several centuries to drive flour mills and small manufacturing establishments. In agriculture man was still largely dependent upon his own physical strength and the work of his domestic animals. Later the steam engine was developed and applied to the operation of factories. This and the development of machine tools and machinery accelerated the industrial revolution and ultimately resulted in our modern industrial civilization which is founded upon the low-cost mass production of goods that can be sold cheaply throughout the world.

The Newcomen steam engine was invented in 1705 to pump water from the English coal mines. It was fairly well developed by 1720 and remained in extensive use for the 50 years. In 1763 a self-taught man the son of a Russian soldier Polzunov worked out the project of the first universal steam engine. The construction of the engine involved great difficulties due to lack of qualified assistants, lack of the necessary instruments and in general lack of help and support. Polzunov had to do almost everything with his own hands.

Polzunov’s engine had been working from August to November 10, 1766, when it was stopped and put out of operation because of a leak in the boiler. But, Polzunov did not live to see the results of his work. He died in poverty on May 27, 1766.

Later on in the course of the industrial revolution in England a number of inventors designed steam engines with a view to meeting the urgent demand for these machines.

A prominent place among these early inventors belongs to James Watt. James Watt, an instrument maker at the University of Glasgow, while repairing a model of a Newcomen engine, noticed the large waste of energy due to alternately heating the steam cylinder with steam and cooling it with injection water.

He realized that this loss could be reduced by keeping the cylinder as hot as possible with insulation and using a separate condenser or water-cooled chamber which could be connected to the steam cylinder at the proper time by a valve. He patented the idea of the separate condenser in 1769. Subsequently, he closed the top of the steam cylinder with a cover or cylinder head, introduced steam alternately on both sides of the piston, and thus made the engine double acting. He invented a governor to regulate the speed of the engine, a slide valve to control the admission, expansion, and exhaust of the steam, a pump to remove the air and condensate from the condenser, and, in fact, brought the steam engine to a fairly high state of development.

In 1882 Thomas Edison started the Pearl Street Station in New York for the purpose of sipp1ying electricity to the users of the new incandescent lamp, thus laying the foundation for great central-station industry which now supplies the general public with electric light and power. Parsons patented a reaction turbine in

14, and in 1889 de Laval was granted patents on an impulse turbine. By 1910 the steam turbine had replaced the reciprocating steam engine in the central-station industry.

During the last decade, the gas turbine in the form of the turbojet and turboprop engines has replaced the reciprocating internal combustion engine in the military combat airplane and the faster and larger commercial aircraft. The gas turbine is also being used in such applications as electric power generation, natural gas transmission line pumping, and locomotives.

The recent development, of the rocket threatens to revolutionize warfare with guided missiles and earth satellites. Since the rocket carries its own supply of oxygen for the burning of its fuel, it is capable of operating at altitudes where the earth's atmosphere is highly rarefied.

THE STEAM POWER PLANT

The function of a steam power plant is to convert the energy in nuclear reactions or in coal, oil or gas into mechanical or electric energy through the expansion of steam from a high pressure to a low pressure in a suitable prime mover such as a turbine or engine. A noncondensing plant discharges the steam from the prime mover at an exhaust pressure equal to or greater than atmospheric pressure. A condensing plant exhausts from the prime mover into a condenser at a pressure less than atmospheric pressure.

In general central-station plants are condensing plants since their sole output is electric energy and a reduction in the exhaust pressure at the prime mover decrease the amount of steam required to produce a given quantity of electric energy. Industrial plants are frequently noncondensing plants because large quantities of low-pressure steam are required for manufacturing operations. The power required for operation of a manufacturing plant may often be obtained as a by-product by generating steam at high pressure and expanding this steam in a prime mover to the back pressure at which the steam is needed for manufacturing processes.

The steam-generating unit consists of a furnace in which the fuel is burned, a boiler, superheater, and economizer, in which high-pressure steam is generated, and an air heater in which the loss of the energy due to combustion of the fuel is reduced to a minimum. The boiler is composed of a drum, in which a water level is maintained at about the mid-point so as to permit separation of the steam from the water, and a bank of inclined tubes, connected to the drum in such a manner as to permit water to circulate from the drum through the tubes and back to the drum. The hot products of combustion from the furnace flow across the boiler tubes and evaporate part of the water in the tubes. The furnace walls are composed of tubes whish are also connected to the boiler drum to form very effective steam-generating surfaces. The steam which is separated from the water in the boiler di1im then flows through a superheater which is in effect a coil of tubing surrounded by the hot products of combustion. The temperature of the steam is increased in the superheater to perhaps 800° to 11000 F, at which temperature the high-pressure superheated steam flows through suitable piping to the turbine.

Since the gaseous products of combustion leaving the boiler tube bank are at a relatively high temperature and their discharge to the chimney would result in a large loss in energy, an economizer may be used to recover part of the energy in these gases. The economizer is a bank of tubes though which the boiler feedwater is pumped on its way to the boiler drum.

A reduction in gas temperature may be made by passing the products of combustion through an air hewer which is a heat exchanger cooled by the air required for combustion. This air is supplied to the air heater at normal room temperature and may leave the air heater at 400° to 600° F, thus returning to the furnace energy that would otherwise ,be wasted up the chimney. The products of combustion are usually cooled in an air heater to an exit temperature of 275° to 400° F, after which they may be passed through a dust collector which will remove objectionable dust and thence through an induced-draft fan to the chimney. The function of the induced-draft fan is to pull the gases through the heat-transfer surfaces of the boiler, superheater, economizer and air heater and to maintain a pressure in the furnace that is slightly less than atmospheric pressure. A forced-draft fan forces the combustion air to flow through the air heater, duct work, and burner into the furnace.

Coal is delivered to the plant in railroad cars or barges which are unloaded by machinery. The coal may be placed in storage or may be crushed and elevated to the overhead raw-coal bunker in the boiler room.

The coal flows by gravity from the overhead bunker to the pulverizer or mill through a feeder which automatically maintains the correct amount of coal in the mill. In the mill the coal is ground to a fine dust. Some of the hot air from the air heater is forced through the mill to dry the coal and to pick up the finely pulverized particles and carry them in suspension to the burner where they are mixed with the air required for their combustion and discharged into the furnace at high velocity to promote good combustion.

The high-pressure, high-temperature steam is expanded in a steam turbine which is generally connected to an electric generator. From 3 to 5 per cent of the output of the generator is needed to light the plant and to operate the many motors required for fans, pumps, etc., in the plant. The rest of the generator output is available for distribution outside the plant.

The condensed steam, which is normally at a temperature of 700 to 1000 F, is pumped out of the condenser by means of a hot-well pump and is discharged through several feed-water heaters to a boiler feed pump that delivers the water to the economizer.

Most steam power plants of large size are now being built for operation at steam pressures of 1500 to 2400 psi, and in some plants pressures up to 5000 psi are being used, Steam temperatures of 1000° to 11000 F are in general use. Turbine-generator capacities of 250,000 kW (1 kilowatt = 1.34 horsepower) are common, and units of 500,000 kW are in operation. Steam-generating units capable of delivering 3,000,000 lb of steam per hr are now in operation. Overall efficiency of the plant from raw coal supplied to electric energy delivered to the transmission line depends upon size, steam pressure, temperature, and other factors, and 40 per cent is now being realized on the basis of a full year of operation.

THE INTERNAL-COMBUSTION-ENGINE POWER PLANT

The internal-combustion-engine power plant including essential auxiliaries is shown diagrammatically in Fig. 2. The fuel is burned directly in the cylinder of the engine or prime mover, and the high pressure thus generated drives the piston downward and rotates a crankshaft.

Air is supplied to the engine through a silencer1and cleaner, the function of which is to reduce noise and remove dust which would accelerate cylinder and piston wear if allowed to enter the cylinder.

A supercharger is installed in the air-intake system. The function of the supercharger is to increase the amount of air supplied to the cylinder by acting as an air pump. This in turn permits burning more fuel and obtaining more power from a given size of cylinder. An intake manifold is used to distribute the air equally from the supercharger to the various cylinders of multicylinder engine.

The exhaust system consists of an exhaust manifold for collecting the discharge gases from each of the cylinders into a common exhaust line, an exhaust silencer or muffler for reducing noise, and the exhaust stack for disposing of the exhaust gases to the atmosphere without creating a public nuisance.

The cooling system includes a pump for circulating water through the cylinder jackets and heads of each cylinder and a heat exchanger to remove the energy absorbed in the engine by the cooling water. The heat exchanger may be air-cooled as in the automobile radiator, or it may be water-cooled. Seldom is raw water fit to circulate directly through the jackets of an internal-combustion engine.

The lubricating oil may be passed through a cooler, filter, and reservoir and is supplied to the engine under pressure by means of an oil pump, usually to a hollow crankshaft. The oil serves as a lubricant for the rubbing surfaces of the engine and also as a coolant.

The fuel system consists of a storage tank from which the fuel may be supplied to a small day tank or reservoir. The oil is filtered and pumped as needed to the fuel-injection system which is an integral part of the engine.

Since the fuel is burned directly in the cylinder of the prime mover, the internal-omb1stion-eng1ne power plant is simpler and more compact than the steam power plant. It is seldom built in engine sizes of more than 4000 hp, whereas a 300,000-hp steam turbine is common. It is more efficient than a steam power plant of comparable size but not so efficient as large steam central-station plants, which moreover can burn a cheaper grade of fuel. Consequently, the internal-combustion engine is used primarily in the transportation field for driving automobiles, buses, truck, tractors, locomotives, ships, and airplanes where a compact, light-weight, efficient power plant of relatively small size is necessary.

THE GAS-TURBINE POWER PLANT

Air is compressed in an axialfiow compressor from atmospheric pressure to a pressure which is usually between the limits of 75 and 120 psi. The compressed air may then flow through a regenerator or heat exchanger in which the hot exhaust gas from the turbine is utilized to increase the temperature of the air, thereby recovering energy that would otherwise be lost to the atmosphere. Fuel is sprayed into the combustor in which it combines chemically with the oxygen in the air to produce a hot gas leaving the combustor at some temperature between 1200° and 1700°F. The pressure of the air decreases lightly between the compressor discharge and turbine inlet because of friction, but the increase in temperature in the regenerator and combustor results in more than doubling the volume. The hot gas then expands in the turbine in which it does enough work to drive the compressor as well as an electric generator or some other suitable machine. The exhaust gases leaving the turbine are cooled in the regenerator before being discharged to the atmosphere.

Where space and weight limitations are critical or fuel is cheap, the regenerator may be omitted with a substantial decrease in efficiency. Te turboprop engine as applied to the airplane operates without a regenerator and with a geared propeller as the load. In the turbojet engine as applied to the airplane, the turbine develops only enough to drive the compressor and exhausts into a nozzle at a back pressure considerably in excess of atmospheric pressure. The rearward expansion of the exhaust gases from the nozzle at high velocity creates the thrust which propels the airplane.

THE NUCLEAR POWER PLANT

In the nuclear power plant energy is released in a reactor by nuclear fission. A coolant is pumped through the reactor to absorb and remove this energy and thereby prevent an excessive temperature in the reactor. In the more common types of nuclear power plants, the high-temperature coolant that leaves the reactor flows through a heat exchanger in which steam is generated.

Extensive provisions are made to protect the operating personnel and the general public from the hazards of radioactivity by the installation of radiation and containment shields which enclose all radioactive components of the system.

The heat exchanger serves as a steam boiler. The steam flows through a turbine and associated equipment that are identical in design and arrangement with similar equipment in a conventional steam power plant. In other words, the nuclear reactor, heat exchanger, and pump replace the fuel- burning equipment and the steam generator of the conventional steam power plant.

CHAPTER I

BURNING EQUIPMENT

There are two general methods of firing fuel commonly employed: I) on stationary grates, or 2) on stokers. Also coal may be pulverized to the consistency of 70 per cent through a 200-mesh screen and burned in suspension. The types of solid fuel encountered in various parts of the world and the general conditions under which they must be burned are so variable that it is impossible to design one type of grate or stoker that is exactly suited to all fuels. The problem becomes one rather of suiting the equipment to the type of fuel to be handled.

To a certain extent, the design of the furnace must be considered coincidentally with the selection of fuel-burning equipment, so that satisfactory ignition and heat release may be ensured. The choice of equipment for a given set of conditions is limited, and, although any stoker will burn any fuel only one design as a rule will give satisfactory results. Coals may be broadly classified as follows:

Group 1. This group includes the anthracites and semi-anthracites which should be burned without agitation of the fuel bed.

A fuel of this class is satisfactorily burned on traveling-grate or chain-grate stokers, on which the coal is fed in a comparatively thin, uniform layer. As combustion progresses, the ash covers the surface of the stoker and acts as a protective blanket, the fuel being supplied with combustion air as it travels toward the ashpit.

Group 2. This group includes the bituminous coals of the caking type which require agitation of the fuel bed to break up the mass of coke as it forms as well as to resist the tendency of this fuel to fuse into a mat, or cake, that resists the passage of air and retards the process of combustion. Underfeed stokers of the multiple-retort type are designed to burn coals of this class, for the plungers have a characteristic forward and upward motion. By breaking up the surface of the fuel bed, more air passages are created, with a tendency to increase combustion rate. A few coals of this class have a low ash-fusion temperature with a resulting tendency to fuse and jam the operating parts of the stoker. These coals, particularly if high in sulphur, should be avoided as stoker fuels.

Group 3. This group includes midwestern coals and most of the western bituminous coals. These do not tend to soften but form masses of coke, they require no agitation of the fuel bed and are burned to best advantage on chain-grate stokers.

Group 4. This group consists of most of subbituminous coals and lignites which do not fuse when heated and do not require agitation. They have a tendency to disintegrate or slack on the grate as well as drift and sift through if disturbed. They have a tendency to avalanche on inclined grates and are most satisfactorily burned on chain- or traveling-grate stokers.

FURNACES

A furnace is a fairly gas-tight and well-insulated space in which gas, oil, pulverized coal, of the combustible gases from solid-fuel beds may be burned with a minimum amount of excess air and with reasonably complete combustion. Near the exit from the furnace at which place most of the fuel has been burned, the furnace gases will consist of inert gases such as $C0_2$, N_2 and H_20 vapor, together with some O_2 and some combustible gases such as CO, H_2, hydrocarbons, and particles of free carbon (soot). If combustion is to be complete, the combustible gases must be brought into intimate contact with the residual oxygen in a furnace atmosphere composed principally of inert gases. Also, the oxygen must be kept to a minimum if the loss due to heating the excess air from room temperature to chimney-gas temperature is to be low. Consequently, the major function of the furnace is to provide space in which the fuel may be burned with a minimum amount of excess air and with a minimum loss due to the escape of unburned fuel.

The design of a satisfactory furnace is based upon the “three T’s of combustion”: temperature, turbulence, and time.

For each particular fossil fuel, there is a minimum temperature, known as the ignition temperature, below which the combustion of that fuel in the correct amount of air will not take place.

The ignition temperature of a fuel in air as reported by various investigators depends somewhat upon the methods used to determine it and, for some common gases, is as follows:

Hydrogen (H_2)	1075-1095° F
Carbon monoxide (GO)	1190-12150 F
Methane (CH_4)	1200-13800 F
Ethane (C_2H_6)	970-1165° F

If the combustible gases are cooled below the ignition temperature, they will not burn, regardless of the amount of oxygen present. A furnace must therefore be large enough and be maintained at a high enough temperature to permit the combustible gases to burn before they are cooled below the ignition temperature. In other words, the relatively cool heat-transfer surfaces must be so located that they do not cool the furnace gases below the ignition temperature until after combustion is reasonably complete1.

Turbulence is essential if combustion is to be complete in a furnace of economical size. Violent mixing of oxygen with the combustible gases in a furnace increases the rate of combustion, shortens the flame, reduces the required furnace volume, and decreases the chance that combustible gases will escape from the furnace without coming into contact with the oxygen necessary for their combustion. The amount of excess oxygen or air required for combustion is decreased by effective mixing. Turbulence is obtained, in the case of oil, gas, and powdered coal, by using burners which introduce the fuel-air mixture into the furnace with a violent whirling action. High-velocity steam or air jets and mixing arches may be used to increase the turbulence in furnaces fired with coal on stokers.

Since combustion is not instantaneous, time must be provided for the oxygen to find and react with the combustible gases in the furnace. In burning fuels such as gas, oil, or pulverized coal, the incoming fuel-air mixture must be heated above the ignition temperature by radiation from the flame or hot walls of the furnace. Since gaseous fuels are composed of molecules, they burn very rapidly when thoroughly mixed with oxygen at a temperature above the ignition temperature. However, the individual particles of pulverized coal or atomized oil are very large in comparison with the size of molecules, and many molecules of oxygen are necessary to burn one particle of coal or droplet of oil. Time is required for the oxygen molecules to diffuse through the blanket of inert products of combustion which surround a partially burned particle of fuel and to react with the unburned fuel. Consequently, oil and pulverized coal burn with a longer flame than gaseous fuels.

The required furnace volume is dependent, therefore, upon the kind of fuel burned, the method of burning the fuel, the quantity of excess air in the furnace, and the effectiveness of furnace turbulence. The shape of the furnace depends upon the kind of fuel burned, the equipment employed to burn the fuel, and the type of boiler used to absorb the energy if the fuel is burned for steam generation.

Industrial furnaces in which the objective is to create and maintain a region at a high temperature and the furnaces of small steam boilers are constructed of fire brick, a brick that has been developed to withstand high temperatures without softening, to resist the erosive effects of furnace atmospheres and particles of ash, and to resist spalling when subjected to fluctuating temperatures. Low vertical walls may be constructed of fire brick in the conventional manner. High walls which are subject to considerable expansion, may be tied to and sectionally supported by an external steel frame. When a boiler furnace is operated at high capacity, the temperature may be high enough to melt or fuse the ash which is carried in suspension by the furnace gases. Molten ash will chemically attack and erode the fire brick with which it comes into contact. Also, if the ash particles are not cooled below the temperature at which they are plastic or sticky before they are carried into the convection tube banks of the boiler, they will adhere to these surfaces, obstruct the gas passages, and force a shutdown of the unit. Moreover, the function of a boiler is to generate steam, and the most effective heat-transfer surface is that which can “see” the high-temperature flame and absorb radiant energy. The rate of heat absorption expressed in Btu per hour per square foot of projected wall area may be from 1000 to 10,000 times as great as the heat-transfer rate in the boiler surface with which the products of combustion are in contact last before being discharged up the chimney. Consequently, the walls of furnaces for large steam boilers are constructed of boiler tubes.

CYCLONE FURNACE (CRUSHED COAL)

The cyclone furnace is a water-cooled horizontal cylinder (5 to 10 ft in diameter) into which coal is introduced.

As the coal moves from front to rear, combustion air is introduced tangentially at high velocity and about 35-in water gage pressure. This causes a whirling or centrifugal action, with the solid fuel particles moving to the periphery of the combustion chamber where their movement is retarded by molten slag that covers its walls. Although the finer fuel particles burn in suspension, the cyclone method of combustion is primarily a surface-burning process. The solid fuel particles in the liquid ash coating on the walls are scrubbed by the incoming air stream, providing intimate coal and air mixing. Combustion in the cyclone furnace is complete and has practically no carbon loss.

The cyclone furnace is water-cooled as an adjunct to the boiler circulation system. It is attached to the steam generating unit, which may have either of two types of secondary furnaces: 1) the water screen type, in which a water screen of tubes divides the furnace into lower and upper sections; and 2) the open furnace type. In the water screen furnace, the fly-ash loading of the flue gases will be about 10 per cent of the total ash fired. In the open furnace, the loading will be about 15 per cent. This refuse may be collected and returned for reinjection.

Some stations find the cyclone furnace advantageous and there are definite sales trends in its favour. As it is not necessary to pulverize the coal, a considerable saving is obtained in both initial investment and also in operating expense. This furnace has been proved to be suitable for a wide range of coals and for firing gas or oil either in combination with coal or as stand-by or substitute fuel. The cyclone furnace is also capable of burning waste or by-product fuels such as wood, chars, and cokes.

PULVERIZED COAL FURNACE

Coal may be fired as a finely powdered fuel that is injected into the furnace. The coal is pulverized to a fineness of 70 per cent or more through a 200 mesh sieve. It is then transported by hot primary air (which also dries the coal) to the furnace.

The majority of all central steam generators operating at 200,000-lb steam per hr and over are fired by pulverized coal. The number of pulverizers are determined by pulverizer capacity and stand-by requirements. Larger installations have two, three or four pulverizers. Provision for three pulverizers, one for each row of burners plus one for stand-by is not unusual. Pulverized coal-fired boilers may be either the dry bottom or slag-tap type. Vertical, horizontal, opposed, or tangential firing methods may be employed.

The size of the unit, its pressure and temperature, available space, fuel characteristics, ash-fusion temperature, type of burner, and ash removal method determine the volume of the furnace, the extent of water cooling, and the ultimate design of the entire steam-generating unit.

Pulverized coal furnaces are usually convertible to firing with oil or gas. Units near oil refineries may utilize fluid coke.

Pulverized coal firing removes a limitation on the amount of fuel that can be burned in a boiler (with stoker firing there is a definite limit).

The type and multiplicity of burners, their arrangement and the flame shape will determine the furnace width and depth dimensions. The furnace height is a function of the required furnace volume. The exit temperature of the gases should be below the ash-fusion temperature of the lowerest quality fuel to be used. Thus, coal with a large percentage of low-fusion ash will require larger waterwall surfaces, which in turn make a larger furnace volume necessary. Superheater requirements may govern exit temperatures.

All pulverized coal-fired furnaces constructed to-day are partially or completely water-cooled. If tangential firing is used, the furnace must be completely water-cooled, because there is considerable flame impingement. It is desirable to eliminate, as much as possible, blasting of flames against the furnace walls. Molten ash particles stick to and dissolve most refractories. Heat and high sulphur content may induce a slow attack or tube wastage of the water-cooled walls. Flame length varies with coal particle size (the length is shortened by uniformly line pulverization), the percentage and composition of the volatile constituent, turbulence, furnace temperature, arid excess air. With proper mixing, the flame length may be as short as 10 ft. Helical or U-shaped paths may be provided for long flames, the furnace shape being adapted to the available space.

In a wet-bottom (slag-tap) furnace, 40 to 60 per cent of the total fired ash leaves with the combustion gases, and in a dry-bottom furnace, 80 to 90 per cent. An individual burner may be reduced to about 35 per cent of its maximum continuous rating. With 15 to 22 per cent excess air, the unburned combustible is under 1 per cent. The excess air requirements will vary from 10 to 30 per cent. As the percentage of ash increases, the amount of excess air must also increase if the combustible loss is to be held to a constant minimum. For optimum efficiency, the combustible loss is balanced against the dry gas loss.

GAS BURNER

Gas is burned in many industrial furnaces because of its cleanliness, ease of control of furnace atmosphere, ability to produce a long slow burning flame with uniform and gradual energy liberation, and ease of temperature regulation. Natural gas is used for steam generation in gas-producing areas and in areas served by natural-gas transmission lines where coal is not available at a competitive price. It is also burned extensively in coal- or oil-fired units during the summer months in districts served by natural-gas pipe lines, at which time the absence of the domestic heating load creates a temporary surplus of natural gas. By-product gas such as blast-furnace gas may be available at the steel mills for steam generation. Because of the variable or seasonal supply of gaseous fuels, combination burners have been developed to permit the simultaneous burning of the available gas together with pulverized coal or oil in an amount sufficient to produce the required steam.

When a molecule of combustible gas is mixed with the oxygen necessary for its combustion at a temperature above the ignition temperature, combustion is practically instantaneous. For steam generation, where a short flame is desired in order to reduce the required furnace volume, the burner should provide for rapid and thorough mixing of the fuel and air in the correct proportions for good combustion. For such applications, a good burner is primarily a proportioner and mixing device. In industrial furnaces where long “lazy” flames are desired, slow and gradual mixing of the air and fuel in the furnace is necessary.

In the burner the gas, under pressure in the supply line, enters the furnace through a burner port and induces a flow of air through the port. Mixing is poor, and a fairly long flame results. The flame can be shortened by use of the ring burner, in which the gas flows through an annular ring and induces air flow both around and within the annulus of gas.

STOKERS

A stoker should not only be designed from the combustion point of view, but it must be mechanically strong to with stand all working stresses due to high temperature, etc. A simple design will ensure low first cost, minimum maintenance and operation for long periods without failure. Some of the factors to be aimed at in stoker design are: maximum rates of burning, highest continuous efficiency and the unlimited choice of fuels.

Any study of the use of stokers must begin with an analysis of the four principal constituents of coal, namely, moisture, volatiles, mixed carbon and ash, or more generally, water, tar, coke and dirt. These determine the features which should be embodied in the stoker and furnace equipments so that proper treatment of the coal at the correct time is effected on its passage through the furnace. Whichever of the two types he used the coal has to be taken from the bunkers to the feeding hoppers on the boilers. The coal falls by gravity from the bunkers through a valve into feeding chutes. In sonic installations automatic weighers are included in the downspouts between the cut-off valves and the boiler feed hoppers. The cut-off valves maybe operated from the firing floor by means of chains. The chutes are one of two types namely, traversing and fixed.

There are usually two or three chutes for large boilers. The traversing clinics travel the full width of the feeding hopper, the motion being affected by means of a continuously rotating screwed shaft which engages with a special nut attached to the chute. The operating shaft has right- and left-hand helical grooves and the nut is designed so that at the end of its travel it reverses automatically.

The chutes are operated from the stoker drive, there being two or four chutes for large boiler units. Coal chutes are of welded mild steel plates, wearing plates also being included.

SPREADER STOKERS

The spreader stoker is designed to throw coal continuously onto a stationary or moving grate. A spreader stoker is equipped with a moving grate which travels toward the feeder mechanism and discharges the refuse continuously. Coal is fed from the hopper by means of a reciprocating feeder plate having a variable-speed drive which for best performance should be regulated automatically to feed coal in accordance with the demand for energy.

The coal is delivered by the feeder to a rapidly revolving drum or rotor on which are fastened specially shaped blades which throw the fuel into the furnace and distribute it uniformly over the grate. Coal can be distributed thus for a total distance of about 22 ft. The feeder mechanism is built in standardized widths, and several units may be installed across the front of the larger furnaces. Air is supplied by means of a blower to the space under the moving grate through an adjustable damper. The active fuel bed is normally not over 1 $^{1}/_{2}$ in. deep so that an adequate supply of air can penetrate the fuel bed and enter the furnace. Active fuel beds much thicker than 1112 in. will produce excessive amounts of smoke. Much of the volatile matter is distilled from the coal before it strikes the fuel bed, and the caking properties of the fuel are thus destroyed, thereby making it possible to burn even the strongly caking bituminous coals. Since the fuel bed is thin and undisturbed and the ash is cooled by the flow of air through it, trouble with clinkering or fusing of the ash is uncommon, and this stoker can burn almost any kind of bituminous coal. Since the finer sizes of coal are burned in suspension, large furnaces are required, and objectionable quantities of dust may be discharged from the installation if it is not designed correctly and if dust collectors are not installed lo clean the gases leaving the steam-generating unit. Also, it is standard practice to install high-velocity steam jets in the furnace to promote turbulence, improve combustion, and reduce smoke.

Large units provided with continuous ash-discharge grates are capable of burning 12 to 15 tons of coal per hr. Small units may have stationary grates with clean-out doors through which the ashes may be removed manually with a hoe, or they may have dump grates operated by a power cylinder in which grate sections may be tilted periodically to dump the ashes.

The spreader stoker is simple in construction and reliable in operation. It can burn a wider variety of coal successfully than any other type of stoker. Maximum continuous combustion rates of 45 to 60 psf of grate area per hr are normally used. When provided with automatic regulation of fuel and air in accordance with the demand for energy, this stoker is very responsive to rapidly fluctuating loads.

However, it is not so adaptable to light-load operation as other types of stokers because of the difficulty of maintaining ignition and combustion in the very thin fuel bed with a cold furnace. 1t is because of the thin fuel bed and the continuous, uniform firing of coal that the spreader stoker overcomes the smoke-producing problem associated with the thick intermittently hand-fired fuel bed.

CHAIN- AND TRAVELLING-GRATE STOKERS

A chain-grate stoker has a moving grate in the form of a continuous chain. The upper and lower runs of the chain are supported on a structural steel frame. The chain is driven from the stoker front by means of sprockets mounted on a rotating shaft which is actuated by a ratchet mechanism and hydraulic cylinder. The grate bars are made of heat-resistant cast Iron, are cooled by the air supplied for combustion, and form a flat undisturbed surface for the fuel bed.

Coal from the stoker hopper is placed on the moving grate in a uniform layer, the depth of which is controlled by the vertical movement of an adjustable fuel gate. The depth of the fuel bed is usually between 3 and 8 in depending upon the kind of fuel being burned. The speed of the grate may be adjusted, usually between the limits of 4 and 20 in. per mm, so that the combustible material is burned before the ash is discharged from the rear end into the ashpit.

The shearing action of adjacent grate bars as they pass around the curved supporting member at the rear of the stoker provides a self-cleaning action for the grate bars. Air is supplied under adjustable pressure to several compartments under the grate. Thus the supply of air to various sections of the fuel bed may be adjusted to suit the combustion requirements.

When bituminous and other high-volatile coals are burned, high-velocity air jets are installed in, the front furnace wall. The volatile matter that is released from the incoming green coal is mixed with the swirling turbulent air that is introduced above the distillation zone. Two important results are thereby accomplished: 1) the volatile matter is burned smokelessly, and 2) a high-temperature zone is formed which provides for stable ignition of the incoming coal. The existence of this highly incandescent zone of turbulent combustion over the front end of the stoker makes mixing arches in the furnace unnecessary, and an open furnace with vertical walls similar to the spreader-stoker furnace may be used.

The small sizes of anthracite which cannot be sold for a domestic fuel and the small sizes of coke which are too small to charge into the blast furnace, called coke breeze, are important stoker fuels in certain localities. These fuels contain practically no volatile matter. Because of the fine size and large total surface of the incandescent carbon in the fuel bed, all the oxygen combines with carbon a short distance above the grate unless fuel-bed air velocities are so high as to almost lift the fuel from the grate. Under these conditions, large amounts of fine particles of carbon are blown upward into the furnace.

It is necessary to maintain a hot zone above the entering fuel to ignite the fuel on the grate. Accordingly, furnaces for burning anthracite and coke breeze are constructed with a long rear arch and over-fire air injection through the rear arch.

The net effect is to maintain a hot zone over the incoming fuel and to blow the fine particles of carbon onto the front of the stoker so as to assist ignition and retain them in the combustion zone until they are burned. Over-fire air injection and a high furnace are necessary to burn the CO that is formed in the fuel bed.

The travelling-grate stoker is similar in general appearance and operation to the chain-grate stoker except that individual grate bars or keys are mounted on carrier bars which extend across the width of the stoker and are attached to and driven by several parallel chains. Since adjacent grate bars have no relative motion with respect to each other, this stoker is particularly applicable to the burning of the fine sizes of anthracite and coke breeze in which all the fuel may pass through a screen having 3/16-in, round openings.

CHAPTER II

HEAT TRANSFER AND STEAM GENERATION

Boilers, superheaters, economizers, condensers, evaporators, coolers, and heaters are types of equipment that are used to transfer energy from one fluid to another through a metal surface that prevents the fluids from mixing. Since most of this equipment operates at temperatures that are considerably different from room temperature, the equipment and interconnecting piping are insulated to prevent transfer of- energy to or from the atmosphere. The designs of the amount of heat-transfer surface and its arrangement and the selection of the insulation to be applied to the equipment are based on the laws of heat transfer and economics.

MODES OF HEAT TRANSFER

Heat has been defined as energy that is being transferred across the boundaries of a system because of a temperature difference. This transfer may occur through the mechanism of conduction, convection, or radiation, either separately or in combination.

Heat is transferred by conduction through a solid, partly as a result of molecular collisions but primarily as a result of a flow of electrons which is induced by a temperature difference. Metals that are good conductors of electricity are also good conductors of heat. Poor conductors (good insulators) are solids that have low density because of the presence of large numbers of small pores or pockets containing air which reduce to a minimum the cross-sectional area of the solid material through which the electrons may flow. Conduction also occurs in liquids and gases at rest, that is, where there is no motion other than the random •mot ion of the molecules. Since the energy is transferred as a result of random molecular collisions, the conductivity of liquids and gases is low as compared to the conductivity of solids.

Convection occurs when, either because of a difference in density or because of the operation of a fan or pump, a fluid flows across a hot or cold surface and exchanges energy with that surface. The heated or cooled fluid may then flow to some other region. Since convective heat transmission always involves a flowing fluid, the laws governing heat transfer by convection are closely related to the laws of fluid dynamics.

Radiation involves the transfer of energy through space in the form-of electromagnetic waves that are different from light waves only in their length (frequency). Since radiant energy travels in straight lines with the velocity of light and may be absorbed, reflected, or transmitted by the receiving surface in a manner similar to the action of light, the laws o optics are important in the study of radiant-energy transfer.

In general, a heat exchanger consists of a metal wall through which heat flows from one fluid to another. Heat transfer through the wall follows the laws of conduction. Heat transfer between the moving fluid and the wall involves convection, in addition to which radiation may be important at high temperatures.

STEAM GENERATION

Steam is used for space heating, in manufacturing processes, and for power generation. Except for hydroelectric power plants, practically all the central-station generating capacity is in the form of steam turbines. Because of the magnitude of the load and the economies that are effected through the use of the smallest possible number of largest machines, most central-station turbines now being built are in the size range of 1000,000 to 600,000 kw. It is standard practice to install one steam-generating unit per turbine. Consequently, these turbines require steam-generating units in the capacity range of 750,000 to over 3,000,000 lb of steam per hr.

The steam boilers a pressure vessel in which feedwater can be converted into saturated steam of high quality at some desired pressure. When other heat-transfer surfaces such as superheater, air heater, or economizer surfaces are combined with boiler surface into a unified installation, the name steam-generating unit is applied to the complete unit.

Boilers in which the water is inside the tubes are called water-tube hollers, whereas boilers that have the hot products of combustion in the tubes and the water outside the tubes are called fire-tube boilers. Boiler heating surface is defined as that surface which receives heat from the flame or hot gases and is in contact with water. The area is based on the surface receiving the heat, that is, the outside area of water tubes and the inside area of fire tubes.

BOILERS

Fire-tube boilers. These are boilers with straight tubes that are surrounded by water and through which the products of combustion pass. The tubes are usually installed within the lower portion of a single drum or shell below the waterline.

Water-tube boilers. These are boilers in which the tubes themselves contain steam or water, the heat being applied to the outside surface. The tubes are usually connected to two or more drums set parallel to, or across, the centerline. The drums are usually set horizontally.

Tube shape and position. The tubular heating surface may be classified: 1) by form — either straight, bent, or sinuous or 2) by inclination — horizontal, inclined, or vertical.

Firing. The boiler may be either a fired or an unfired pressure vessel. In fired boilers the heat applied is a product of fuel combustion. A nonfired boiler has a heat source other than combustion.

Circulation. The majority of boilers operate with natural circulation. Some utilize positive circulation in which the operative fluid may be forced “once 1through” or controlled with partial recirculation.

Furnace position. The boiler is an external combustion device in that the combustion takes place outside the region of boiling water. Au heat must be transferred through the heating surface to reach the water. The relative location of the furnace to the boiler is indicated by the description of the furnace as being internally or externally fired: 1) the furnace is internally fired if the furnace region is completely surrounded by water-cooled surfaces; 2) the furnace is externally fired if the furnace is auxiliary to the boiler or built under the boiler.

General shape. During the evolution of the boiler as a heat producer many new shapes and designs have appeared.

Some of these boilers have become- popular and are widely recognized in the trade, including the following:

1. Fire-tube boilers — horizontal return tubular, short firebox, compact, locomotive, vertical tube (seam jenny),
Scotch type, and residential units.

2. Water-tube boilers — both horizontal straight tube and bent tube units. The horizontal straight tube boiler may have a box type header made of steel plate, or a sectional header each section of which connects the tubes in a single vertical row. The bent tube boiler may have one to four drums. If the drum is parallel to the tubes, the boiler is long — longitudinal drum; if across the tubes, it is a cross drum. If the furnace is enclosed with water-cooled surfaces, it is a waterwall (water-cooled) furnace.

THE TWO-DRUM WATER-TUBE BOILER

A typical small two-drum water-tube boiler is fired by a spreader stoker equipped with a dump grate. By means of baffles, the gases are forced to follow a path from the furnace to the boiler exit. This arrangement of gas flow is known as a “three-pass” design. A water level is maintained slightly below the midpoint in the-steam drum. Water circulates from the steam drum to the lower or mud drum through the six rows of tubes in the rear of the boiler-tube bank where the comparatively low gas temperature results in a low heat- transfer rate circulation is from the mud drum to the steam drum through the front boiler tubes and the side-wall furnace tubes. The side-wall furnace tubes are supplied with water from the mud drum by means of circulators connected to rectangular water boxes located in the side walls at the level of the grate. Water for the front-wall tubes is supplied to a round front-wall header by downcomer tubes connected to the steam drum and insulated from the furnaces by a row of insulating brick. Most of the steam is generated in the furnace-wall tubes and in the first and second rows of boiler tubes which can “see” the flame in the furnace and absorb energy by radiation.

Boilers of this type have been standardized in a range of sizes capable of generating 8,000 to 50,000 lb of steam per hr.

The position of the drums and the shape of the tubes result in a compact unit having a well-shaped and economically constructed furnace. By simple changes in the arrangement of furnace-wall tubes, the design can be adopted to almost any kind of firing equipment and fuel.

THE BENT-TUBE BOILER

The bent-tube boiler offers many advantages over the straight-tube boiler, including the following: 1) greater economies in fabrication and operation because of the use of welding, improved steels, waterwall construction, and new manufacturing techniques; 2) greater accessibility for inspection, cleaning and maintenance; 3) ability to operate at higher steaming rates and deliver drier steam.

The main elements of the bent-tube water-tube boiler are essentially drums (or drums and headers) connected by bent tubes. With a water-cooled furnace, bent tubes are arranged to form the furnace enclosure, making it integral with the boiler.

The early bent-tube boilers were of the four-drum type. Although many operators still prefer it, there is a decided trend to use two drums or three drums.

In modern bent-tube units, the capacity is held to less than 20,000 lb steam per hr per ft of width. The smaller bent- tube boiler has been fairly well standardized into a relatively small number of types. The boiler is either of refractory wall or waterwall construction, sometimes with a steel casing designed for nonpressure operation. Popular boilers are the two-drum low head, the three-drum low head, two-drum inclined as well as various package boiler designs. The standardized design used in industrial plants is available in capacities to 100,000 lb steam per hr. Design pressure varies from 160 to 825 psi with temperatures up to 850° F.

Integral furnace. In its early development stages, the bent-tube boiler was set over a brick or refractory furnace, and all heat-absorbing surfaces were inside the boiler itself. As furnace size and temperatures increased, refractory maintenance became excessive, particularly when firing with pulverized coal.

The higher gas temperatures caused increased slagging or fouling of the boiler surfaces. The furnaces were first partly then later completely, water-cooled to overcome these difficulties. Besides decreasing maintenance and boiler slagging, the waterwalls also generated steam, provided excellent circulation, and aided in obtaining higher capacities.

Furnace waterwalls were first applied to existing boilers, the water circulation being more or less independent of the boiler circulation. Later the furnace water-cooled surface and the boiler surface were integrated.

With the advent of pulverized coal, it became necessary to prevent the ash from slagging at the bottom of the furnace. This was accomplished by installation of a waterscreen, consisting of a crisscross of water tubes protecting the furnace floor (and the ash) from radiation. As furnace input increased, the entire floor was water-cooled and designed for continuous or intermittent discharge of molten slag. Still later a redesign of the floor resulted in the dry-ash furnace bottom.

Design. With the exception of models of obsolete design or of very recent development, such as the positive circulation boiler, the bent-tube boiler is inherently a multidrum boiler.

There may be two, three or four drums-one lower drum with the remainder at the top of the boiler. The lower drum is the mud drum, which has a blowdown valve for removal of sludge and concentrations of salts. The upper drums are steam and water drums.

Although they are called steam drums, actually some of them may be water filled. .Steam separators (drum internals) eliminate entrained moisture and precipitates, purifying the steam.

The tubes are either inclined or arranged in vertical banks within the combustion space, or they may comprise water walls backed with refractories. The bent tube allows great flexibility in design, particularly with regard to drum arrangement, as it may enter the drum radially.

Boiler and furnace wall tubes are usually supported by the drums or headers to which they are connected. Some boilers are bottom supported, and others are suspended from the upper drums.

The gas baffles are arranged in many different patterns, with the gas flowing across and along the tubes in one or more passes. The tendency toward slag adherence is decreased if tubes are vertical or nearly vertical. To avoid particularly abrasive coal ash or unsatisfactory fusion characteristics, the boiler design must consider both these possibilities.

The bent-tube boiler is suitable for operation with oil, gas, coal, bagasse or wood. Burning methods include oil or gas burners and stoker firing. For sizes, over 100,000 lb steam per hr pulverized coat or crushed coal (cyclone furnace) firing is used. The firing is usually manually or semiautomatically controlled.

THE HORIZONTAL STRAIGHT TUBE BOILER

The horizontal srtaight tube boiler covers a range of capacity and pressure between that of the fire-tube boiler and the large central steam generator. It is used in industrial applications primarily for process steam, occasionally for heating, and sometimes for power generation. The horizontal straight tube boiler is limited to an hourly production of about 10,000 lb steam per ft of boiler width. It is simple in operation and has low draft loss.

The straight tube boiler is made up of banks of tubes that are usually staggered, the tubes are inclined at an angle (5 to 15 deg) to promote circulation and expanded at the ends into headers.

The header (either a box header or a sectional header) provides flat surfaces for tube connections. It may be connected to the drum by means of circulation tubes (downcomers or downtakes for supplying water to the tubes, uptakes or risers for discharging water and steam from the tubes) or by sheet steel saddles. The drum may be either longitudinal (long) or across (cross) with reference to the axis of the boiler tubes. Some boilers have a portable firebox with wrapper and furnace sheets instead of a drum. The high end is usually the firing end. The area of the heating surface (and the capacity) is varied by changing the tube length and the number of tube row in both height and width. The tubes, 3 to 4 in. in diameter, are spaced 7 to 8 in. on centers horizontally and 6 in. on centers vertically (except slag screen tubes, which are on about 12 in. centers) The tubes are all of the same diameter and length, never over 18 to 20 ft.

As the pressure increases, the header design changes. Greater tube spacing is required, and the tubes must be smaller in diameter.

Internal fireside baffles may be horizontal (parallel with and between the tubes) or vertical (across. the tubes). The baffling is arranged for two or three gas passes across the tubes. In the headers opposite the tube end, there is a handhole of sufficient size to permit removal or renewal of the tubes and the inspection of tubing and cleaning of the tube interior. Handholes are elliptical in shape, machined to form a smooth gasket seat and fitted with forged steel handhole plates.

Superheaters with a maximum temperature rise of about 1000 F may be installed. They are termed overdeck and interdeck depending upon their location in the boiler.

Circulation. The steam and water rises along the inclined tubes to the front headers, then through the headers and circulation tubes to the drum. The water then circulates through the downcomers to the rear header and finally to the tubes to complete the cycle. In the long drum boiler, the water is diverted by a baffle plate back through the steam drum. In the cross drum boiler, steam separators (drum internals), are often used to eliminate entrained moisture and precipitates, thereby purifying the steam. If the tubes discharge to the steam drum at or above the waterline, the boiler is known as an exposed-tube boiler, otherwise it is a submerged-tube boiler.

Fuels and fuel firing. The horizontal straight tube boiler is suitable for operation with oil, gas, coal, bagasse, or wood.

Burning methods include oil and gas burners with hand or stoker firing. Pulverized coal firing is rarely used. The firing is usually manually controlled.

THE HORIZONTAL-RETURN TUBULAR BOILER

In the horizontal-return tubular (HRT) fire-tube boiler the boiler shell is a horizontal cylinder closed at each end by a flat tube sheet or head. The fire tubes, which are usually 3 to 4 in. in diameter, extend through the boiler from one tube sheet to the other and are rolled or expanded into the tube sheets at each end, thus serving not only as flues through which the hot combustion products flow but also as tie rods to hold the flat tube sheets in place against the steam pressure in the boiler The flat surfaces of the heads above the tubes are braced to the boiler shell by diagonal braces.

The boiler supported by a steel frame, is provided with a brick setting which encloses the furnace, and is fired by a single-retort underfeed stoker. The gaseous products of combustion from the stoker pass over a bridge wall at the rear of the stoker which is intended to promote turbulence, then through the brick furnace under the boiler shell to the rear of the boiler. They then flow through the boiler tubes to the front of the boiler after which they pass a damper and are discharged to a chimney.

A water level is maintained a short distance above the top tubes so as to provide adequate surface for the separation of the steam from the water and, at the same time, to keep water in contact with all surfaces across which hot gases are flowing. The water level in the boiler is indicated by a water column which is connected to the boiler by two pipes, one above and one below the water level. The water in the water column is thus maintained at the same level as in the boiler, and this level is indicated by a glass tube attached to the water column.

A blow-off line is connected to the bottom of the drum at the rear. Valves in this line are opened periodically and some of the boiler water is blown to a sewer, thus carrying out of the system the impurities that are coming into the boiler in the feedwater. It is common practice in these small boilers to add chemicals to the feedwater. These chemicals are intended to prevent the scale-forming impurities in the feed- water from precipitating on the heating surfaces as an adherent scale. If the boiler produces dry steam, all these impurities remain in the boiler. They must be removed by periodic blowdown in order to maintain the concentration in the boiler water below a level that will cause scale formation.

The boiler shell is provided with suitable opening for the attachement of spring loaded safety valves, feed-water inlet, a steam outlet nozzle, and manholes or cleanouts,

Since this boiler is provided with a brick furnace which is external to the boiler itself, it is known as an externally fired boiler.

SUPERHEATERS

Superheated steam is produced by causing saturated steam from a boiler to flow through a heated tube or superheater, thereby increasing the temperature, .enthalpy, the specific volume of the steam.

It should be noted that in an actual superheater there J will be a decrease in steam pressure due to fluid friction in the superheater tubing.

Maximum work is obtained when a fluid expands at constant entropy, that is, without friction and without heat transfer to the surroundings. By calculations it will be found that the constant-entropy expansion of 1 lb of dry saturated steam at 1000 psia to a final pressure of 1.0 psia will result in the conversion into work of 417 Btu, whereas the expansion of superheated steam at the same initial pressure, 1000 psia but at 10000 F, to the same final pressure of 1.0 psia will result in the conversion into work of 581 Btu, an increase of 39.3 per cent.

In addition to the theoretical gain in output due to the increased temperature of superheated steam as compared to saturated steam, there are additional advantages to the use of superheated steam in turbines The first law of thermodynamics states that all the work done by the turbine comes from the energy in the steam flowing through the turbine.

Thus, if steam enters the turbine with an enthalpy of 1300 Btu per lb and the work done in the turbine is equivalent to 300 Btu per lb of steam, the enthalpy of the exhaust steam will be 1300—300 = 1000 Btu per lb, neglecting heat transfer to the surroundings. If sufficient energy is converted into work to reduce the quality of the steam below about 88 per cent, serious blade erosion results because of the sandblasting effect of the droplets of water on the turbine blades.

Also, each I per cent of moisture in the steam •reduces the efficiency of that part of the turbine in which the wet steam is expanding by 1 to l/2 per cent. It is necessary, therefore, that high-efficiency steam turbines be supplied with superheated steam. The minimum recommended steam temperature at the turbine throttle of condensing turbines for various initial steam pressures is as follows:

Throttle Steam Pressure, psig	*Minimum Steam* Temperature, °F
400	725°
600	825°
850	900°
1250	950°
1450	1000°
1800	1050°

Large power plants currently being built in regions of high fuel cost are designed for operation at pressures of more than 1500 psig. At these high pressures, a reduction in the annual fuel cost of 4 to 5 per cent can be made by expanding the steam in the turbine from the initial pressure and 1000 to 11000 F to an intermediate pressure of about 30 per cent of the initial pressure, returning the steam to the steam-generating unit, and passing it through a second superheater, known as a reheater, where it is superheated to 1000 to 11000 F, and then completing the expansion of the steam in the turbine. For initial steam pressures above the critical pressure (3206 psia), a second stage of reheating is employed.

The decreased strength of steel at high temperature makes it necessary to use alloy steels for superheater tubing where steam temperatures exceed 800° F. Alloy steels containing 0.5 per cent of molybdenum and I to 5 per cent of chromium are used for the hot end of high-temperature superheaters at steam temperatures up to 1050° F, and austenitic steels such as those containing 18 per cent chromium and 8 per cent nickel are used for higher temperatures.

Superheaters may be classified as convection or radiant superheaters. Convection superheaters are those that receive heat by direct contact with the hot products of combustion which flow around the tubes. Radiant superheaters are located in furnace walls where they “see” the flame and absorb heat by radiation with a minimum of contact with the hot gases.

In a typical superheater of the convection type saturated steam from the boiler is supplied to the upper or inlet header of the superheater by a single pipe or by a group of circulator tubes. Steam flows at high velocity from the inlet to the outlet header through a large number of parallel tubes or elements of small diameter. Nipples are welded to the headers at the factory, and the tube elements are welded to the nipples in the field, thus protecting the headers from temperature stresses due to uneven heating during final welding.

The amount of surface required in the superheater depends upon the final temperature to which the steam is to be superheated, the amount of steam to be superheated, the quantity of hot gas flowing around the superheater, and the temperature of the gas. In order to keep the surface to a minimum and thus reduce the cost of the superheater, it should be located where high-temperature gases will flow around the tubes. On the other hand, the products of combustion must be cooled sufficiently before they enter the superheater tubes so that any ash that may be present has been cooled to a temperature at which it is no longer sticky or plastic and will not adhere to the superheater tubes. In a modern two-drum steam generating unit fired by a continuous-ash-discharge spreader stoker, the superheater is located ahead of the boiler convection surface and at the gas exit from the furnace. In installations burning coal having a high content of low-fusing-temperature ash, it may be necessary to place a few boiler tubes ahead of the superheater.

ECONOMIZERS AND AIR HEATERS

The largest loss that occurs when fuel is burned for steam generation is the so-called “sensible heat” carried away in the hot flue gas. The efficiency of a steam-generating unit provided with good fuel-burning equipment is a function of the flue-gas temperature.

Theoretically, the minimum temperature to which the products of combustion may be cooled is the temperature of the heat-transfer surface with which they are last in contact. In the conventional boiler the theoretical minimum flue-gas temperature would be the saturation temperature of the water in the boiler tubes. The relative amount of boiler heat-transfer surface required to’oo1 the products of corn bust inn from 15000 F to lower temperatures is based on saturated water in the boiler tubes at 1000 psia. It will be noted that, as the temperature difference decreases, each increment of added surface becomes less effective and that the amount of surface required to cool the gases from 700° to 600° F is about 60 per cent of that required to cool the gases from 1500° to 700° F.

In general, it is not economical to install sufficient boiler surface to cool the gases to within less than 150° F of the saturation temperature of the water in the tubes, because sufficient heat cannot be transmitted to the tubes at such low temperature difference to pay for the cost of the boiler surf act.

The gases must be cooled from the boiler exit-gas temperature to the flue-gas temperature required for high efficiency by means of heat exchangers supplied with fluids at temperatures less than the saturation temperature at the boiler pressure. This can be done in an air heater supplied with the air required for combustion at room temperature or in an economizer supplied with boiler feedwater at a temperature considerably below the saturation temperature, or both. In many installations, it is economical to install a small boiler and a large economizer and air heater and to deliver the gases to the economizer at temperatures as high as 900° F rather than to cool the gases to lower temperatures by a larger boiler.

In a typical economizer feedwater is supplied to the inlet header from which it flows through a number of parallel circuits of 2-in. o.d. tubes1 of considerable length to the discharge header. If the inlet header is at the bottom so that the water rises as it flows from tube to tube, the hot gas normally enters at the top and flows downward. Thus the coldest gas will be in contact with the coldest tubes, and it is possible to cool the gas to within 125° to l5O'l of the temperature of the inlet water if sufficient surface is installed.

Since the economizer has water in the tube and a dry gas around the tube, the major resistance to heat transfer is on the gas side. In order to increase the surface exposed to the gas per linear foot of tube and thus increase the effectiveness of the tubular surface the economizer has fins welded to the top and bottom of each tube. This increases the surface available for heat transfer from the gas without substantially increasing the pressure drop of the gas as it flows across the surface. The gas flows at right angles to the tubes, and the 2-in, finned tubes are staggered to promote effective scrubbing of the outside surface by the gas so as to improve the overall heat-transfer coefficient.

Where scale-free feedwater is available or acid cleaning of heat transfer surfaces is used to remove scale, the flanged return bends may be eliminated. The flow circuits then consist of continuous welded tubing between inlet and outlet headers.

TYPES OF ECONOMIZERS

Economizers for power station service are of two classes, steaming and non-steaming. Both have been used and choice will depend largely on the feed-water temperature and the boiler pressure. If the turbines are bled to such an extent that the final feed-water temperature is raised to within a few degrees of the saturation temperature, it is apparent that no further heat can be added in an economizer unless a steaming economizer is used. The function of this economizer is to supply the boiler with a percentage of wet steam along with the feed water and a number of pipe connections are taken from the economize outlet to the boiler drum. A saving may be effected in both capital cost of the boiler and building with large steaming economizers. The construction and location of both classes of-economizers are similar, the chief difference being that only one outlet connection is required on the non-steaming economizer. With a steaming economizer, boiler baffles are eliminated resulting in a reduction of draught loss and fan power. During intermittent feeding with cold feed, temperature changes occur at the economizer inlet joints which may result in joint failure.

Modern economizers are constructed with steel tubes, which are necessary for high pressures. In order to conserve space, the tube surface is usually made iii one continuous loop with connection pieces between the ends of the horizontal tube sections. Early designs used cast-iron tubes, the tubes being screwed into the headers. In modern economizers the tubes made of steel are usually $2^1/_2$ or 3 in. in diameter and are rolled into one or two headers only. Feed water is fed to one end of the lower header and distributed to each of the parallel-tube circuits., The last tube element may be rolled directly into the 'drum,- and there is a growing tendency in design to eliminate all bolted return bends, the tube being in one continuous loop.

In constructions of continuous and of return bends, the bends are usually mad of forged steel and are carefully machined to receive the tube ends. Gaskets which are necessary where the tube ends bear against the female joint of the return bend, may be of some soft material such as cranite. In order to keep the gas passage restricted to the straight section of the tubes and to give support to the tubes, it is customary to use tube sheets of cast iron. The outside casing is then made of removable steel-plate panels which are insulated, it thus being necessary to remove the whole side to obtain access to a certain tube. When there is a reversal of gas passage, soot hoppers are commonly placed below the economizer to collect any soot carry-over from the boiler, the soot, being piped to the ashpit.

Economizers when used in combination with air heaters are practically always set nearest to the boiler flue-gas exit. Although most economizers do not heat the feedwater to a point where it vaporizes, a number of steaming economizers have been built and operate successfully. In these, the individual parallel-tube elements run separately to the top rear drum of the boiler and are rolled directly into the drum. Relief connections between the drum and the economizer are not provided. In addition to a gain in over-all boiler efficiency of 10 to 12 per cent, depending upon the drop in gas temperature, an economizer will provide nearly as much, additional generating capacity. Maintenance, it is claimed, will amount to as little as $^1/_2$ to 1 per cent per year.

THE AIR HEATER

The tubular air heater is constructed by expanding vertical tubes into parallel tube sheets which form the top and bottom surfaces, respectively, of the gas inlet and outlet boxes. The tube bank is enclosed in an insulated casing so constructed that the inlet air at room temperature can be admitted to the heating surfaces at the upper end from a fan or blower. The air passes downward around the tubes in a direction opposite to the flow of the hot gases and leaves the air heater at the lower end of the tube bank. Deflecting baffles are installed to guide the air and reduce frictional resistance at the turns. A by-pass damper and baffle permit by-passing the air around the upper half of the tube surface on light load when there is danger of corrosion due to low flue-gas temperatures. Long tubes closely spaced to maintain high air and gas velocities and countercurrent flow of gases and air make it possible in many installations to cool the gases to a temperature 1000 to 200° F below the temperature at which the hot air is discharged.

Let us consider another type of air heater which operates on the regenerative principle. A drum filled with corrugated sheet-steel plates is rotated about a vertical shaft at about 3 rpm by means of a small motor. Hot flue gas passes downward through the right side of the rotor from a duct connected to the economizer or boiler. An induced-draft fan may be connected by a duct to the lower side of the air-heater casing. This fan induces a flow of the gases through the boiler, economizer, and air-heater surfaces, and discharges them to waste up the chimney. The cold air from a forced-draft fan flows upward through the left side of the rotor, where the air is heated, after which it is delivered through suitable duct work to the stoker or burner in the furnace. Any point on the corrugated sheet-metal surface of the rotor is rotated alternately into the hot descending gas stream and the cold ascending air stream, thus transferring energy from the hot gas to the cold air.

Radial seals with rubbing surfaces on them are mounted on the rotor and make contact with a flat selection of the casing between the hot-gas and cold-air ducts, thus-1rnininiizing leakage between the two streams of fluid. The depth of the rotor is normally between 3 and 4 ft. The unit is also made for operation about a horizontal shaft with horizontal flow of gas and air where building space makes such an arrangement desirable.

The maximum air temperature that can be used in stoker-fired installations without increasing grate maintenance is about 300° F, since the grate surface which supports the hot fuel bed must be cooled by the air to a temperature below which the iron grates-will not be damaged. Air temperatures of 600° F are often used with pulverized coal. Since the stoker limits the heat-recovery possibilities dl the air heater, both economizers and air heaters are usually installed in stoker-fired high-pressure steam-generating units. Where oil, gas, or pulverized coal is burned, an air heater is often installed without an economizer, although in many high-pressure units it may be more economical to reduce the boiler surface and use an economizer. The air heater is necessary in modern pulverized-coal plants since the coal is dried in the pulverizer by hot air to reduce power consumption and increase the capacity of the mill.

AIR PREHEATERS

Air preheaters are installed to preheat the air required for combustion, the heating medium being the flue gases leaving the economizer. The use of preheated air assists early gasification and ignition of the carbon and promotes high furnace temperature.

The final temperature of the air will depend upon the method of firing, and classes of coal. For pulverized fuel firing air temperatures of 450° to 650° F are possible, whereas in stoker-fired boilers the maximum permissible temperature would be about 400° though in practice temperatures of 250° to 300° F are more usual for chain-grate stokers. Preheated air is a necessity with pulverized fuel firing, a decided advantage to stoker-firing and is the only simple means available for the reduction of the final flue-gas temperature.

There are four types of heaters: 1) tubular; 2) plate; 3) rotary or regenerative; 4) tubular-needle or gilled.

In the tubular heater the air is passed across the tubes and the flue gases pass through the tubes or vice versa. Cleaning is easier when the gases pass through the tubes. The rate of heat transfer is low and the space occupied is generally prohibitive. This type of heater may be used with high temperatures. Trouble is experienced in cleaning long tubes and there is added disadvantage in that considerable space is necessary for withdrawal of the tubes.

The plate type was very popular until the rotary heater was developed. The gilled or needle type of heater is also in use. The tubes are of cast iron, the gases passing through plain tubes and the air over the pointed gill surfaces.

THE STEAM-GENERATING UNIT

For operation at pressures below the critical pressure, a steam-generating unit consists of a boiler, superheater, air heater, and (or) economizer. The furnace walls are either partially or fully covered with boiler tubes. In general, most of the steam is generated in the furnace-wall tubes since they can absorb radiant energy from the high-temperature flame.

A typical stoker-fired steam-generating unit in the smaller size range, has a capacity of 72,500 lb of steam per hr. The gases as they leave the completely water-cooled furnace pass across the superheater surface, then the convection tubes of the boiler, then upward through a small economizer, downward through a tubular air heater, dust collector, and fan, to the chimney. The boiler is of the two-drum type without gas baffles; that is, it is a single-pass boiler. The internal baffles in the steam drum are so arranged that the last lour rows of boiler tubes in which the heat-transfer rate is quite low are downcomers. Since a major item in the cost of a boiler is the drums, as many boiler tubes as possible are placed between the drums. A large amount of surface is required to cool the gases from the temperature at which they leave the superheater to the final temperature.

Depending upon the steam pressure, the feedwater is heated in regenerative feed-water heaters to 275° F to over 600° F, depending on pressure, before being admitted to the economizer. Essentially, the economizer raises the feed-water temperature almost to the saturation temperature, the boiler supplies the latent heat, and the superheater supplies the superheat. It will be noted that, as the pressure increases, a decreasing portion of the total energy absorption occurs in the boiler and that, for pressures above the critical, there is no boiler. Supercritical-pressure steam generators essentially are economizers connected to superheaters. There is no steam drum since there is no boiling and no steam to be separated from water at a constant temperature.

At the higher pressures at which natural circulation boilers may be used, the boiler becomes a smaller part of the installation and the superheater and reheater become a larger portion of the total heat-transfer surface.

Modern high-capacity steam-generating units have been developed to the point that they can be depended upon to carry heavy loads continuously for months at a time. Their reliability is approximately equal to that of modern steam turbines. Consequently, most new central-station power plants are built on the unit system: that is, with each turbine generator supplied with steam from its own steam-generating unit. Thus, turbine-generator units in capacites up to 500,000 kw are being supplied with steam from a single steam-generating unit. One of the major reasons for this arrangement is the decreased cost per unit of capacity which results from increased size.

HIGH-CAPACITY, HIGH-EFFICIENCY STEAM-GENERATING UNITS

Such units are currently being designed for capacities from 750,000 to 3,000,000 or more lb of steam per hr at pressures of 1200 to 5000 psia and temperatures of 950° to 1200° F. Because of the quantity of fuel burned, they are designed for efficiencies of 87 to 90 per cent and always include a large air heater. They are fired by pulverized coal or cyclone furnaces, or, where the economics of the situation permit, by gas or oil or a combination of these fuels. Since it is standard practice to install one steam generator per turbine, they are very carefully designed to insure reliable and continuous operation for long periods of time. Depending on boiler-insurance requirements and state laws, they may be operated for two to three years without a major shutdown for cleaning and overhaul.

In a single-drum unit having a capacity of 800.000 lb per hr at 1350 psig and 9550 F superheat temperatures two large downcomers deliver water from the steam drum to the four headers that supply the furnace-wall tubes in the front, rear, and side walls of the furnace. These furnace tubes deliver their steam-water mixture to the boiler drum. Practically all the steam is generated in the furnace walls. The steam flows from the boiler drum to a heat exchanger that is used for superheat control and then through the counter- flow superheater. It should be noted that the hot end of the superheater is next to the furnace.

There are four rows of boiler tubes between the superheater and the economizer. Final cooling of the gases occurs in a regenerative air heater.

A considerable number of large steam generators of the forced-circulation type have been installed for operation at pressures from 1800 to 2700 psig. Feedwater is fed through a conventional counter-flow economizer to a boiler drum. Also, steam from the boiler drum flows through a conventional superheater. Water from the boiler drum flows by gravity to a circulating pump which discharges into a distributing header. Water from the distributing header flows through long small-diameter boiler tubes located in the walls and roof of the furnace to the drum, where the steam is separated and the water returns to the pump. Orifices at the inlet to each circuit at the distributing header correctly proportionate the water among the many parallel circuits so that each one receives its proper share. The circulating pump raises the water pressure to about 40 psi above the drum pressure, this being sufficient to overcome the resistance of the flow-controlling orifices and the long circuits of small-diameter tubing. These tubes may be constructed of thinner walls than would be required by the larger tubes that are used in natural-circulation boilers and may be arranged so that the flow is upward, horizontal, downward, or any combination thereof.

In the conventional forced-circulation boiler, the amount of water circulated is four to five times the amount of steam generated and an effective steam-separating drum is as essential as in the natural-circulation boiler. Recent development in feed-water treatment have resulted in feedwater of high purity. This has made it possible to build steam-generating units in which the large horizontal steam drum has been eliminated.

The conventional steam drum is replaced by a vertical water separator. Water is pumped through small-diameter tubes in the furnace walls and is converted into steam of high quality which is discharged into the water separator. Here the small amount of unevaporated water is separated from the steam and is blown down to a lower pressure, carrying out with it any impurities that have been concentrated in the water as a result of evaporation. The dry steam from the separator then passes through four sections of superheater tubing, designated as superheater I, II, III and IV, to the turbine. The steam is resuperheated in the reheater to the initial temperature at a pressure of about 30 per cent of the initial pressure. An economizer and air heater are provided to cool the products of combustion to the low temperature necessary for high efficiency.

For operation at pressures above the critical pressure, 3206 psia, water does not boil. No boiler drum is required, and the steam generator becomes essentially a continuous circuit of steamless steel tubing with intermediate headers of small diameter. Such a unit is known as a “once-through” steam generator.

The unit is fired by eight 10-ft-diameter cyclone furnaces arranged to discharge from opposite sides into a common secondary furnace. The gases flow upward through the secondary furnace and through three parallel vertical passes to three air heaters. The walls of the three parallel vertical passes are constructed of closely spaced steam-generating tubes. The primary and secondary superheater, the first and second reheaters, and the economizer are located in these passes.

The feedwater flows from the economizer section to the cyclones through outside downcomers. From the cyclone, the fluid flows upward through the secondary furnace-wall tubes and the convection section baffle-wall tubes which form the walls of the three parallel gas passes above the furnace. From the baffle walls, the fluid flows through the primary superheater, a heat exchanger or attemperator that is used for superheat control, and then through the secondary superheater to the superheater outlet and turbine. The transition from water to steam occurs in the upper part of the furnace enclosure.

After expansion in the turbine to an intermediate pressure, the steam is reheated in the first-stage reheater to 1050° F. After further expansion in the turbine, it is reheated in the second-stage reheater to 1050° F. It should be noted that the superheaters and reheaters occupy a major part of the total volume of the Installation.

Final superheat and reheat temperatures are controlled by a heat exchanger between the primary and secondary superheater, damper above the economizers in the three parallel vertical gas passes, and recirculation of gas from a location beyond the economizer to the secondary furnace above the cyclones.

C H A P T E R III

HEAT EXCHANGERS

As stated above all power and refrigeration plants contain equipment which has as its major function the transfer of heat from one fluid to another. This equipment includes boilers, superheaters, economizers, heaters, coolers, condensers, and evaporators and is called a heat exchanger. The same laws of heat transfer, fluid flow, and economics apply to all heat exchangers. Heat exchangers differ in design characteristics only because of the different functions which they perform and conditions under which they operate.

Two heat exchangers commonly found in stationary power p1ants are the steam condenser and feed-water heater. They are distinct and separate pieces of equipment, and they differ in their relative positions and primary functions in the cycle. The purpose of the feed-water heater is to increase the overall efficiency of the cycle. This is accomplished by heating the boiler water before it enters the boiler with either waste steam or steam extracted from the turbine. With the feedwater entering the boiler at high temperatures, the boiler is relieved of a part of its load and temperature stresses within the boiler are reduced. Feed-water heaters are designed as direct-contact heaters or surface heaters.

DIRECT-CONTACT FEED-WATER HEATERS

The direct-contact heater is often called an open heater, although it may operate at pressures above atmospheric pressure. A typical direct-contact heater consists mainly of an outer shell in which are trays or pans. Water enters at the top of the shell. It fees by gravity over rows of staggered trays which break up the solid stream of water. Steam entering near the center of the shell intimately mingles with the water and condenses.

In condensing, the steam gives up heat to the water. The heated water and condensate mixture is collected at the bottom of the shell and is removed by a boiler feed pump. A float control operating the inlet water valve maintains a constant level in the feed-water tank. A vent at the top removes the excess steam and the noncondensable gases. In the larger heaters where the vented steam is appreciable, a vent condenser may be employed. Water, before it enters the tray section of the feed-water heater, is passed through coils in the vent condenser. Heat is transferred from the vented steam to the water as the steam is condensed. The condensate from the vent condenser is retur3ed to the heater. Noncondensable gases are expelled to the atmosphere,

Because of the stress limitations of the heater shell, the steam pressure is limited to a few pounds per square inch above atmospheric pressure, although pressures to 70 psia have been used. Consequently, the feedwater is rarely heated above 2200 F. If direct-contact heaters are used in series, a feed-water pump must be installed ahead of each heater. The advantages of the direct-contact feed-water heater are: 1) complete conversion of the steam to water is accomplished;

2) noncondensable corrosive gases are removed from the feedwater; 3) the removal of impurities in the water is possible; 4) the water is brought to the temperature of the steam; 5) the heater acts as a small reservoir.

CLOSED PEED-WATER HEATERS

Closed heaters or surface-type feed-water heaters are of the shell and tube design. Generally, the water is introduced to the heater through tubes around which the steam circulates. Closed heaters may be classified as single- or multipass and straight tube or bent tube. In a single-pass heater the water flows in only one direction. In a multipass heater the water reverses direction as many times as there are passes. In a two-pass straight tube type of closed feed-water heater water enters at the bottom of one end of the heater and flows through the lower bank of tubes to the opposite end where its direction is reversed. The water returns through the upper bank of tubes to the outlet at the top. Steam enters the shell at the top and flows toward each end, and condensate leaves the shell at the bottom.

A floating head is provided to permit the tubes to expand. Vents at the top are provided to remove gases trapped in the shell. This heater is designed for a water pressure of 1100 psi. Closed heaters placed in series require only one feed-water pump unless the pressure drop through the heaters is high. If bent tubes are used in place of the straight tubes, no floating head is necessary. However, the bent tubes may be difficult to clean.

In closed heaters the feedwater can never be heated to the temperature of the steam, but generally the terminal temperature difference at the outlet is not greater than 15° F.

To maintain a high overall heat transfer for the heater the water velocity should be high, but pumping costs will limit the velocity. A balance between pumping costs and the amount of heat transferred will result in water velocities of 3 to 8 fps. Generally, the heaters are rated in terms of the square feet of heat-transfer surface and of the quantity of heat transferred.

CONDENSERS

The primary function a condenser is to reduce the exhaust pressure of the prime mover. A reduction in the exhaust pressure will increase the pressure and temperature drop through the prime mover and will result a corresponding increase in efficiency and output. Secondary functions of the condenser are: 1) to reduce the amount of make-up boiler feedwater by condensing the steam in order that it can be returned to the boiler; 2) to remove air or other noncondensable gases which are corrosive.

Like feed-water heaters, condensers are classed as direct-contact or surface types.

The direct-contact condenser is a jet condenser consisting of water nozzles, a steam-and-water-mixing chamber, and a Venturi-section or a tailpipe. The jet condenser may be used where it is not necessary to reclaim the condensate.

Although it requires more cooling water than a surface condenser, the jet condenser has the following advantages: 1) construction and operation are simple: 2) no vacuum pump is required to remove noncondensab1e gases from the steam.

The jet condenser is used mainly for small prime-mover irtal1aions in industry.

The conventional surface condenser is of shell and tube construction. Cooling water presses through the tubes, and steam circu1ates around the tubes and is condensed and removed. At no time do the steam and condensate come into contact with the cooling water. Condensers like feed-water heaters, are classified as single- or multipass and straight or bent tube.

Generally, condensers used with prime movers are the straight-tube single- or multipass type.

In a single-pass surface condenser water enters from the bottom left, passes through the tubes, and leaves at the upper right. Steam enters the condenser shell from above, circulates around the nest of tubes, and then flows toward the center or core which is the zone of lowest pressure. Air and other noncondensable gases are removed from one end of the core at the vents. The condensed steam or condensate flows by gravity to the condensate well or hot well. The condensate is then removed from the well by a pump.

Because cooling water is usually corrosive in nature, condenser tubes are often made of special alloys of copper or aluminium. Among these are admiralty metal, muntz metal, arsenical copper, and aluminium brass.

The tubes may be rolled into each end plate. In this case expansion is taken care of by bowing the tubes. The tube of some condensers are rolled into and keyed to one end plate and are free to move in the other end plate. Leakage between the tube and end plate is prevented by packing. Expansion and contraction of the condenser shell may be taken care of by providing an expansion joint in the shell wall at one end.

Owing to the expansion and contraction of the exhaust line or nozzle leading from the turbine to the condenser, all condensers are either rigidly suspended from the turbine o connected to turbine by an expansion joint. In the former case, the condenser may be placed on spring supports. The spring supports permit the condenser to rise or fall without overloading the turbine exhaust line. In the latter case, the condenser will be rigidly anchored to the floor. All expansion or contraction in the turbine exhaust line will be taken up in the expansion joint.

There are a number of condenser auxiliaries that are essential to the proper functioning of the condenser: 1) a condensate hot well for collecting the condensate; 2) a condensate pump to return the condensate to a surge tank where it can be reused as boiler feedwater; 3) a circulating pump for circulating the cooling water; 4) an atmosphere relief valve for relieving the pressure in the condenser in case the condenser or auxiliaries do not function properly; 5) an air ejector or a vacuum pump for removing the noncondensable gases from the condenser.

The condensate pump and circulating-water pump are generally of the centrifugal type. If the source of the cooling water is a lake or a river, there is no need for water conservation. However, in many localities, the water supply may be low. In such a case, the cooling water, after passing through the condenser, is pumped to a cooling pond or cooling tower where it is cooled by contact with air and then is recirculated through the condenser.

If noncondensable gases are permitted to collect in the condenser, the vacuum in the condenser will decrease. A decrease in the vacuum will result in a decrease in the pressure drop through the turbine and Swill affect adversely the turbine efficiency. Also, the noncondensable gases are highly corrosive. Thus, their removal in the condenser is essential. They may be removed by a vacuum pump or by a steam-jet air ejector.

Steam enters the first and second stages through nozzles where it acquires a high velocity. The air and some vapor from the main condenser are entrained by the high-velocity steam and are compressed in the first stage, forcing tube. The forcing tube is the Venturi-shaped section. The steam and vapor are condensed on the intercondenser and drained to the hot well of the main condenser.

Air in the intercondenser is then entrained by high-velocity steam leaving the second-stage nozzles and is compressed further in the second stage, forcing tube. Steam is condensed in the aftercondenser and is drained to the main condenser. The air is vented to the atmosphere. Normally, condensate from the turbine condenser is used as cooling water to condense the steam in the ejector. Both the condensate and cooling water will then be returned to a surge tank.

CHAPTER IV

TURBINES

The steam turbine is prime mover in which a part of that form of energy of the steam evidenced by a high pressure and temperature is converted into kinetic energy of the steam and then into shaft work.

The basic advantage of the turbine over other forms of prime movers is the absence of any reciprocating parts. With only rotating motion involved, high speeds are attainable. Since power is directly proportional to torque times speed, an increase in the rotative speed materially decreases the value of the torque required for a given power output A decrease in the required torque permits a reduction in the size of the prime mover by reducing the length of the torque arm or the force acting on the torque arms Also, with the absence of any reciprocating parts, vibration is greatly minimized. Owing to the high rotative speeds available with relatively little vibration, the size and cost of the driven machinery, of the building space, and of the foundations are greatly reduced. These advantages are most apparent in large prime movers and permit the steam turbine to be built in sizes of over 350,000 hp in single units, and 760,000 hp in compound units.

TYPES OF TURBINES

Steam turbines may be broadly grouped into three types, the classification being made in accordance with the conditions of operation of the steam on the rotor blades. The groups are as follows:

1. *Impulse.* This may be divided into

a) Simple impulse	Pressure compounded
b) Compound impulse	Velocity compounded
c) Combined impulse	Pressure velocity compounded

2. *Reaction* subdivided into

a) Axial flow

b) Radial and axial flow

3. *Combinatio*n of 1 and 2.

1. Impulse Turbines. In an impulse turbine the potential energy in the steam due to pressure and superheat is converted into kinetic energy in the form of weight and velocity by expanding it in suitably shaped nozzles.

The whole of the expansion takes place in the fixed nozzle passages. As there is no expansion in the passage between the rotor blades, the steam pressure is the same at the inlet and outlet edges of these blades. The steam impinges on the wheel blades causing the wheels to rotate. The expansion is carried out in stages referred to as “pressure stages”, each stage being separated from the next by a diaphragm with nozzle openings through which the steam passes on its way through the turbine.

a) Simple impulse. This type has a considerable number of pressure stages, a wheel in each stage having one row of blades. To obtain high economy it is necessary that the steam should flow through the turbine with high velocity. This is attained by provision of a large number of pressure stages, the greater the available heat drop, the greater the number of stages. In the simple impulse turbine a wheel of comparatively large diameter is used in the first stage which can deal efficiently with a large energy drop. This large wheel, under nozzle control of the steam can maintain a higher efficiency over a wider range of load than a small one could and is less liable to be affected by changes of steam conditions. An added advantage of a large wheel is that the maximum rating of the machine can be obtained without by-passing which results in a flat consumption curve being maintained over the whole output range.,’

b) Compound impulse. This turbine has comparatively few pressure stages, a wheel in each of them provided with two or more rows of blades. Low velocity steam is obtained by the provision of what are usually termed “velocity stages” in each of the pressure stages. In these velocity stages the steam after passing through the first row of blades on a wheel is re-directed on to the second row of blades on the same wheel, and successively on to other rows of blades on this wheel, if provided. The steam is re-directed by arranging stationary blading between each two adjacent rows of wheel blading so that the steam leaving the first row of blades on a wheel in a backwards direction, enters the first row of stationary blades where its direction is reversed ready for entering the second row of blades on the wheel and so on. This action is repeated in each pressure stage on the turbine.

c) Combined impulse. This turbine is a combination of the types a) and b). It consists of one or more pressure stages with a wheel in each of these stages provided with two or more rows of blades. In the velocity compounded impulse turbine the “carry-over” velocity and the speed of the shaft are much less than with the simple impulse machine. Each disk carrying the moving blades is perforated, thus maintaining the same pressure on both sides of the wheel. The pressure velocity compounded design is generally known as the “Curtis” type. The pressure compounded turbine has a higher efficiency since the pressure drop per stage may be arranged to give the most suitable jet velocity for a given speed of the machine.

2. Reaction Turbines. In the reaction turbines expansion takes place in both the stationary and rotating passages and the pressure at entrance to the rotor blades is therefore greater than at exit.

a) Axial flow. In a pure reaction turbine expansion should take place only as the steam passes through the moving blades, the turning effect being due to the reaction consequent on the increase in velocity which accompanies expansion. The reaction turbine has a ring of stationary blades instead of a diaphragm with nozzle passages between the blades of each pair of adjacent wheels. The steam expands in the fixed blades, increasing its velocity, which is imparted to the moving blades on the impulse principle.

Steam is supplied, direct to the blading system without expansion in nozzles and the rotation produced is chiefly due to the reaction set up by the steam between the stationary and rotating blades while expanding in them.

b) Radial flow. The Ljungstrom turbine is really a combined radial and axial flow machine. The flow of steam is radial, being admitted at the center of the blade discs and flowing outwards, the steam then being inverted to axial flow in the last stages. The turbine may be constructed for single or double motion. With the double motion design the discs rotate in opposite directions at equal speeds and the relative speed of the blades is therefore equal to twice the running speed. This design consists of one group of radial flow double rotation blading and two groups in parallel of low pressure axial flow single rotation blading, the divided flow in the final stages assisting in the reduction of the “leaving losses”. Each steam rotor is coupled to an alternator which carries half the total output.

3. Combination Turbines. This type consists of a machine embodying the “impulse” and “reaction” principles, the high-pressure turbine being the impulse section and the intermediate and low-pressure turbines being the reaction section. Where the term reaction is used it is to be understood that - this refers to the “impulse-reaction” type of turbine. The practice in large output high speed sets is to include reaction blading at the low pressure end. The blade areas are large and therefore the leakage areas are proportionately small, and as a double-flow exhaust is used the end thrust is balanced. These arrangements enable the length of the turbine to be reduced.

Further Classification. As the output capacities and working conditions have affected the construction of each particular make it has been suggested that the following particulars be given for each turbine: 1) number of shafts, 2) number of cylinders, 3) number of exhausts, 4) the speed.

Many types of industrial turbines are in use today, depending upon the conditions under which they must operate. They are classified as high-or-low-pressure turbines, according to the inlet pressure of the steam, and as superposed, condensing, and noncondensing turbines, according to the exhaust steam pressure. A superposed or high backpressure turbine is one that exhausts to pressures well above atmospheric pressure, 100 to 600 psi. A superposed turbine operates in series with a medium-pressure turbine. The exhaust steam of the superposed turbine drives the medium-pressure unit. The noncondensing turbine has lower exhaust pressures, but the steam still leaves at atmospheric pressure or above 15 to 50 psi. The exhaust steam may be used for drying or heating processes.

The condensing turbine operates at exhaust pressures below atmospheric pressure and requires two auxiliaries: a condenser and a pump. The condenser reduces the exhaust steam to water. As the steam is condensed and the water is removed by a pump, a partial vacuum is formed in the exhaust chamber of the turbine. This type of turbine is used chiefly for the low-cost electric power it produces.

If steam is required for processing, a turbine may be modified by extracting or bleeding the steam.

Extraction takes place at one more point between inlet and exhaust, depending upon the pressures needed for the processes. The extraction may be automatic or nonautomatic. Generally, factory processes require steam at a specific pressure, in the case, and automatic-extraction turbine is necessary. When steam is needed within the power plant itself for heating boiler feed-water, nonautomatic extraction is generally used.

Turbines may be classified according to their speed and size. Small turbines, varying in size from a few horsepower to several thousand horsepower, are used to drive fans, pumps, and other auxiliary equipment directly. The speed of these units is adjusted to the speed of the driven machinery or is converted by a suitable gear arrangement. These turbines are used wherever steam is readily available at low cost or where exhaust steam is needed.

Turbines for the production of electric power range in size from small units to those of over 500,000 kw, and the trend is toward even larger units.

Sometimes turbogenerator units are constructed to operate at 3,600 or 1,800 rpm. The selection of the speed depends almost entirely on the size of the turbogenerator desired. The speed of 3,600 rpm is preferred whenever the size of the turbine permits. The turbine operating at the higher speed has the following advantages: lighter weight, more compactness, and great suitability for high-pressure, high-temperature operation.

With a few exceptions turbines larger than 100,000 kw will operate at 1,800 rpm. All turbines of smaller capacity will run at 3,600 rpm. However, because of the advantages of the 3,600 rpm unit and because of the greater efficiency of large units turbine manufacturers will continue to raise the upper limit of speed and capacity.

Generally, turbogenerators on a single shaft and within a given speed range are constructed, with either a single or a double-rotor.

The double-rotor arrangement is used for only the largest turbines falling within a given up speed range. A double-rotor unit is c1led tandem-compound turbine, and the flow is double-exhaust to accommodate the large volumes of steam occurring at the low-pressure end.

CHOICE OF TYPE

In large power station using high pressures and temperatures the compound impulse and the axial flow reaction are most common although radial flow machines up to 40MW, 1,500 rpm, have been adopted. The single shaft turbine is sound, simplifies operation and is general for small and medium sizes.

With radial flow turbines two alternators and two shafts are usual. Another case requiring two shafts is where it is economically justifiable by reason of high steam pressure to have a high pressure section running at a higher speed than a low pressure section. In deciding upon the number of cylinders the efficiency is nearly always of primary importance, and if this is to be a maximum with a large high-pressure turbine at least two cylinders will be necessary. A single- cylinder machine is cheaper in first cost than a multi-cylinder machine of the same output. It is possible to build single-cylinder turbines up to 80 MW at 1,500 rpm and up to 30 MW at 3,000 rpm, but general practice favours multi-cylinder sets for these larger sizes and also to separate high-pressure and low-pressure cylinders if the initial steam conditions are high. In the latter case the multi-cylinder turbine has the advantage that the separate ‘high-pressure cylinder and its components which are subjected to the initial high pressure and temperature may be kept reasonably small. In this way the stresses in these rotating and stationary parts may be kept within the safe limits of the materials available for use.

Further advantages of the use of multi-cylinder sets are that the diameters of the shafts may be kept within reasonable dimensions and designed to ensure that the critical speed is well above the running speed. The multi-cylinder turbine has resulted in a reduction of clearances rendered possible owing to the extremes of temperature in any one casing being reduced, thus enabling a turbine to be run up to speed much quicker than with a large single cylinder. The reduction in diameter of the wheels and shortening of the shafts reduces the stresses and tendency to whip. In some designs of multi-cylinder turbines the H. P. cylinder is of the “pure-reaction” type or even combined impulse and reaction. Some manufacturers do not employ reaction blading in H. P. cylinders on account of the small clearances which are necessary to obtain reasonably good efficiencies. The higher the initial steam pressure, the smaller will be the blade heights at the H. P. end, and it therefore follows that the blade tip clearance with unshrouded blades must be very small to keep down the leakage over the blade tips. Alternatively, if the blades in high-pressure reaction turbines are shrouded to permit of safe blade tip clearances, the axial clearances must be kept very fine.

The disadvantages are that the overall length of the turbine is increased thereby necessitating larger building space and introducing additional losses by the use of interconnecting piping. The number of exhausts to be used will depend chiefly on the size of the turbine. The output of a single exhaust turbine is governed by the area of the exhaust annulus, the latter being limited by the blade tip speed. Losses at the exhaust are composed of the leaving losses and exhaust losses. The former are due to the carry-over velocity of the steam leaving the last row of blades. This loss may be reduced by using a double or triple flow exhaust arrangement, which in turn increases the output of the set. On the other hand the gain is offset by the additional floor space and cost of accommodation. A small drop in pressure must exist if steam is to flow from the last wheel to the condenser, and the heat energy required to produce this-flow and make up for the losses due to eddies, etc., is termed the exhaust 1oss. With a given maximum exhaust area and given back pressure the output is limited if the efficiency is to be maintained and not impaired by high leaving and exhaust losses. To overcome this difficulty at the exhaust end turbines are usually of the multi-cylinder type arranged with single or double flow in a low pressure cylinder. With large output and low speed, a two cylinder turbine with a single-flow low-pressure cylinder can be used, as the low speed enables the requisite exhaust area to be obtained in a single exhaust.

The simplest type is the single-cylinder turbine, for it is compact and has few parts. Single-cylinder turbines with duplex exhausts are also adopted. The duplex exhaust turbine consists of two sets of low-pressure blading of the rotor, through which the steam flows in parallel, the two streams being brought together in the exhaust branch. With the double-flow turbine the axial thrust is balanced, since the flows are in opposite directions. In turbines having an intermediate cylinder the steam flow may also be arranged in the opposite directions, thus balancing the thrust. The volume of steam leaving the last wheel of a large turbine is enormous and it is more efficient and cheaper to discharge it to two or more condensers

The performances of the various types for a given output are very similar and the choice of make is usually decided by the capital cost, steam conditions, output, speed, efficiency, and the opinions of the engineers concerned.

THE TURBINE NOZZLE

The turbine nozzle performs two functions:

1. It transforms a portion of the energy of the fluid, acquired in the heat exchanger and evidenced by a high pressure and temperature, into kinetic energy.

2. a) In the impulse turbine it directs the high-velocity fluid jet against blades which are free to move in order to convert the kinetic energy into shaft work; b) In the reaction turbine the nozzles, which are free to move, discharge high-velocity fluid. The reactive force of the fluid against the nozzle produces motion, and work is done.

For the first function to be performed efficiently, the nozzle walls must be smooth, streamlined, and so proportioned as to satisfy the changing conditions of the steam or gas flowing through the nozzle.

For the second function the nozzle should discharge the fluid at the correct angle with the direction of blade motion to allow a maximum conversion of kinetic energy into work.

The main consideration in nozzle design is o provide a nozzle of proper wall contour. The contour of the walls depends upon the conditions of the fluid required by the turbine and upon certain properties of the fluid which are influenced by these established conditions. For nozzle design the engineer has at his disposal four fundamental tools or relations. They are: 1) the first law of termodynamics; 2) the equation of continuity of flow; 3) the characteristic equation of state of the fluid; 4) the equation of the process.

CHAPTER V

PUMPS, DRAFT; FANS, BLOWERS, COMPRESSORS

One of the most important problems of the engineer is the efficient and controlled transfer of fluids from one point to another. This transfer may be opposed by gravitational force, by some other external force, or by friction. Under certain conditions the gravitational force and other forces may it to aid the transfer, but friction always exists as a force opposing motion. The engineer attempts to reduce the effect of friction and at the same time takes advantage of useful forces to produce a motion of the fluids under conditions that can be controlled.

As previously defined, a fluid is a substance in a liquid, gaseous, or vapor state which offers little resistance to deformation. Common examples of the three states of a fluid are water as a liquid, air as a gas, and steam as a vapor. All these types of fluids have a tendency to move because of natural forces acting on them. A city may be supplied with water flowing by gravity from high ground. Air may circulate in an auditorium because of its own temperature difference. Steam rises through the water in a boiler owing to the difference in density or specific weight of steam and water. In many cases, however, the circulation is inadequate, and mechanical equipment must be built to supplement the natural circulation. Often mechanical circulation is the only means of obtaining the desired fluid flow. The equipment for producing this fluid flow is divided into two major classes: pumps for handling liquids, and fans, blowers, and compressors for handling gases or vapors.

Both classes of equipment in various forms may be found in the modern stationary power plant or small mobile power plants such as the aircraft engine, Diesel locomotive, or automobile engine.

PUMP TYPES

The conditions under which liquids are to le transported vary widely and require a careful analysis before the proper selection of a pump can be made. Generally, the engineer purchasing a pump consults with pump manufacturers to obtain the best type for a particular job. However, a fundamental knowledge of the basic types of pumps that are available and a realization that there is a wide variety of the basic types are of great value to the prospective purchaser.

The conditions that will influence the selection of the type of pump are: 1) the type of liquid to be handled: that is, its viscosity, cleanliness, temperature, and so on; 2) the amount of liquid to be handled; 3) the total pressure against which the liquid is to be moved; 4) the type of power to be used to drive the pump.

Pumps may be divided into four major classifications:

1. Piston pumps or reciprocating pumps driven by engines or electric motors.
2. Centrifugal pumps driven by steam turbines or electric motors.
3. Rotary pumps driven by steam turbines or electric motors.
4. Fluid-impellent pumps which are not mechanically operated but are fluid-pressure-operated.

CENTRIFUGAL PUMPS

The centrifugal pump consists of an impeller or rotating section to produce the flow and a casing to enclose the liquid and to direct it properly as it leaves the impeller. The liquid enters the impeller at its center or "eye" and parallel to the shaft. By centrifugal force the liquid passes to the impeller rim through the space between the backward curved blades. The velocity of the liquid with respect to the impeller is in a direction opposite to the impeller motion. The impeller blades are curved backward to permit the liquid to flow to the rim of the impeller with a minimum of friction. As the liquid leaves the impeller, it is thrown in a spiral motion forward with a certain velocity.

The water is guided away from the impeller by two basic types of casing: the volute, and the turbine or diffuser. Liquid enters the impeller at the “eye”, is thrown to the outside, and leaves the pump through the expanding spiral, or volute casing. The casing has the volute shape to permit flow with a minimum of friction and to convert a part of the velocity head into static head. The static head is the head that overcomes resistance to flow.

The turbine or diffuser pump has the same type of impeller as the volute pump. The casing has a circular shape, and within the casing is a diffuser ring on which are placed vanes. The vanes direct the flow of liquid and a decrease in the velocity of the liquid occurs because of an increase in the area through which the liquid flows. Thus, part of the velocity head is converted into static head as in the volute pump. For a multistage pump, the diffuser pump has a more compact casing than the volute pump. The diffuser-pump design is adaptable to differences in flow conditions since the same casing can be used with various arrangements of diffuser vanes. In the volute pump a variation in the requirements of the volute casing demands alternations in the casing itself. Generally, the volute pump will be used for low-head high-capacity flow requirements and the diffuser pump for high- head requirements.

Both volute and diffuser pumps are classified by the type of impeller, the number of stages, and the type of suction or intake used. A pump having two “eyes” on the impeller is called a double-suction pump. The double suction, one “eye” located on each side of the impeller, permits forces acting on the impeller to be balanced, thus reducing the axial thrust on the shaft. Also, the double-suction pump is used for handling hot water where there is danger of water flashing into steam at points of low pressure. The double suction offers little resistance to flow; thus, low-pressure areas are less apt to occur. The double-suction pump is used also for large capacities.

When two or more impellers are mounted on the same shaft and act in series, the pump is called a multistage pump, the number of stages corresponding to the number of impellers. A boiler-feed pump is capable of delivering 415,000 1b of water per hr against a pressure of 1500 psi. Multistaging produces better performance, higher pump efficiency, and smaller impeller diameters for high-pressure heads. Usually each stage produces the same head, and the total head developed is the number of stages times the head produced per stage. The types of impellers installed in centrifugal pumps are as numerous as the uses to which the pumps are put. Classification, however, can be made by designating the direction of flow of the fluid leaving the impeller. All pumps have the intake parallel to the impeller shaft. The discharge, however, may be radial, partially radial and axial, or axial. In the radial-type impeller the suction and discharge are at right angles. The radial impeller may be of the closed or the open type. The term closed or open refers to the fluid passage within the impeller. The open impeller has one side of the flow path open to the pump casing or housing. The closed impeller has both sides of the flow path enclosed by the sides of the impeller. The partially radial impeller discharges at an angle greater than 90 degrees with intake and is of the open-impeller design.

The axial-flow impeller discharges at an angle of approximately 180 degrees with the intake and is generally of the propeller type.

Each of the impeller types has a specific purpose. The axial-flow type is used to pump large quantities of fluid against a relatively small static head.

It is not a true centrifugal pump but is designed on the principles of airfoil shapes. The radial pump is used for handling smaller quantities of fluid against a high head, because the centrifugal force is high but the flow path is small and restrictive. The open impeller is designed to handle dirty liquids such as sewage, where the flow path must be less restrictive. The partially radial impeller covers intermediate pumping conditions.

MECHANICAL DRAFT

In power-plant engineering the fan plays an important part. Generally, in small-furnace installations a stack can produce a draft sufficiently high to supply air adequately to the fuel bed and to remove the flue gases. But the present-day capacities of boilers and furnaces require mechanical draft to supplement the natural draft produced by the stack. Mechanical draft is divided into two systems: forced draft and induced draft. In the forced-draft system the fan is located on the air-intake side of the furnace. A positive pressure, a pressure above atmospheric pressure, is produced under the fuel bed and acts to force air through the bed. The forced-draft system is necessary in installations where the pressure drop in the intake system and fuel bed is high. The pressure drop will be high in installations employing air preheaters and/or underfeed stokers. The underfeed stoker has an inherently deep fuel bed and a correspondingly high resistance to air flow.

Generally, the pressure in a furnace should be slightly less than atmospheric pressure. If it is too high, there will be leakage of asphyxiating gases into the boiler room and the tendency for blow-back when furnace inspection doors are opened. If the pressure in the furnace is too low, there will be air leakage to the furnace with a corresponding reduction in the furnace temperature. Because of these restrictions on the desirable pressure within the furnace, the forced-draft system is generally accompanied by a natural-draft system, in order that the removal of the flue gases may be accomplished. However, if the stack draft is inadequate owing to the high resistance created by the furnace passes, economizers, and air preheaters, an induced-draft system is generally added to supplement the stack draft. In the induced-draft system a fan is placed in the duct leading to the stack.

When a forced- and an induced-draft fans are used in combination the system is called balanced draft. The forced-draft fan produces a positive pressure which decreases slightly through the duct work and sharply through the air preheater and fuel bed. If the system is properly controlled, a pressure of a few hundredths of an inch of water less than atmospheric pressure is maintained in the furnace proper. The pressure continues to drop through the boiler passes, economizer, and air preheater until it is raised by the induced-draft fan and by the stack to atmospheric pressure.

The present trend is to construct more furnaces with gas-tight casings in order that they may be operated under pressures well above atmospheric pressure. Combustion efficiency is improved at elevated pressures, and the induced-draft fan with its high maintenance cost can be eliminated completely. A number of furnaces using the cyclone burner are now designed to operate at pressures as high as 80 in. of water above atmospheric pressure.

FANS

Fans are used extensively in the heating and ventilating industry and in most power plants. Their basic design principles fall into two classes: axial-flow fans and centrifugal- or radial-flow fans. Axial-flow fans are basically rotating air-foil sections similar to the propeller of an airplane.

The simplest axial-flow fan is the small electric fan used for circulating air in rooms against very little resistance. Axial-flow fans for industrial purposes are the two-blade or multiblade propeller type, and the multiblade air-foil type. Air enters the fan suction from the left and flows over the rotor with a minimum of turbulence owing to the streamline form of the rotor and drive mechanism. The air stream is straightened by guide vanes located on the discharge side, thus decreasing the rotational energy of the air by converting it to energy of translation.

The axial-flow fan operates best under conditions where the resistance of the system is low, as in the ventilating field. The axial-flow fan occupies a small space, is light in weight, is easy to install, and handles large volumes of air

Centrifugal fans may be divided into two major classes: 1) the long-blade or plate-type fan, and 2) the short-blade multi-blade fan. The blades of either type may be pitched toward the direction of motion of the fan, radially, or away from the direction of motion of the fan.

A plate-type radial-blade rotor with double inlet is best suited for handling dirty gases, since there are no pockets in the blades to catch and collect the dirt. The rotor has wearing strips welded to the blades to increase their life. The fan is designed for induced-draft service. The housing of such a fan may have catch plates in the scroll face to collect the fly ash.

BLOWERS

Blowers may be divided into two types: 1) rotary, and 2) centrifugal. A common type of rotary blower is the Roots two-lobe blower. Two double-lobe impellers mounted on parallel shafts connected by gears rotate in opposite directions and at the same speed. The impellers are machined to afford only a small clearance between them and between the casing band impellers. As the lobes revolve, air is drawn into the space between the impellers and the casing, where it is trapped, pushed toward the discharge, and expelled. The air is trapped and discharged in volumes equal to the space between the impellers and casing, and the operation is repeated four times for each rotation of the shaft.

In order to change the volume rate of flow or volume Capacity of the blower, the blower speed is changed. The pressure developed by the blower will be whatever is necessary to force the air through the piping system. The volume of air delivered by the blower will not change appreciably with variations in resistance to flow. Thus, the blower is called a positive-displacement blower.

Note that at a speed of 600 rpm an increase in pressure from 2 to 3 psi increases the power required by 1.5 times, but the capacity remains fairly constant. Care should be taken in operating any positive-displacement blower. A safety valve or limit valve should be placed on the discharge line to prevent the discharge pressure becoming excessive in case the outlet is fully closed. The limit valve will prevent overloading the discharge line and the driving motor. The advantages of the rotary blower are: 1) simple construction, 2) positive air movement, 3) economy of operation and low maintenance.

Centrifugal blowers and compressors operate on the same principles as centrifugal pumps and resemble to a marked degree the closed-impeller centrifugal pumps. A single- stage single-suction blower is capable of delivering 15,000 cfm against a pressure of 3 psi. The casing or housing is constructed of heavy steel plate, and the impeller is an aluminum-alloy casting. If care is taken in providing the proper drive motor, the overload characteristics of the centrifugal blower will cause no trouble.

For volumes greater than those that can be handled by the single-stage single-suction blower, a single-stage double-suction blower is used. This blower is capable of supplying 26,000 cfm of air at 60° F and atmospheric pressure against a 54-in. water column or 2 psi.

CENTRIFUGAL COMPRESSORS

Multistage centrifugal blowers when capable of handling gases against pressures greater than 35 psig are generally classed as compressors. They resemble multistage centrifugal pumps, and many of the problems encountered in their design are similar to those encountered in pump design. The impellers of a complete centrifugal compressor unit are of the single-suction type, and passages lead the air or gas from the discharge of one impeller to the suction side of the next impeller.

Because of an increase in temperature of the gas or air as the pressure is increased, cooling is generally necessary. If the pressures are not high, cooling water circulated in labyrinths between impellers may be sufficient. When high pressures are encountered, the gas may be cooled in interstage coolers. The reason for maintaining the gas at a low temperature is to permit an increase in the mass rate of flow with a corresponding reduction in size and horsepower.

Axial-flow compressors are designed on the principles of the airfoil section, and the blade shapes will be similar to the axial-flow fan.

These compressors are an essential part of the gas-turbine cycle. The gas is not cooled between stage, because a portion of the additional work necessary to compress the gas adiabatically over the work necessary to compress it isothermally will be recovered in the gas turbine. The advantages of centrifugal and axial-flow blowers and compressors are: 1) nonpulsating discharge of the gas, 2) no possibility of building up excessive discharge pressures, 3) a minimum of parts subject to mechanical wear, 4) no valves necessary, 5) a minimum of vibration and noise, 6) high speed, low cost, and small size or high capacity.

CHAPTER VI

POWER-PLANT CYCLES

A cycle is a series of operations or events which occur repeatedly in the same order. A power cycle or power- plant cycle is such a series of events which regularly repeat themselves for the purpose of converting a portion of the stored energy of a fuel into work. There are two general types of power cycles, the closed cycle and the open cycle.

In the closed cycle a working fluid begins at some initial condition, undergoes certain changes through a series of regular events, and returns to the initial condition. Theoretically, no replenishment of the working fluid is necessary.

THE RANKINE CYCLE

The simplest ideal or theoretical power-plant steam cycle is the Rankine cycle. The system contains: 1) a steam- generating unit by which energy is added to the fluid in the form of heat transfer from a burning fuel; 2) a prime mover or steam turbine 3) a condenser by which energy is rejected to the surroundings by heat transfer, and 4) a boiler feed-water pump.

The following assumptions are made for the Rankine cycle:

1) The working fluid, usually water, is pumped into the boiler, evaporated into steam in the boiler, expanded in the prime mover, condensed in the condenser, and returned to the boiler feed pump to be circulated through the equipment again and again in a closed circuit under steady-flow conditions, that is, at any given point in the system, the conditions of pressure, temperature, flow rate, etc., are constant.

2) All the heat is added in the steam-generating unit, all the heat that is rejected is transferred in the condenser, and there is no heat transfer between the working fluid and the surroundings at any place except in the steam-generating unit and the condenser.

3) There is no pressure drop in the piping system, there is a constant high pressure, p_1, from the discharge side of the boiler feed pump to the prime mover, and a constant low pressure, p_2, from the exhaust flange of the prime mover to the inlet of the boiler feed pump.

4) Expansion in the prime mover and compression in the pump occur without friction or heat transfer, in other words, they are frictionless adiabatic or isentropic expansion and compression processes in which the entropy of the fluid leaving the device equals the entropy of the fluid entering the device (pump or turbine).

5) The working fluid leaves the condenser as liquid at the highest possible temperature, which is the saturation temperature corresponding to the exhaust pressure p_2.

If the steam-generating unit is a boiler only, the steam that it delivers will be wet, and its quality and enthalpy can be determined by throttling calorimeter. If a superheater is included in the steam-generating unit, the steam that is delivered will be superheated and its enthalpy can be determined from its pressure and temperature by use of the superheated steam table or the Mollier chart.

The condensate leaving the condenser and entering the boiler feed pump is always assumed to be saturated water at the condenser pressure, and its enthalpy can be found from the steam tables at the given condenser pressure.

Since this cycle assumes frictionless adiabatic or ideal expansion of the steam in the prime mover, the Rankine-cycle efficiency is the best that is theoretically possible with the equipment. Better theoretical efficiencies are possible by using more equipment in more complex cycles.

It should be noted that only a small part of the energy supplied in the boiler as heat' is converted into work and the rest is lost in the condenser.

The loss resulting from the heat transferred to the condenser cooling water is, to a large extent, inescapable. The temperature of the cooling water varies only with the atmospheric conditions; thus, it remains almost constant. To lower it by artificial means would require the expenditure of additional energy.

THE SIMPLE, OPEN, GAS-TURBINE POWER CYCLE

The power plant consists of three elements: the compressor, the combustion chamber, and the gas turbine.

In the actual gas-turbine power plant, 65 to 80 per cent of the turbine output is required to drive the compressor. In the steam-turbine power plant, the working fluid is condensed with a very large reduction in volume so that less than 1 per cent of the turbine output is required to operate the boiler feed pump which corresponds to the air compressor of the gas-turbine power plant. Consequently, for the same net plant output, the gas turbine must produce three to four times as much power as a steam turbine. Such heat-transfer equipment as boilers, economizers, superheaters, condensers, feed-water heaters, forced- and induced-draft fans, and extensive piping system, all of which are necessary in an efficient steam power plant, are eliminated in the simple gas-turbine power plant. However, if maximum efficiency is desired in the gas-turbine power plant, large heat exchangers, water-circulating pumps and piping are necessary, and the gas-turbine plant loses much of its simplicity.

The efficiency of a simple gas-turbine power plant depends upon the temperature of gas supplied to the turbine and upon the pressure ratio, p_2/p_1.

For a given turbine-inlet temperature, there is a particular pressure ratio which gives maximum efficiency, and this optimum pressure ratio increases with inlet temperature. The marked increase in efficiency with increase in inlet temperature should be noted. As the high-temperature characteristics of metals are improved and inlet temperatures higher than 1,500°F become practical, the use of the gas turbine as an economical prime mover will expand rapidly.