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LIGHT, HEAT AND POWER IN BUILDINGS

BY

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PREFACE.

In this volume the object is to present in compact form the main facts on which selection of the sources for light, heat and power in buildings should be based. The problem for which a solution is sought is to determine the kind of equipment that will yield the service required in any case at the least total cost. Such a purpose leaves little room for discussions of theory relating to any particular class of apparatus, which has already been done in separate and larger volumes. It follows that the only novelty to be expected here is that of arrangement, by which the costs of service from widely different sources are set down side by side.

Should this arrangement prove convenient for those charged with the selection of apparatus for light, heat and power, the labor spent on the following pages will have accomplished its purpose.

ALTON D. ADAMS.

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Light, Heat and Power in Buildings.

CHAPTER I.

COSTS OF HEAT, LIGHT AND POWER FROM PUBLIC GAS AND ELECTRICAL SUPPLY AND FROM COAL.

An open gas flame of sixteen candle power consumes five cubic feet of average gas per hour. At one dollar per 1,000 cubic feet, the cost of this gas flame is 100 × .005 = 0.5 cent hourly. Ten cents per kilowatt-hour is a moderate rate for electrical energy. Fifty-six watts is a fair rate of energy consumption for an incandescent lamp of sixteen candle power. Such a lamp requires an hourly expense of 10 × .056 = 0.56 cent at the rate for energy just named. Simple, non-condensing engines, with good boilers, will readily yield each horse-power hour of work with a consumption of four pounds of fairly good coal. If this coal costs three dollars per ton of 2,000 pounds, the expense for fuel per horse-power hour amounts to 300 × 0.002 = 0.6 cent. This brake horse-power, when delivered on the shaft of a dynamo which has an efficiency of 90 per cent., produces an output of 746 × .90 = 671.4 watts. At 56 watts each, the number of sixteen candle power lamps that may be supplied from this output is 671.4 ÷ 56 = 12. As the fuel cost of the horse-power hour is 0.6 cent, the charge against each sixteen candle power lamp is 0.6 ÷ 12 = 0.05 cent hourly.

Gas from public supplies usually contains 20 to 40 per cent. of the heating power of coal, from which it is derived, according to its variety. It seems at once evident from this fact that gas is ill-suited for general warming in buildings, and when the cost of heat derived from gas at current public rates is considered, its common use to heat buildings is seen to be entirely impracticable. As an illustration, take average city gas, yielding 650 heat units per cubic foot and selling for one dollar per 1,000 cubic feet. This gas yields, therefore, 650 × 1,000 = 650,000 heat units for one dollar on perfect combustion. Good anthracite coal has a heating power of 13,000 units per pound, or 13,000 × 2,000 = 26,000,000 heat units per ton. The amount of gas to supply heat equivalent to that from one ton of coal is therefore 26,000,000 ÷ 650 = 40,000 cubic feet, costing forty dollars at the rate named. Considered as a general heating agent, electric energy is in a much worse position as to the portion of the energy of coal that it can deliver, and as to its cost at usual rates, than is gas. Ten cents per kilowatt-hour is a low average rate for electric energy, and as the kilowatt-hour is the equivalent of 3,412 heat units, this rate gives 34,120 units of heat for one dollar. To equal in heating power one ton of coal, the kilowatt-hours necessary are 26,000,000 ÷ 3,412 = 7,620, costing 7,620 × .10 = 760.00 dollars at the rate named. In practice, the actual cost of electrical energy at ten cents per kilowatt-hour, when used for general warming, is less than the cost of coal at 760 dollars per ton, because nearly all of the electrical energy is available as heat in the apartments warmed, while more than 75 per cent. of the total energy of coal is seldom so available.

Mechanical power may be produced in buildings by means of either steam, gas or electrical energy. Power from steam implies both a boiler and engine. Gas develops power by means of an engine only, and electrical energy is transformed into mechanical work by a motor.

For apparatus of equal quality, to develop a given power, the steam boiler and engine will usually cost most, the gas engine a somewhat less amount, and the electric motor least. The cost of either of these equipments for power production is very small compared with the fuel or energy it consumes during its useful life, so that a moderate advantage in efficiency, or in the cost of power development, may more than offset a considerable excess in the first cost of the plant.

It has been previously shown that a good steam plant should deliver a horse-power hour at a fuel cost of 0.6 cent, when using fair coal at a price of three dollars per ton. Gas engines of small and moderate capacity, such as are commonly used in city buildings, may be fairly expected to consume twenty cubic feet of gas per delivered horse-power hour. The gas implied in this rating is of the quality generally distributed for illuminating purposes in towns and cities, having a heating power of not less than 650 units per cubic foot, on perfect combustion. If a gas of lower heating power is used, as one of the so-called fuel or producer gases, which may develop as little as 150 heat units per cubic foot, the consumption per unit of work will increase in inverse ratio to the energy of combustion. The lowest rate common for illuminating gas in the United States is one dollar per 1,000 cubic feet, and, while this rate is in force for but few cities, the cost of power may be stated for it as a convenient basis from which to compute the cost at other rates. At one dollar per 1,000 cubic feet, twenty feet of gas, to develop one brake horse-power hour, cost $100 \times 0.20 = 2$ cents. As coal to produce this same unit of work was found to cost 0.6 cent, the fuel outlay for power from gas at one dollar per 1,000 cubic feet is more than three times as great as that for coal at three dollars per ton. Electrical energy for power production in motors can usually be had at materially lower rates than those charged when it is devoted to lighting purposes. A frequent rate for energy supplied to electric motors is 3.33 cents per electrical horse-power hour, corresponding to a charge of 100 dollars for a horse-power year of 3,000 working hours. Electric motors do not, of course, deliver as mechanical work the equivalent of all of the electrical energy that they absorb, and the average efficiency of small and medium sizes may be taken at 80 per cent., under the conditions of use. The exact figure for motor efficiencies increases slowly with the capacity of the motor. The average loss of 20 per cent. in motors raises the cost of their delivered work to $3.33 \div .80 = 4.16$ cents per horse-power hour. It thus appears that for the rates named the primary development of power in buildings with electric motors costs more than twice as much as that from gas and nearly seven times as much as that from coal, so far as the outlay for fuel and energy is concerned. In this comparison it should be noted that the steam is developed on the premises, while the gas and electrical energy are procured from the public supply. Fuel or energy is obviously only one of the items that go to make up the cost of power in buildings, and whether it is the most important should be decided on the circumstances of each case. Notwithstanding the low cost of fuel for the production of steam power, such power would be the most expensive possible where its total was small, no heating was required and it was necessary to employ an engineer for the care of the engine and boiler. For the case just named, where the power is quite small, and especially if it is fluctuating in amount and intermittent in point of time, electrical energy from the public supply would usually be the most economical source of power. Where heat is necessary in season to an amount nearly equal to or exceeding the capacity of the exhaust steam that would result from the desired power production, the steam plant is usually the most economical primary source of power. In some other cases, where the necessary amount of heat is less than that which would be available from the exhaust of a steam engine of sufficient power capacity, a gas engine may be the means best suited for cheap primary power. This last is quite apt to be true where the use of power, though at a considerable rate, takes place during only a very few hours each day, or at times of day that are far apart. The gas engine is especially suited to the case just cited, because its waste heat is available for warming; it can be started at once without previous preparation, such as is necessary to get up steam in a boiler, and because the labor involved in its operation is less in amount and less exacting as to skill than that necessary on a steam plant. As an offset to the cost of energy for its operation, when employed as a primary source of mechanical power, the electric motor requires only a trifling amount of attention, involving but a moderate degree of skill, and is ever ready for immediate use without previous preparation. The efficiency of the electric motor is six to ten times as great as that of steam or gas engines, and its wasted heat, that might be devoted to warming, is a very trifling matter. The primary source of mechanical power in city building is usually located in the basement, in a space especially devoted to it, and certain features, such as heat, noise and vibration, that may belong to the apparatus are of minor importance compared with what they would have if it were located at various points through the building. For the great majority of large city buildings that require mechanical power for a variety of purposes, such as electric lighting, elevators and ventilation, as well as a large amount of heat for general warming, the steam plant is the most economical source of power.

CHAPTER II.

GAS, ELECTRICITY, STEAM AND HOT WATER IN THE DISTRIBUTION OF HEAT, LIGHT AND POWER.

Gas and electrical energy are usually available for distribution as lighting agents in modern buildings. The electrical energy is capable of ready production in buildings and is also generally available from the public supply. As illuminating gas cannot be readily produced in most buildings, it is open to the disadvantages of high cost. Three main disadvantages, aside from its cost, attach to the use of gas for illuminating purposes. These are its effect to heat and vitiate the air, the secondary quality of gas illumination, and the limits imposed on lamp arrangements, due to the presence of an open flame. If air is to be maintained at a fair standard of purity in a building, the use of gas for extensive illumination largely increases the volume of air to be handled per hour, because of the products of combustion given off. As is well known, the quality of ordinary gas light is decidedly inferior to artificial illumination produced by some other means, both as to the sensation produced on the eye and the permanent effects on it of extensive use. In some cases of illumination, particularly where an artistic effect is desired, it is difficult or impossible to attain the result with gas, because of the flame and combustion. Electrical energy is almost an ideal source of illumination. Electric light is more pleasing to the human eye and less harmful on continued use than any other artificial illumination. As incandescent electric lamps involve no combustion whatever, and arc lamps only a trifling amount, their use adds nothing to the volume of air necessary to maintain any required standard of purity. Incandescent lamps, having their hot parts entirely enclosed in an air-tight globe, may be readily placed in any position or among any surroundings desired for artistic effects. Where it is necessary to place lamps so that they are difficult of access, the incandescent electric variety is particularly suitable, because the light can be instantly produced or extinguished without any electro-magnetic mechanism at each lamp, as is necessary for gas burners under such circumstances. The wires required for the distribution of electric energy throughout a building occupy little more space than is required for gas pipes, and should be the subjects of scarcely more attention after they are properly installed. Heat is distributed in buildings for two distinct classes of service, general warming and industrial purposes, such as cooking and the chemical and mechanical arts. For general warming the demand for heat extending over a long period daily is fairly constant during such periods and its total amount is large, though very high temperatures at any particular point are not necessary. In the chemical and mechanical arts, and also frequently for cooking, the demand for heat is variable and intermittent, and its total amount is comparatively small. Industrial operations are very exacting, however, as to the degree of heat required at certain points, and temperatures must often be much above those necessary for general heating. A serious objection to the use of gas for general warming, in addition to its high cost, without the employment of some agent, as air, water or steam, to distribute the heat, is that a fire must be maintained in every room. If gas is employed to heat air, water or steam at some suitable point, it ceases to be an agent of heat distribution in a building and can be considered only as a fuel. Air, water and steam are readily heated in suitable apparatus with any desired fuel, and the ease with which either may be distributed through a building renders each of them a good agent for general warming. Where hot water or steam are used for warming, their heat is derived directly from the gases of combustion and the radiation from the incandescent fuel. If air is to be the agent of heat distribution, it is usually desirable and necessary, especially in large plants, to prevent contact of the air with the heated surfaces of boilers and furnaces, because their temperatures are so much greater than that desired for heated air that the quality of the air is injuriously affected. In most large plants, therefore, where air is the agent of heat distribution, it is heated by contact with coils that contain either hot water or steam. This water or steam is supplied from a boiler, and the loss incident to the second transfer of heat, or that from water or steam to air, is quite small in good apparatus. In the matters of first cost and required space, the distribution of heat by hot air is at a disadvantage compared with that by some other means, especially where it is used exclusively. This disadvantage is due to the large volume of air necessary to supply the required heat and to the consequent sizes and arrangements of conduits for it. Where due provision must be made for ventilation, the primary disadvantages as to the size and cost of air conduits are largely offset by their double service in the distribution of both heat and pure air. Probably the most economical arrangement, as to both first cost and that of subsequent operation, where both heating and ventilation are desired, includes conduits of sufficient size to transmit the heated air necessary for ventilation and the necessary steam or hot water radiators to supply the remainder of the required heat. Steam possesses many advantages for the distribution of heat in buildings, and is probably more extensively used for that purpose in large plants than any other agent. The cost of pipes for steam heating in buildings and the room they require are moderate, but such a system is by no means ideal. One difficulty with steam distribution for general warming is the lack of heat regulation in the coils and radiators. Steam does all of its work as a heating agent at nearly constant temperature. Thus, steam at five pounds gauge pressure, or one that is seldom necessary to exceed in the heating system of a building, has a temperature of 227 degrees Fahr., while, after it has condensed to water at atmospheric pressure, thus yielding 970 heat units per pound, the temperature is still 212 degrees. An inevitable result of the nearly constant temperature of steam heated surfaces is the waste of heat in mild weather, and more or less discomfort in over-heated apartments. Among the small disadvantages connected with a steam heating system are noises due to the collection of water in pipes and radiators, and an unpleasant odor of the steam that at times escapes through air valves on radiators. The system of heat distribution, by means of hot water circulating through the pipes and radiators, compares very faborably with steam heating in several particulars. The pipes for hot water heating, where the circulation of the water is maintained by the difference in temperature between the water in the outflow or supply pipe and that in the return, are usually somewhat larger than steam pipes would be for an equal supply of heat. This excess in the size of hot water pipes over those for steam and equivalent service, adds only a moderate per cent. to their cost and still less to their required space Two of the most distinct advantages of the hot water heating system are its capacity for temperature regulation and to maintain a gradually diminishing supply of heat during some hours after the fire in the boiler furnace has been banked or gone out. While the temperature of steam is nearly constant at all of the pressures commonly employed in warming buildings, the temperature of water in the low pressure system, or that open to the air, may be at any desired point below 212 degrees. In mild weather, or when less than the maximum rate of heat delivery is desired for general warming, a hot water system may be readily operated at any temperature that gives the heat supply desired. The capacity of water to store heat and then to give it off gradually renders it unnecessary to keep boiler fires in active operation during the entire period of each day that heat is necessary. Owing to the same property of water, the temperature of buildings heated with it does not fall as low during the daily period when fires are not in action, as is the case where steam is the heating agent. One result of the use of water instead of steam for heat distribution is that the daily hours of labor in the boiler room may be materially reduced. Reduction of the heat given off by a hot water system in mild weather, to the amount actually necessary to maintain the required temperature in a building, by lowering the temperature of the water and radiating surfaces, obviously tends to economy in fuel. The less the temperature of the heating surfaces of a boiler the larger is the amount of heat that is extracted from the gases of combustion. In steam heating above atmospheric pressure the temperature of at least a part of the boiler must be higher than 212 degrees at all times when any heat whatever is wanted. In hot water heating the temperature of the circulating water is varied to meet the demands for heat, being only 212 degrees at its highest point. It follows that the average temperature of boiler surfaces are materially lower in a hot water than in a steam heating system, and the gases of combustion may therefore be delivered to the flue with less of the fuel energy in them. This tends to high efficiency. Where a steam plant is used for the double purpose of heat and power, and the exhaust steam from engines is to be employed in the heating system, the system of distribution by hot water presents some especial advantages. To circulate the exhaust steam through the pipes and radiating surfaces of a building, it is most common to operate the engines on two to five pounds back pressure. This back pressure reduces both the capacity and efficiency of engines, especially when they are of the compound type. There are certain special equipments on the market for use in connection with steam heating systems that make practicable the circulation of the steam at or below atmospheric pressure, but unless these equipments are used the back pressure in the case of engines has to be reckoned with. If, instead of circulating the steam from engines through the entire heating system of a building, it simply goes to a bank of coils for heating hot water, the back pressure on engines may be so reduced, without any special equipment, as to become a very small factor. Hot water may thus be raised to a temperature of 212 degrees, or that of a regular low-pressure hot water system. Circulation from these hot water coils through the heating system of a building takes place just as though the water was heated directly by the fire under a boiler. If it seems desirable in any case to reduce the sizes of pipes necessary for the hot water, where the circulation depends entirely on the difference in temperature in the outflow and return pipes, the hot water may pass through a pump that maintains any desired rate of circulation, through a heating system of any dimensions, and pipes of any size. If the average amount of exhaust steam available is less than that required by the heating system, the small addition to the exhaust, resulting from the use of a pump, will usually be condensed in the heating coils, so that the cost of pumping the hot water will be very slight. In this way the cost of pipes for a large system of hot water heating may be materially reduced below that of steam pipes for equivalent service. Another decided advantage of the system of hot water heating, in connection with a steam power plant, is the ability, by means of a hot water tank, to store the heat of exhaust steam, produced during one period of the day, for use at another. Some of the demands for power in large buildings are far from evenly distributed throughout the usual working hours of the day, and this is particularly true of the electric lighting load, which is mostly concentrated in three or four hours. Where exhaust steam is distributed through the heating system of a building, any excess above the amount that the system will condense during any particular period must be devoted to some other purpose or wasted. With a system of hot water distribution, if the total heat of the daily product of exhaust steam does not exceed the total daily requirement for heat in the building for general warming, the surplus heat of the exhaust during any period of the day may be stored and subsequently utilized. Probably the best system for both heating and ventilation in a large building, where both first cost and the expense of operation is considered, includes hot water and hot air, each circulated by mechanical means, under average circumstances. In the distribution of heat for mechanical and other industrial purposes, considerations as to the supply of heat at just the right time and to the required degree are paramount, and the sum total of heat consumed is usually a secondary matter. The decided advantages of electrical energy and gas for heat production in many industrial operations, owing to the effective control made possible with them, of the time and degree of heat supply, often more than offset their high cost per unit of heat energy actually furnished. For some industrial purposes, where a nearly uniform and moderate degree of heat is required in comparatively large amounts through considerable periods, as in cooking and drying operations, hot water and steam are more available than gas and electrical energy, because of the low cost per unit of the heat they contain. The extended discussion of industrial applications of heat is beyond the limits of the present work.

Quite distinct from the question as to the most economical source of the primary mechanical power in a building is that of the distribution of power to its several parts. While power may be developed with a steam plant in the basement of a building at a much less cost than that for which gas or electrical energy can be bought for equal results, it frequently happens that the power is required in a number of small units throughout the building and very little of it can be applied to its ultimate use near the steam engine. A complete solution of the question of power production in modern buildngs must therefore include the means for its distribution to the points where it is wanted.

There are four methods, either of which may be applied to power distribution in buildings, namely, mechanical equipment, such as belts and shafting, steam pipes to the several points where power is wanted, connected to engines there located, gas pipes running to suitably located gas engines, and electric circuits and motors. Distribution by mechanical appliances or by steam pipes and engines is only possible, for most instances, when the primary power plant is located in the building. Electrically distributed power may be had from either a local or a public plant. Gas pipes and engines must usually derive their supply from the public service mains.

Power distribution by mechanical means involves the cost of belts, shafting and pulleys. For steam power distribution, pipes and small engines must be provided. In like manner distribution by gas implies the necessary pipes and gas engines. If the energy is to be distributed electrically, wiring circuits and motors are necessary where the supply is taken from an outside source, and to these must be added an item for dynamos, when the primary source of the power is in the building. Where the power of a local steam plant is to be distributed the first cost of engine, shafting and belting, of steam pipes and a number of small engines, and of engine, dynamo, wiring and motors for the same delivery of power at the points where it is desired, should be compared. The cost of steam pipes and small engines connected at points where the power is wanted will not differ greatly in many cases from the cost of one or more larger engines of equal ultimate capacity, and the belts and shafting necessary to distribute the power. A large engine, dynamo, wiring and electric motors are quite sure, in most cases, to cost more than the same engine with the shafting and belting necessary for distribution. To fairly decide between these three methods of distribution, the efficiency, convenience and the objectionable features of each should be considered, as one or more of these items may much more than offset that of first cost. Where gas or electric energy from an outside source is to be distributed in a building for power purposes, gas pipes and engines must be paid for in one case and electric wiring and motors in the other. As a rule the gas pipes and engines will cost more than the electric circuits and motors. The costs of operation for the gas and electric equipments when supplied from the public mains has already been shown, and they include the questions of efficiency. The main permanent objection to gas pipes for engines, over electric circuits for motors of equal capacity, is the greater amount of room necessary to the former. Objections to gas engines are about the same as those to steam engines, and will be considered when the latter are taken up. When the distribution of power in a building from a local plant is considered the relative importance of the efficiency, convenience and objectionable features varies with the character of the building where the distribution takes place. In a factory building efficiency and convenience of operation, as they affect the cost of production, are of prime importance. For an office building, the absence of any very objectionable features is the most necessary requisite. Between these extreme classes of buildings there are a large number where convenience of operation and objectionable features are of variable importance, but efficiency as to the consumption of fuel is highly desirable in almost every case. Where steam is distributed to the various parts of a building through long pipes for a number of small engines, two serious sources of loss are encountered. The long pipes are certain to condense considerable steam, and if they are not well insulated for heat the loss by condensation rises to a large amount. Much more serious than the loss of heat from pipes with good insulation is that in the small engines themselves. While a large, simple engine should deliver a brake horse-power hour on not more than thirty pounds of dry steam, small engines of three to ten horse-power generally have a consumption of two to four times this rate. Including the losses from condensation in long pipes, it is probably safe to say that a considerable number of small engines, scattered over a large building and supplied from the main boilers, consume fully three times as much steam per unit of work as would one or more large, simple engines for the same aggregate power, when located near the boiler plant. If the conditions of service are such as to warrant the use of compound engines for large units, the equipment of numerous small engines would be at a still greater comparative disadvantage. So low is the efficiency of numerous small engines at considerable distances from a boiler plant that the use of such equipments is mostly confined to a few cases where special conditions seem to warrant it. The power necessary to keep belts and shafting in motion varies, among other factors, with their extent, and is nearly constant whatever the power transmitted at any particular time.

A system of shafting in first-class condition as to alignment, and only moderate in extent, may have an efficiency as high as 75 per cent. when transmitting the maximum power for which it was designed, though 50 to 60 per cent. are much more common figures in actual work. As soon as the maximum rate of work slackens, the efficiency falls accordingly, being for the case cited about 50 per cent. at one-half, and zero at one-fourth the full engine load. Most of the power required in city buildings is decidedly intermittent in character, and nearly all classes of work partake of the fluctuating quality to a considerable extent. It follows that belts and shafting seldom work at their maximum capacity during any long period at a time, and often run with little or no load for some hours of each day. Where belts and shafting distribute power through a building of considerable size, it may be fairly said that the average all day efficiency of transmission is usually less than 40 per cent. This condition obviously leaves a large margin for improvement by some other method of distribution. A part of this possible improvement is attained by the electrical method of power distribution. For electrical working the main engine or engines, instead of driving by belt a system of extensive shafting, are coupled to one or more electric generators. These dynamos supply energy to electric circuits that extend to every part of the building where power is wanted, and are there connected to electric motors of suitable capacities. No such difference exists between the efficiencies of large dynamos and of comparatively small motors, as was found to be the case between large and small steam engines. Thus at full loads the efficiencies of large dynamos of one hundred to several hundred horse-power capacity each should be 91 to 93 per cent., while the efficiencies of motors from two to five horse-power capacity each should be 80 to 85 per cent. The efficiency of the electrical distribution is obviously the combined efficiencies of the dynamos, lines and motors concerned. At full load the efficiencies of large dynamos may be taken at 92 per cent., electric circuits 96 per cent. and motors 83 per cent., giving a figure of $.92 \times .96 \times .83 = .816$, or 81.6 per cent. for the combined efficiency of distribution. The efficiency of dynamos and motors drops with their loads, and a fair figure at one-half load for the machines just mentioned would be 88 per cent. for the dynamos and 72 per cent. for the motors. Loss in wiring, however, decreases with the square of the load, so that when the amperes flowing are reduced one-half the loss is cut down to one-quarter of its former amount, or to one-half the per cent. for the latter as for the former load. In the present instance, therefore, the line efficiency rises to 98 per cent. at one-half load.

Combining the several values just given for the efficiency of dynamos, motors and wiring at one-half load, it appears that the efficiency of the electrical distribution under this condition is 88 × .98 × .72 = 62 per cent., nearly. These values for the efficiency of electrical distribution at full and one-half load show an improvement over those for belts and shafting that corresponds to a large part of the theoretically possible saving. A satisfactory feature of the efficiency characteristics of the electrical equipment is that they remain nearly constant during the life of the apparatus and are not subject to serious deterioration, as is the efficiency of belts and shafting, which suffers with changes in tightness and alignment.

Further important contribution is made to the all day efficiency of electrical power distribution by the fact that all line and motor losses stop when the motors are shut down. Electrical power distribution in a building will often show an all day efficiency twice as great as that of belts and shafting.

In buildings for factory and for some mercantile purposes, first cost and the subsequent efficiency of operation are the points that determine the selection of the equipment for such power transmission as is required.

Quite a different rule must be followed in buildings of the higher classes, where the tastes and convenience of tenants require the first consideration. Undesirable heat, the element of danger, noise and vibration must be eliminated to the largest practicable extent from methods of power transmission in most buildings for office, amusement, residence and retail trade purposes. Belts and shafting obviously include all of these objectionable elements, except that of heat, and also require a very considerable amount of room, so that they are rightly excluded from buildings in the classes just named. High pressure steam pipes and the small scattered engines which they may be used to supply involve an element of danger to persons and property because of the possible escape of steam. Their surfaces at high temperature give off an amount of heat that may be very disagreeable in warm weather, and the noise and vibration incident to the reciprocating motions are not to be tolerated above the basement in a large number of instances. Gas engines and their supply pipes also include an element of danger from the escape of gas, while the escaping heat from the engine itself and the attendant noise and vibration are quite as objectionable as where steam is the motive power. In addition to the disadvantages just pointed out for small scattered engines supplied by steam or gas pipes, the labor cost in the operation of such engines is a comparatively large item. Electric power distribution in buildings remains to be considered as to the presence of the undesirable features just noted. As the pressure at which electrical energy is distributed in buildings is not usually great enough to cause injury to persons, the element of danger incident to the developed power is reduced to its lowest point. Electric motors have so high an efficiency, usually 80 to 90 per cent., that the amount of waste heat they give off may be neglected for most practical purposes. The efficiency of electric wiring in buildings is even higher than that of motors, being usually above 95 per cent., so that such wiring has very little appreciable change in temperature. The moving parts of electric motors differ materially from those of engines, in that the motions of the former are entirely rotary, while many of the latter are reciprocating. The noise and vibration that are almost always present with the operation of engines, apart from a solid foundation, are easily avoided with electric motors, in whatever part of a building they may be placed. In an electric motor there are only two sets of wearing surfaces, the bearings of the shaft and the commutator. All of the lubrication necessary for these surfaces is automatic, and the motors operate hours and even days at a time without any necessary attention whatever beyond starting and stopping at the desired times. The absence of danger, objectionable heat, noise and vibration with electric motors, together with the trifling amount of their required attention, make it practicable to distribute electric power through all parts of the best classes of buildings, for elevators, ventilation and a variety of other purposes.

The dependence of electric light, heat and mechanical power on the combustion of fuel has now been pointed out. The economic advantage of the production of these three forms of energy in a single plant has also been considered. Efficiency and cost of operation, and also the facility of distribution in different ways in plants for light, heat and power in buildings has been discussed. Several general conclusions can be readily deduced from the foregoing matter. Buildings can be warmed by the combustion of coal in their local plants at fuel cost far below those incurred where heat is derived from the public supply of gas or electric energy. If mechanical power is wanted in a building to an extent that does not require more steam during the cold months than would be necessary for heating alone, both the power and heating may be had during these months with a small increase in the amount of fuel that would be consumed for heating. Only a small increase in the total steam and fuel consumed at a building during cold weather for heating is necessary if energy for electric light is taken from the same boilers. It follows from the foregoing that the most economical means to supply light, heat and power in many large buildings is a local plant of steam boilers, engines and dynamos. This is especially true where the demands for each or all of these forms of energy are of long daily duration and large in amount. Where the requirement for heating is comparatively small, and light or power are wanted in considerable amounts during short or intermittent daily periods, so that the labor of operation for a steam boiler bears an unusually large proportion to the total expense of plant operation, a gas engine may save enough labor to compensate for the increase of fuel expense over that for a steam boiler and engine.

CHAPTER III.

ADVANTAGES OF THE COMBINED PRODUCTION OF LIGHT, HEAT AND POWER FROM STEAM.

Light, heat and power supplies in buildings are too often treated as independent problems, heat being derived from one source, light from another and mechanical power from a third. Another frequent practice is to combine the source of heat and power, and then derive light from an independent supply. Either of the plans just named is quite sure, under ordinary circumstances, to result in more than the necessary cost. The best solution of the problem, where light, heat and power are required in a building, is to so combine equipment that all three are generated in the same plant or by the same fuel. The advantage of the combined plant lies in the fact that a moderate addition to the equipment required for heating and a slight increase in the fuel it consumes will usually suffice for the production of all the power and light desired in an office or mercantile building. Even where only heat and light are wanted it is usually much cheaper to make such additions as will produce light in connection with the heating plant than to derive the light from a public supply. To demonstrate these facts it is only necessary to consider the several equipments necessary for the production of light, heat and power and the proportions and relations between the amounts of energy consumed for each purpose, and then the charges for public supply. Heat is, of course, the almost exclusive source of light and power in buildings and coal the usual fuel. The usual agents of heat distribution in large buildings are steam and hot water, also air heated by passing over steam coils. To supply steam or hot water, boilers are necessary, their capacity being about the same for either service. The steam coils for hot air also imply boilers. The only essential difference in the operation of a steam boiler for heating or power is that of gauge pressure. For steam heat alone the gauge pressure is usually not more than ten pounds, while for power with simple engines it may be anywhere from twenty to one hundred pounds by the gauge. The commonly accepted unit of heat is the amount required to raise the temperature of one pound of water from 39.1 to 40.1 degrees Fahrenheit, where water has its greatest density. The heat absorbed by one pound of water in passing through an increase of one degree in temperature at any point from 32 to 212 degrees Fahrenheit is very nearly equal to the heat unit. To convert one pound of water at 40 degrees, the lowest temperature common for boiler feed to steam at 10.3 pounds gauge pressure requires 1,147.1 heat units, while, if the pressure is raised to 100.3 pounds, the heat units absorbed by each pound of steam are only 1,177. In other words, to raise feed water at a temperature of 40 degrees to steam at 10.3 pounds pressure for heating, requires .974 of the heat and fuel that are required if the pressure is increased up to 100.3 pounds for power purposes. In a steam heating system the water of condensed steam is usually returned to the boilers at a temperature of about 212 degrees, at which one pound of water contains 172.9 units of heat above what it has at 40 degrees. As the water in a heating boiler is thus used over and over, the real expenditure of heat per pound of steam produced at 10.3 pounds pressure is 974.2 units. In like manner, if the water of condensed steam used for power purposes at 100 pounds pressure is returned to boilers at the temperature of 212 degrees and thus repeatedly used, the heat absorbed by the steam per pound is 1,004.1 units, and the heat for one pound of steam at 10.3 pounds pressure is 97 per cent. of this amount. It is thus evident that the consumption of fuel to generate any given quantity of steam for power purposes in a simple engine is only about 3 per cent. more than the fuel necessary to produce an equal quantity of steam at low pressure for heating. If all of the steam used in engines was condensed during their operation, the facts just cited would have little bearing on the economic use of the same boilers for both heating and power; but the smaller part of the steam entering engines is condensed therein. The temperature limits in engine cylinders are such that only a fraction of the heat in the steam entering them can be extracted for power production and the remainder escapes as exhaust steam and water. The proportion of steam and water leaving an engine cylinder is the main factor to determine the heat that may be used for other purposes. If the engine exhausts at atmospheric pressure, the temperature of both the water and the steam on leaving the cylinder is 212 degrees, as this is the highest temperature that either can have at that pressure. Each pound of water in the engine exhaust contains only 172.9 heat units above water at a temperature of 40 degrees, but each pound of steam contains 1,138.6 heat units, or 965.7 more than one pound of the water, this being the latent heat of steam, or the amount of heat necessary to change one pound of water at the temperature of 212 degrees to steam of that temperature at atmospheric pressure. If it is desired to utilize the exhaust steam of engines in a heating system, it will frequently be necessary to let the engines exhaust at a pressure a little above that of the air to give the required flow of steam in the heating pipes, but this back pressure on the engines, as it is called, is seldom more than five pounds. As the total contained heat of steam above water at 40 degrees is 1,138.6 heat units at atmospheric pressure, and only 1,143 heat units at five pounds above the atmosphere, and as the water of condensed steam may be expected to cool to 212 degrees before it leaves the heating pipes, the heating power of steam may be considered the same as at atmospheric pressure within these limits. The weight of exhaust steam and water leaving an engine cylinder must equal the weight of steam entering it from the boilers. Water and steam make up the engine exhaust in varying proportions that depend on several factors, but a fair relation for single cylinder engines is 80 per cent. steam and 20 per cent. water. As 1,004 heat units must be added to one pound of water at 212 degrees to produce one pound of steam at 100.3 pounds gauge pressure, and this steam, when it is reduced to about five pounds pressure at the engine exhaust, can yield 965.7 units to a heating system, one pound of exhaust steam has 96 per cent. of the heating power of the same weight at 100.3 pounds pressure. But as only 80 per cent. of engine exhaust is steam, the actual heating power of the exhaust, compared with the heat imparted to water at 212 degrees to generate steam at 100.3 pounds pressure, is 76.9 per cent. That is, the use of steam in simple engines absorbs only about 23 per cent. of the heat required to produce it from water at 212 degrees. Applying this per cent. to the latent heat of steam at air pressure—that is, 965.7 units—shows that for each pound of steam supplied to the engines 772.5 units of heat may be extracted from the exhaust before it becomes water at 212 degrees temperature. To obtain 965.7 heat units from a boiler devoted exclusively to warming, requires the addition of only that amount per pound to water at 212 degrees, since it is considered that all the water of condensed steam returns to the boiler at that temperature. In order to derive 965.7 heat units from exhaust steam, however, on the above basis, the heat that must be added to water at 212 degrees is found from a division of the 965.7 by 76.9, which shows the amount to be 1,255 units, or an increase of 30 per cent. over the heat necessary in a boiler used only for warming. If, therefore, the entire steam supply from a boiler is to be used for power in simple engines and the exhaust applied to heating, 30 per cent. more fuel will be necessary than that required for the heating alone.

It is next in order to determine the amounts of power and heating that may be done with the same steam. In simple engines of moderate capacity, subject to some variation of loads, it is fair to put the steam consumption at 30 pounds per brake horse-power hour. As found above, 772.5 units of heat may be derived from each pound of steam entering the engines for the heating system by utilizing the exhaust steam. At the rate of 30 pounds of steam per horse-power hour, the exhaust may supply 23,175 heat units for warming purposes hourly for each horse-power delivered by the engines. Other factors remaining constant, the rate at which heat is given off by radiating surface depends on the difference between its temperature and that of the surrounding air. An average value for the hourly emission of heat from radiating surfaces is 1.75 units per square foot for each degree by which its temperature exceeds that of the surrounding air. With radiating surfaces at 212 degrees and the surrounding air at 70, the difference is 142 degrees, and the heat given off by each square foot of radiation, on the basis of 1.75 units per degree of difference, is 248.5 heat units per hour. As each horse-power hour was found to yield exhaust steam containing 23,175 latent heat units, it is able to supply 93 square feet of the radiating surface just considered. If 3.5 heat units are required for each cubic foot of heated space per hour, a rate that is usually ample for warming offices and stores, 71 cubic feet may be heated by each square foot of radiating surface and 6,603 cubic feet per horse-power of engine delivery. By an increase of 30 per cent. in the fuel necessary to supply 93 square feet of radiating surface in a simple heating plant, one brake horse-power may be delivered by a simple engine, in addition to the maintenance of the radiating surface, as before.

Having noted the relation between the work of engines and the heating capacity of their exhaust steam, it remains to determine the illumination that the power corresponding to any heating effect can produce. One brake horse-power at the engine shaft, delivered to a good dynamo at 90 per cent. average efficiency, produces an output of 671.4 watt of electrical energy, since 746 watts are the equivalent of one mechanical horse-power. At a consumption of 3.5 watts per candle-power, a rate now regularly attained with incandescent lamps, the 671.4 watts maintain 211.3 candle-power of electric illumination. This illumination may be had in lamps ranging from ten to several hundred candle-power each, as desired. If the usual lamp of sixteen candles is selected, consuming 56 watts, twelve may be operated for each horse-power delivered to the dynamos. It thus appears that 30 pounds of steam, entering the simple engine, supplies one brake horse-power hour, the exhaust 93 square feet of radiation, and, if the power is applied to a dynamo, operates twelve incandescent lamps of sixteen candle-power each during one hour. The fuel cost of the brake horse-power hour, or for the incandescent lamps, is obviously only the increase over that necessary for each 93 square feet of radiation hourly when this is supplied directly from the boiler, provided that at least this much radiating surface is necessary. To determine the money cost of the 30 per cent. increase in the heat required of boilers where power as well as heating surface of a given amount is to be supplied, the efficiency of boilers must be considered. Good boilers of moderate capacity, as commonly used in large buildings, should evaporate as much as 7.5 pounds of water at 212 degrees to steam at 100 pounds pressure per pound of coal burned, and many are doing much better than this. On this basis, four pounds of coal must be burned to supply 30 pounds of steam to an engine for the delivery of one brake horse-power hour. At a price of $3 per ton, these four pounds of coal cost .6 cent. It has already been shown that the steam for the engine absorbs from the boiler 1.3 times the heat that is taken by steam used only in the radiators that the exhaust for each horse-power of engine output will supply. In other words, 77 per cent. of the heat absorbed by the steam for engines is applied by means of the exhaust to the heating surface, and would be required for this surface if the engine was not in use. The .6 cent expended to supply steam to an engine for one horse-power hour should therefore be charged .77 or

.462 cent to heating and .138 cent to power production. If this one horse-power is applied to the production of electric light in twelve incandescent lamps of sixteen candle-power each, the fuel cost per lamp hour is 0.011 cent. It may be questioned whether all of the exhaust steam from engines used to operate dynamos for electric light can be utilized during the heating season, and a few figures will give some information on the subject. The space that can be heated by the exhaust steam per brake horse-power of engines in operation has been shown to be 6,603 cubic feet. A room 10 feet from floor to ceiling, and with a floor space of 20 feet by 33, contains 6,600 cubic feet. The floor of this room includes 660 square feet, and if one sixteen candle-power lamp is allowed for each 55 square feet the room will have twelve of these lamps. As twelve of the sixteen candle-power lamps are maintained per horse-power delivered to a dynamo, and the exhaust steam per horse-power heats the room in question, it seems that the dynamos operated by simple engines will supply energy to illuminate the space that the exhaust steam will heat. The illumination here assumed is about the average, while the space warmed per unit of heat represents frequent practice. It should also be noted that the comparison just made is based on the simultaneous use of both light and heat. The facts are that in the heating season lamps are in use only one-half to one-fourth of the hours per day that steam is required in the radiators. These facts still further increase the space that may be lighted over that which may be heated from the energy of steam used by dynamo engines. The lack of coincidence in point of time during each twenty-four hours in the demands for light and heat in buildings is an obstacle to the economic application of steam to heating and the production of electric energy. The demand for heat is greatest during the morning hours, but continues in a large degree throughout the day. Much the greater part of electric lighting, on the contrary, is crowded into the late afternoon and evening. As a result, the supply of exhaust steam, while entirely inadequate for heating purposes during the first half of the day, is much greater than can be immediately utilized during some hours in the second half. There are means at hand, however, by which either heat or electric energy not wanted at the time of its production may be stored and applied during a subsequent period.

CHAPTER IV.

EFFICIENCY IN PRODUCTION AND DISTRIBUTION OF HEAT, LIGHT AND POWER FROM HOT WATER AND STEAM.

When a boiler has transferred a portion of the heat resulting from combustion of fuel to its contained water and steam, the first step toward the production of light, heat or power at the points where it is desired has been taken. Escape of heat which does no useful work from the furnace and boiler is only the first of a series of losses that intervene between the latent energy of the fuel and the desired effects. Heat imparted to the contents of the boiler may be desired for consumption in that form of energy, or this heat may be transformed to power or light, as required. If the water or steam of the boiler are devoted to heating purposes, a large share of the contained energy may become available at the point of final use, but where power or light is the ultimate object the possible per cent. of energy that may appear as useful effect is much smaller. Heat from a boiler may be distributed for general warming by either hot water or steam. If the water is heated under open-air pressure and to a temperature of about 212 degrees, nearly 181 heat units must be added to each pound of water when its initial temperature is 32 degrees Fahrenheit. Only a fraction of this temperature can be taken from the water by radiators under ordinary conditions, because the cost of radiators and their required space become too great unless a high average temperature is maintained. Allowing for an ordinary case a fall of 40 degrees for the temperature of water while in radiators, it appears that water entering boilers at 32 degrees and leaving them at 212 will have 22.1 per cent. of its added heat extracted by radiators, if only its first round of circulation is considered. This result presumes no loss of heat from the pipes that conduct the water to and from the radiators. Such an escape of heat may be a loss if the pipes are in a space where heat is not wanted, or may be treated the same as heat from the radiators if the pipes are in heated space. When water returns to boilers from its first round through the radiators enough heat to compensate for the lost temperature must be added. Disregarding, then, any loss from pipes, the efficiency of hot water distribution in the present case is 22.1 per cent. for the first round of circulation. In each subsequent round of circulation the water yields for useful effect all of the heat corresponding to the 40 degrees of temperature last added by the boiler, and the efficiency is 100 per cent. Where a hot-water heating system is in active operation during a large number of hours per day, the amount of heat necessary to raise the volume of circulating water from its initial outside temperature to 212 degrees is trifling compared with the total heat subsequently imparted to the water. Consequently, the efficiency of the heating system beyond the boiler may be nearly 100 per cent. A small loss should be allowed to cover leakage and evaporation from the pressure tank, so that where there is no waste radiation from pipes, and the period of active operations extends through the larger part of each day, distribution efficiency may be fairly taken at 95 per cent. Presuming boilers to transfer to their contained water 70 per cent. of the total energy of fuel consumed, the useful heat derived from hot water may represent .95 × 70 = 66.5 per cent. of the possible heat from the combustion of coal. In steam heating at air pressure, with water having an outside temperature of 32 degrees, nearly 181 heat units must be added to each pound of water, as before, and in addition to this 966 heat units will be absorbed by each pound when it is converted into steam, making a total of 1,146 units per pound. Presuming, as before, that the heat escaping from pipes is as useful as that from radiators, the steam heating system may deliver for useful effect 966 ÷ 1,146 = 84.3 per cent. of the heat imparted to the contents of the boiler, considering only the first production and condensation of steam. The same per cent. of efficiency applies constantly to cases where the condensation from radiators is lost and does not return to the boilers. If all of the condensed steam is returned to the boilers, the distribution system may have an efficiency of 100 per cent., after the boiler water has once been raised to a temperature of 212 degrees. Some of the steam in pipes and radiators is quite sure to escape through small leaks and at the air valves, so that an efficiency of 100 per cent. is not reached for the heating effect of steam sent into the pipes from water at 212 degrees.

It may be fairly assumed, however, that the leakage of steam will not amount to more than 5 per cent. with good pipes and radiators. Where a steam heating system is in active use during the larger part of each day, the amount of heat necessary to bring the water required to fill the boilers once to the boiling point is a trifling part of the total. For the case of water from radiators returned to boilers and used over and over, a steam heating system, with a boiler of 70 per cent. efficiency, may be expected to deliver for useful effect 70 × .95 = 66.5 of the possible heat from combustion. From this it appears that for the conditions named the efficiency of steam and hot water heating systems are substantially equal.

Where steam is devoted to power production, the portion of its contained energy that may be recovered as mechanical work is limited by the initial and final temperatures of the steam entering engine cylinders. For the most ordinary conditions in the power plants of buildings, steam is supplied to simple engines at about 100 pounds gauge pressure and is exhausted into open air. Each pound of this steam contains 1,185 heat units above water at 32 degrees Fahrenheit, and as much as 30 pounds are generally consumed per delivered horse-power hour with simple engines. The heat passing into the engine per horse-power developed is thus 1,185 × 30 = 35,550 units per hour. One horse-power hour is the equivalent of 2,545 heat units, so that an engine as above has an efficiency of 2,545 ÷ 35,550 ≐ 7.1 per cent.

With boilers that deliver in steam 70 per cent. of the total energy of the fuel consumed, the combined efficiency of the plant is .70 × 7.1 = 4.9 per cent. If the exhaust steam is used to heat the boiler feed water from a temperature of 32 to 212 degrees, 181 heat units are thereby saved per pound, or 181 × 30 = 5,430 units per horse-power hour. Deducting this amount of heat from the charge previously made against the engine, leaves 35,550 — 5,430 = 30,120 heat units as the consumption of heat per horse-power hour. Dividing the heat equivalent of one horse-power hour by the last named quantity, shows the efficiency of the engine to be 2,545 ÷ 30,120 = 8.4 per cent. Using again the number 0.70 to represent boiler efficiency, the boiler and engine combined yield in the form of mechanical energy 8.4 × .70 = 5.8 per cent. of the total heat of combustion. This number is in marked contrast with the efficiency of 66.5 per cent. found for both hot water and steam heating systems. The frequent practice by which exhaust steam is employed for heating purposes rests on the fact that a pound of steam from the engine is as good in the radiators as is a pound from the boilers. Steam at 100 pounds gauge pressure contains 1,185 heat units per pound above water at 32 degrees temperature. At open-air pressure this same steam still contains 1,146 heat units per pound, showing a loss of only 3.3 per cent. of its contained heat.

In many buildings power developed by steam is desired for use in small quantities at a considerable number of points, and dynamos, wiring and electric motors are the most suitable means of distribution. For this case the losses at the boilers and engines are further increased by others in the electrical equipment. Average efficiencies for dynamos, wiring and electric motors may be fairly taken at 90, 98 and 80 per cent., respectively. The combined efficiency of these three electrical elements is, therefore, 90 × .98 × .80 = 70.5 per cent. For the case of a boiler and simple engine, the combined efficiency was found to be 5.8 per cent., when feed water is sent to the boiler at a temperature of 212 degrees. Combining this figure for efficiency with that just found for the electrical system from dynamo shaft to motor shaft, it appears that the motor will deliver in mechanical work 5.8 × 0.705 = 4.1 per cent. of the energy that complete combustion of the fuel will yield. It should be noted here that the electrical equipment is far more efficient than the steam power plant. While the steam plant named is able to deliver only about 5.8 per cent. of the total fuel energy as mechanical work, the electrical system of dynamos, wiring and motors yields at the motor shaft more than twelve times this per cent. of the work done on the dynamo pulley.

Where steam power is devoted to electric lighting, only dynamos and wiring intervene between the engines and lamps, and the combined efficiency of these two electrical elements is $90 \times .98 = 88.2$ per cent. With the same efficiency as before for the engine and boiler, the electric lamps receive $5.8 \times .882 \doteq 5.1$ per cent. of the energy that may be developed by the fuel consumed. In the lamp, whether arc or incandescent, is seen the one element of an electrical system that is highly inefficient. While the dynamo delivers as electrical energy 90 or more per cent. of the work done on it by the steam engine, electric lamps emit as light less than 2 per cent. of the energy entering them. Comparatively, however, electric lamps are highly efficient, since they yield as light a much higher per cent. of the applied energy than does the tallow dip, the oil burner or the gas jet.

Electric heaters for general warming have an efficiency of 100 per cent.; that is, they transform into useful heat all of the electrical energy sent into them.

As the efficiency of dynamos is 90 or more per cent., the combined efficiency of the dynamo and electric heater is at least this figure for ordinary cases. With a loss of 2 per cent. in wiring between the dynamo and heater, the latter radiates as heat the equivalent of $90 \times .98 = 88.2$ per cent. of the mechanical energy expended to drive the dynamo. If the greater part of fuel energy could be made available as mechanical work at the dynamo, electric heaters would quickly replace every other form, because of their efficiency, each of regulation and the low cost at which they can be made. As matters stand, however, general warming of buildings by electric heaters is impracticable because of the great amount of fuel necessary. This may be seen from the fact that with the above steam plant only 5.8 × .882 = 5.1 per cent. of the heat of coal is radiated by the electric heater.

CHAPTER V.

GENERAL REQUIREMENTS AND SAFETY OF BOILERS—EXPLOSIVE ENERGY.

As the several forms of energy required in buildings all depend ultimately on steam or hot water for their production, in most cases, boilers may be considered of prime importance in the development of light, heat and power. Safe and efficient boilers do not necessarily imply a satisfactory and efficient power plant, but it is safe to say that such a plant cannot be had without these qualities in the boilers. The office of a steam or hot water boiler is obviously to transfer the heat resulting from the combustion of fuel to its contained fluids. That portion of the total heat of perfect combustion that appears in the hot water and steam is a measure of the boiler efficiency. Safety with a boiler depends not only on the strength of its parts in proportion to the strains which they must ordinarily undergo, and on the attachments that tend to prevent accidents, but also on the power of the boiler to do damage under any combination of circumstances. Satisfactory operation of a boiler may depend quite as much on the conditions under which it is placed as on its inherent good qualities. Where fuel is very expensive the first cost of boilers is of small moment compared with their efficiency, but when fuel is very cheap a gain of efficiency may be more than offset by increased interest and depreciation charges on the investment.

In general, a boiler should be selected according to the degree of safety required at the point of use, the cost of fuel, the quality of the water and the shape of the space for which it is intended.

The dangers from boilers are due to the fact that they are great reservoirs of energy. This energy exists in the boiler as heat, but is transformed into motion when a break allows the boiler's contents to escape. An excess of pressure in a boiler above what it is able to resist causes a break, but this excess of pressure is not the destructive force of the explosion, but simply gives that force a chance to act. Where a break in a boiler occurs the heat in its escaping water changes to mechanical energy through expansion of the water into steam, and this expansion operates to project the boiler or its parts with great force and high velocity.

The steam in a boiler is sometimes spoken of as the destructive agent in case of an explosion, but it is really the steam formed after a boiler bursts that does the damage. The energy in the steam of a working boiler under normal conditions—that is, one-half to three-fourths full of water—is small in amount compared to the energy in its water. For example, take a boiler two-thirds full of water and working at 125 pounds gauge pressure. Each cubic foot of dry steam in this boiler contains 351 heat units more than an equivalent weight of water; that is, .31 pounds at 212 degrees. Each cubic foot of water in this boiler, if at the temperature of 352 degrees, to correspond with the steam pressure of 125 pounds gauge, contains about 7,920 units of heat above an equal weight of water, or 55 pounds, at the temperature of 212 degrees. The temperature of 212 degrees is taken as the point from which to compute the energy of both the water and steam, because water flashes into steam under atmospheric pressure at 212 degrees or any higher temperature. Of course, only a little of a body of water at just 212 degrees can change to steam when separated from its source of heat and exposed to the open air, because 966 heat units are absorbed by each pound of steam then formed, and this heat must be taken from and lower the temperature of the body of water. The higher the temperature of a body of water above 212 degrees when exposed to the open air the larger the part of the water that changes to steam. From the above figures it appears that each cubic foot of water in a boiler working at 125 pounds gauge pressure contains 7,920 ÷ 351 = 22.2 times as much heat energy above water at 212 degrees as each cubic foot of steam in the same boiler. If the boiler contains two cubic feet of water to one of steam, the ratio of the energy that the water may liberate when exposed to the air to the energy of the steam is 22.2 × 2 = 44.4 to 1. In the case of a boiler explosion the mechanical work done in hurling the parts of the boiler is thus mostly derived from the expansion of the steam formed from the liberated water. If the water remained in the boiler under normal conditions of operation its contained heat energy would be gradually imparted to the steam during a comparatively long period of time, but when a very large rent in the boiler allows its contents to escape in a few seconds the stored energy of the water is converted into work in so short a time that a very great force is exerted on surrounding materials. When the destructive effects of boiler breaks or explosions are to be considered, it is thus evident that the quantity of water that may escape and the element of time are of the highest importance.

The difference between a bad leak in a boiler that may never be heard of outside the fire room and an explosion that lands the boiler plates half a mile from their foundation is simply one of time during which the contents of the boiler escape. Different boilers of the same working capacity vary much as to the amount of contained water in each, and also as to the rapidity with which this water can escape by a rupture of some of the parts.

Where the highest degree of safety from explosions is desired it is obvious that, other things being equal, boilers should be selected that contain only a small amount of water relative to their capacity, and are of such proportions and construction that their contents will be much retarded in its escape if a break occurs. An excess of internal pressure above what the boiler will withstand is the general direct cause that produces rupture of the parts and the subsequent explosions. This rupture of boiler tubes or plates is usually brought about by their deterioration with rust, their overheating, or else by a large increase of the internal pressure above that for which the boiler was designed. To guard against these dangerous conditions in a boiler its strength should be ample for the intended pressure, its design should be adapted to the kind of water that must be used, the internal as well as the external surfaces should be capable of ready inspection and cleaning, the safety valve should be of a type that is not easily put out of the proper adjustment, either by intent or accident, and the surfaces most exposed to the heat should be protected by one or more fusible plugs. Water that must be used in boilers, in many places, contains quite an amount of mineral matter, which is deposited on the interior surfaces of boilers as steam is formed. Such deposits of mineral matter or scale are very poor conductors of heat, so that the metal of the boiler plates or tubes, where they are attached, instead of remaining at about the temperature of the contained water, may be raised much above that point. As the temperature of iron or steel rises much above that of the water in high pressure boilers it grows materially weaker. It therefore happens that boiler plates and tubes, ample in strength to withstand the pressure for which a boiler is rated, when they are at or near the temperature of the contained water, often fail under the normal pressure because, having been coated with a thick layer of scale, they are overheated and lose their ordinary strength. Rust frequently attacks some parts of boilers more than others, and if the extent of its inroads on all interior surfaces cannot be determined and its progress stayed, points may be developed in a boiler where the strength is far below the necessary standard of safety. It is easy to conclude from these facts that all interior surfaces of boilers should be easy of inspection and capable of being cleaned. It also follows that where mineral deposits are likely to occur a boiler should have as few surfaces as possible where such scale may rest exposed to the flames. As a general rule, these adverse conditions as to scale and rust may be avoided by requirements that only straight tubes, in nearly vertical positions, and plates similarly placed, be exposed to the furnace flames, and that enough room be left between all interior surfaces for full inspection. Safety valves which are intended to limit the possible pressure in a boiler to the normal rating of its parts by an escape of steam when the rated pressure is exceeded may fail through either intent or accident to perform their function. The valve construction should be such that no rusting of its parts can tend to prevent the opening of the valve on an excess of pressure. A valve should not be of a type where the limiting pressure can be raised by simply shifting the position of a weight on a lever arm or tightening a spring. Probably the safest valve is one direct weighted in plain sight.

CHAPTER VI.

BOILER CAPACITY.

Boiler capacity is measured by the amount of heat that may be transferred to the contained water and steam per unit of time, under given conditions as to fuel, firing and draught. A convenient measure of the heating effect in a steam boiler is the evaporation of one pound of water at 212 degrees to steam of the same temperature under atmospheric pressure. One pound of water then evaporated absorbs 965.7 heat units. Where boilers are used for hot water heating it may be more convenient to measure capacity by the product of the pounds of water heated by the temperature through which it is raised in degrees Fahrenheit per unit of time. The unit of heat is the amount necessary to raise one pound of water one degree from the temperature of 39.1 degrees Fahrenheit. The heat absorbed by one pound of water when raised one degree in temperature at any point between 32 and 212 degrees is very nearly the same as the exact unit of heat, and may be treated as the heat unit in ordinary calculations. It follows that the product of the weight of water in pounds heated by a boiler per unit of time by the degrees through which the temperature of the water is raised gives the output of the boiler in heat units for that time. A boiler that raises 966 pounds of water one degree in temperature per unit of time thus has a capacity equal to that of a boiler that evaporates one pound of water from and at 212 degrees under atmospheric pressure during the same period, all other conditions remaining constant. Simple as it thus is to state the capacity of boilers, whether for steam or hot water, in definite units, a less accurate and somewhat misleading rating is often used. It has long been customary to specify boilers as of so many horse-power, but it should be noted that one horse-power effect in a boiler is an entirely different thing from one horse-power with an engine. When delivering one horse-power an engine raises 33,000 pounds one foot high each minute, or overcomes any other resistance through any other distance, so that the product of the resistance in pounds and the distance in feet equals 33,000 foot-pounds of work per minute. Applied to an engine, therefore, the horse-power is purely a measure of mechanical work. As a boiler cannot perform mechanical work directly, its rating in horse-power must have some other meaning than in the case of engines. As work at the rate of one horse-power has a certain heat equivalent per unit of time, this heat equivalent to the energy of one horse-power per minute—that is, to 33,000 foot-pounds—might be thought to be the boiler capacity intended by a rating of one horse-power. One foot-pound is equivalent to .001285 heat unit, so that a mechanical horse-power equals $.001285 \times 33,000 = 42.4$ heat units per minute. The horse-power unit, as applied to boilers, however, has an entirely different meaning, or, in fact, two meanings.

A horse-power in boiler capacity is taken to be some rate of steam production; it is also taken to indicate certain sizes and proportions of boiler parts. Inasmuch as engines in practical use vary as much as three or four times in the amount of steam required per horse-power hour of work, the rating of a boiler in the horse-power of its engine is very unsatisfactory. In order to partially avoid the disadvantages of boiler ratings in horse power, the American Society of Mechanical Engineers decided in 1884 to adopt as a horse-power of boiler capacity the evaporation of 34.5 pounds of water at the temperature of 212 degrees to steam of atmospheric pressure, per hour, this being called the unit of evaporation. The unit thus adopted is equivalent to the evaporation of 30 pounds of water per hour from a temperature of 100 degrees to steam at 70 pounds gauge pressure; it is also equivalent to 33,305 heat units per hour. The adoption of the definition of boiler capacity by the American Society of Mechanical Engineers has done much to aid definite boiler ratings, but the horse-power of boilers is often spoken of in a loose way.

Even if the evaporation of 34.5 pounds of water per hour at 212 degrees to steam at atmospheric pressure be enforced in all cases as the measure of one horse-power in boiler capacity, it is not clear that the use of the term horse-power in boiler ratings has any advantage. As the sole purpose of a boiler is to transfer the heat of combustion to its contained water or steam, the most obvious rating is one based directly on the number of heat units imparted to the water or steam per hour, or the pounds of water heated one degree per hour. If a larger unit of boiler capacity is wanted, the evaporation of one pound of water per hour at 212 degrees to steam at air pressure, which requires 965.7 heat units, may well be chosen for the purpose. Such boiler ratings would simplify the selection of boilers for heating systems, and also for engines of any capacity working at any pressure. In steam and hot water heating the results of calculations as to required service are readily obtained in terms of heat units or of pounds of steam per hour, and these are at once the boiler capacities desired. The fact that boiler capacity is rated in horse-power, each corresponding to the evaporation of 30 pounds of water per hour, at 100 degrees to steam at a gauge pressure of 70 pounds, is of no advantage over a direct rating in heat units when the feed water is at a different temperature, the gauge pressure has some other value, or the engine does not require 30 pounds of steam per horse-power hour. For any other conditions than those included for the feed water, gauge pressure and engine economy in the definition of boiler horse-power, the nominal power of the engine and boiler will not coincide, and the boiler capacity must be reduced to its actual value in heat units per hour.

Take an example that may well occur in practice, where boiler capacity is necessary to supply an engine of 100 indicated horse-power that consumes 20 pounds of steam per horse-power hour at a gauge pressure of 125 pounds, where the feed water is heated to 212 degrees before entering the boiler.

Obviously the horse-power rating on the above basis of the boiler necessary for this case cannot coincide with that of the engine, but the heat in the steam sent to the engine must be computed to find the boiler capacity, and then, if the boiler is to be specified in horse-power terms,' the boiler heating capacity must be reduced to these terms. The above engine, when operating at full capacity, requires 100 × 20 = 2,000 pounds of steam per hour. To evaporate one pound of water of 212 degrees temperature to steam of 125 pounds gauge pressure requires 1,008 heat units, so that the boiler capacity for the present engine must be 1,008 × 2,000 = 2,016,000 heat units per hour. As previously defined, one horse-power of boiler capacity is equivalent to the delivery from fire to water of 33,305 heat units hourly, so that the nominal boiler capacity necessary for the 100-horse-power engine is found from 2,016,000 ÷ 33,305 = 60 horse-power. Such use of the term horse-power in different senses, when applied to engines and boilers, is obviously liable to lead to misunderstandings, to say nothing of the additional calculation it involves. As steam engines are usually rated to consume a certain weight of steam per hour under a given pressure at full load, it is very convenient to specify boilers that will evaporate the required weight of steam from water at the lowest temperature the feed will ever reach, and to the necessary pressure, making a small allowance for leakage.

It is not always possible to foresee the temperature to which feed water may be raised in any particular case, and it is good policy to have a boiler of somewhat greater capacity than is absolutely necessary. For these reasons it is a good practical rule when specifying a boiler to disregard the possible effect of heated feed water and require a boiler that will yield the necessary weight and pressure of steam from water of 32 degrees temperature. This practice can lead to no excessive increase of boiler capacity beyond the necessary point, because only 181 heat units are necessary to raise the temperature of one pound of water from 32 to 212 degrees Fahrenheit, while 966 units are necessary to evaporate the water under air pressure. At most, therefore, not more than 181 ÷ (181 + 966) = 16 per cent. of the heat necessary to change water at 32 degrees to steam at any pressure above the air can be supplied by heating the feed water up to 212 degrees. Not more than 16 per cent. of boiler capacity can be omitted if feed water is heated to 212 degrees, and this per cent, is hardly enough for a good margin. Where boilers are used entirely for steam heating at little more than atmospheric pressure, on the gravity system, the return water is usually nearly up to the 200 degree point, so that a capacity to evaporate the required weight of steam per hour from water at 32 degrees gives about 15 per cent. margin. If the water from radiators is not returned to the boiler at all, or only after it has fallen to a comparatively low temperature in traps, more capacity beyond that necessary to evaporate the necessary amount of water from 212 degrees should be provided. For hot water boilers, it is convenient to specify a capacity to raise the temperature of the weight of water necessary to pass through the heating system per hour a somewhat greater number of degrees, say, 10 to 20 per cent. more than the water it is intended to cool in periods of the greatest demand.

Thus far the capacity of boilers has been treated as to the direct effect to be produced, but this is not usually the most satisfactory way to specify boiler capacity. The heating effect that may be transmitted by any boiler to its contained water and steam depends, of course, on the size and proportion of its parts, but this effect also depends in large measure on the quality of the fuel used, the skill with which the boiler is fired, the draught available, and the degree of efficiency maintained.

Where the capacity of a boiler is to be decided by its performance, the kind of fuel, the draught and the efficiency should also be specified, else contractors can hardly be expected to make the same assumptions on these points.

A more direct and simple way to specify boiler capacity is to fix the more important dimensions of the parts that determine it. The heat of combustion is transferred to the water and steam of boilers in two ways, by contact and by radiation. The amount of heat that may be imparted to the contents of the boiler in a given time depends, among other factors, directly on the amount of surface in contact with the water on one side and exposed to the action of the fire and hot gases on the other. In like manner the amount of fuel that may be consumed under a boiler, other factors remaining constant, depends directly on the area of the grate surface. The heat that may be transmitted to the water of a boiler by a unit of heating surface under definite conditions, like the amount of fuel that may be burned per square foot of grate surface, has been determined by experience.

For a single type of boiler as much as 10 pounds of water may be evaporated from and at 212 degrees by each square foot of heating surface per hour, or, on the other hand, a square foot of heating surface may be allowed for each two pounds of water to be hourly evaporated. It may be advisable to burn as little as eight pounds of coal per square foot of grate surface per hour where the draught is light and a slow rate of combustion necessary. On the other hand, where a very strong draught is available and rapid combustion necessary, 40 or more pounds of coal may be burned on each square foot of grate hourly. In order to determine which of these widely different rates of work for heating surface and grate surface is desirable in a given case it is necessary to consider the causes of these differences.

That part of the boiler heating surface above the grate and surrounding the fire receives a large amount of heat by direct radiation from the incandescent fuel, besides that imparted to it by direct contact with the hot gases. This part of the heating surface above the fire is therefore more effective than any other, and a boiler in which the proportion of surface exposed to direct radiation from the fuel is large may be expected to show a high rate of evaporation under favorable conditions. The boiler surface beyond the firebox derives its heat from the gases of combustion, and the heat transmitted to the water depends directly on the temperature of these gases. In the firebox gases may have a temperature of 2,000 degrees Fahrenheit or more, but as these gases flow through the tubes or over the boiler surface the heat they impart to it results in a gradual fall of their temperature. It follows that the more extended the boiler surfaces over which the gases of combustion pass the smaller will be the amount of heat transmitted to the water by each square foot of surface, on an average, because the rate at which the gases give up heat depends on the difference between their temperature and that of the heating surface. A high rate of evaporation is often obtained per square foot of heating surface in boilers by so limiting their surfaces that the average temperature of the gases, and consequently the temperature at which they escape to the chimney, is high. Such a construction gives a boiler cheap as to first cost per unit of capacity, but very expensive in subsequent operation where fuel must be paid for at ordinary prices.

As the heat of combustion is largely imparted to the gases, the loss of the gases while they are at a high temperature means the waste of a considerable per cent. of the coal consumed. For nearly all cases, save where the cost of fuel is an unimportant item, the heating surface of boilers should be so proportioned that the maximum practicable portion of their heat may be extracted from the gases. A limit to the extraction of heat from the gases of combustion is set by the temperature of water and steam in any particular boiler. It is not profitable to so extend the heating surface of a boiler that the gases are reduced to the temperature of its contents before they escape, as the rate at which heat is transmitted from the gases to the water decreases more rapidly than the differences in the temperatures of these two bodies.

While grate surface is an essential factor in boiler capacity, the relation between the area of a grate and the capacity of its boiler for efficient operation is much more variable than the relation of heating surface to the rate of evaporation. A boiler may give exactly equal results as to capacity and efficiency with grate surfaces that vary as much as 300 or 400 per cent. in area. To rate a boiler by the surface of its grate alone is therefore absurd. Grate surface should be considered not as a measure of boiler capacity, but as a thing to be determined by the capacity in connection with the conditions under which combustion takes place in the furnace.

The heating surface of a boiler adds largely to the cost, as it is extended, but grate surface cost is comparatively small. It is therefore possible to make a cheap boiler with extensive grate surface and large capacity, though the heating surface is relatively very small; but such a boiler is necessarily inefficient, because the gases of combustion do not have time to give up their heat before they escape. The two factors that largely determine the proper extent of grate surface, compared with heating surface, are the quality of fuel used and the available draft. For coals low in ash a very wide range of variation in the weight consumed per square foot of grate hourly is allow-able if the draft is varied accordingly. In other words, the weight of coal that may be burned per square foot of grate hourly depends on the thickness of the fire, and this in turn on the draft pressure that can be had to force air through the bed of coal. With moderate pressures, such as are usually present where natural or chimney draft is employed alone, thin fires, a slow rate of fuel consumption per square foot of grate and a comparatively large grate area are necessary. If mechanical draft is available to any desired pressure, the thickness of fires may be largely increased and the grate area held at a low figure if the amount of air necessary for perfect combustion is forced through the fuel. When the coal employed has a large per cent. of ash it may be impossible to get the required amount of air through a thick fire with even a draft of high pressure, especially if the coal ash has a strong tendency to clinker. If shaking grates or some other are employed to get rid of the ash as fast as the coal is burned, thick fires may be economically employed even where a large portion of ash is present.

When the available draft pressure is small, as is usually the case where a chimney is the only source, thick fires and high rates of combustion per square foot of grate surface are sure to result in poor economy, because sufficient air for complete combustion will not be forced through the coal. As a result of too little air, the gases from the coal are only partly burned and escape with much of their fuel value undeveloped. On the other hand, a very strong draft, with thin fires, may result in even less capacity and economy than do thick fires and low pressure draft. A draft of high pressure may force many times the required amount of air through a thin bed of fuel, and thus greatly reduce the temperature of the gases of combustion and their effect on the heating surfaces.

It should now be evident that the heating surface comes the nearest to a true measure of boiler capacity where a given degree of efficiency is to be maintained. True it is, as pointed out, that a boiler of small heating surface may be made to show a relatively large capacity, because the escaping gases have a very high average temperature while they are in contact with the plates; but this large output per unit of heating surface can only be obtained at the expense of efficiency. The deposit of soot on the fire side of the heating surfaces of boilers and the mineral incrustations on the water sides, as also the tendency of the gases of combustion to flow more rapidly over some of the surfaces than over others, all interfere to some extent with the relation between surface area and boiler capacity. These conditions, however, admit of prevention or cure, and do not change the broad fact that boiler capacity depends on the area of heating surface. When a given capacity and efficiency are required in a boiler a relation is established between the output, the area of heating surface and the rate at which coal is burned in its furnace. The area of the grate surface is not included in these requirements. It is only when the available draft is specified and the quality of coal named in connection with the capacity and efficiency that the area of grate is fixed. A given weight of coal burned per hour may easily give equal results with the same boiler when it forms a thick fire on a small grate with high draft pressure as when spread over a much larger grate for a low pressure draft.

As has been pointed out, some parts of the heating surfaces of boilers are more effective than others, because of their positions, while further differences may arise during operation from deposits of soot or incrustations. Any system of surface measurement that undertook to make allowance for all of these differences would be too complicated for general application. The best way, therefore, to compute the heating surface of a boiler is to include all surfaces in it that have the fire or hot gases on one side and water on the other. In boilers of good proportions and design the differences in effectiveness between the several parts of the heating surfaces nearly offset each other, so that the total surface subject to the action of fire and water in each is usually a fair basis of comparison.

Aside from the very small boilers used for house heating and made in a great variety of forms, those in general use may be divided into five main classes—the plain cylindrical, the flue, the horizontal and vertical tubular, the horizontal internally fired, and the water-tube boilers. The construction and setting of these several types of boilers determine the heating surface of each. That part of the boiler surface that has fire or hot gases on one side and steam on the other cannot fairly be taken as a part of the heating surface, because the amount of heat that the steam will take from hot plates in contact with it is very small compared with the heat absorbed by water. Under normal conditions of operation, plain cylindrical boilers are usually so supplied with water that about two-thirds of their side surfaces are in contact with it. The setting of these boilers in brick work leaves the portion of their sides that are in contact with water and about one-half of one end subject to the action of flames and hot gases. The rule to find the heating surface for a plain cylindrical boiler is thus: Multiply the length in inches by two-thirds of the circumference in inches, and to this product add the area in square inches of one-half of one end of the boiler; divide this total by 144 to get the heating surface of the boiler in square feet.

Cylindrical boilers with one or two flues extending from one head to the other are usually supplied with water and mounted in brick work in much the same way as are plain cylindrical boilers, except that the gases leave the boiler at the front or furnace end after passing through the flues. The rule for heating surface in this type of boiler is therefore: Multiply the length of the boiler by two-thirds of its circumference, all taken in inches; then multiply the length of each flue by its circumference, and this product by the number of flues; next find the area in square inches of one of the boiler heads; take one and one-half times this area and from this product subtract twice the end area of all of the flues; to the remainder add the product representing the outside cylindrical heating surface, and that representing the combined surface of the flues; divide this total sum by 144 to get the area of the boiler heating surface in square feet.

Vertical tubular boilers are internally fired, and the firebox is made up of surfaces with water on their other sides. In this type of boiler the gases of combustion pass upward through the tubes and emerge at the top. The rule to find the heating surface of the vertical tubular boiler is: Multiply the circumference of the firebox by its height above the grate, all dimensions in inches; multiply the circumference of one tube by its length to the water line, and this by the number of tubes; to the sum of these two products add the area of the lower tube sheet, in square inches, and divide the total by 144 to get the area of heating surface in square feet.

Horizontal tubular boilers are usually set in brick work similar to that used with the plain cylindrical, except that an up-take is provided at the front end, so that the gases, after passing to the rear of the boiler along its outside and then entering the tubes and flowing to the front end, may there escape. The rule to find the heating surface of the horizontal tubular boiler is: Multiply the length of the boiler by two-thirds of its circumference, all taken in inches; multiply the circumference of one tube by its length, and this by the number of tubes; to the sum of the products thus found add two-thirds of the area of one tube sheet twice; divide the total sum by 144 to get the heating surface in square feet.

Internally fired horizontal boilers, as used on land, are known as the Cornish and Lancashire types, and are much more generally used in England than in the United States. The Cornish boiler has one every large and the Lancashire has two somewhat smaller internal flues from end to end. These boilers are set in brick work like the plain cylindrical and tubular in some respects. Grates and fires for these boilers are placed in one end of the flues and the gases of combustion pass first through the entire flue length to the rear end, then back to the front of the boiler along its sides and subsequently to the rear again and underneath. The rule to find the heating surface for this type of boiler is: Multiply the total length by two-thirds of the outside circumference of the boiler, all dimensions to be taken in inches; multiply the circumference of one of the flues by its length and by the number of flues; to the sum of these products add two-thirds of the area in square inches of one of the boiler heads; then subtract the sum of the cross-sectional area of the flue or flues and the flue area beneath the grates; divide the remainder by 144 to get heating surface in square feet.

The locomotive type of boiler and also the marine or Scotch boiler belong to the class that are internally fired. Each of these boilers partake of the construction in the tubular boiler, inasmuch as they have internal fire tubes. Neither the locomotive nor marine boiler uses the outside surface for heating the contained water by passing the gases of combustion over it, but each absorbs its heat through the internal firebox, combustion chamber and fire tubes. These boilers vary somewhat in construction, but their heating surface can be readily computed by an application of the principles involved in the rules given for tubular and internally fired boilers. Boilers of the locomotive type are occasionally used in buildings, but marine boilers are seldom employed apart from ships.

Water-tube boilers are mostly externally fired, and the tubes have the water on their insides instead of on their outsides, as in the tubular boiler. These water tubes have their ends connected to one or more water and steam cylinders, made like small cylindrical boilers. Water-tube boilers are made in a large variety of forms, but the same principles as to heating surface apply to all. The rule to find the heating surface of a water-tube boiler is: Multiply the circumference of one tube by the length of all of the tubes exposed to the flames or gases; multiply one-half of the circumference of the steam and water cylinder by its length, and this by the number of these cylinders, if there are more than one; add the products thus found and divide their sum by 144 to get the area of the heating surface in square feet.

Having in mind what the heating surface of a boiler really is, we are in a position to note the relation between heating surface and boiler capacity. Grate surface in any boiler furnace is obviously the area of the grate where the fuel is burned, and its amount in square feet is obtained by a simple multiplication of the length and width.

If boiler performance is to be obtained and stated in pounds of water evaporated from and at 212 degrees per hour or in heat units delivered to the contained water per hour, as is most convenient and accurate, it is desirable to know the average capacity of each square foot of heating surface in terms of heat transfer or evaporative effect per unit of time. The capacity of one square foot of boiler surface as to rate of heat transfer is necessarily a matter of observation and experience. No general result can be stated that applies with minute accuracy to every case, but an average capacity per square foot of heating surface in any well designed and constructed boiler has been found that makes efficient operation possible. This capacity is the evaporation of three pounds of water per hour from and at 212 degrees per square foot of heating surface, on an average. As 965.7 heat units are absorbed by the evaporation of one pound of water at 212 degrees to steam of the same temperature, which must be of atmospheric pressure, the evaporation of three pounds of water corresponds to a transfer from fire to water of 965.7 × 3 = 2,897.1 heat units hourly per square foot of heating surface. If not more than 0.3 pound of coal is burned in the boiler furnace per square foot of its heating surface per hour, a high efficiency is easily attainable with suitable draft and good firing, and the flue gases may be reduced in temperature to about 450 degrees. Thus, if coal develops 13,000 heat units per pound on perfect combustion, if 0.3 pound is burned hourly per square foot of heating surface, and if 2,897 heat units are transmitted to the water by each square foot of surface per hour, the boiler efficiency is 2,897 ÷ (13,000 × .3) = 74 per cent.

Of course, the allowance of one square foot of heating surface for each three pounds of water to be evaporated hourly does not ensure efficient operation, as too much or too little draft, or bad firing, may result in imperfect combustion of the fuel or in too great velocity of the gases. A greater allowance of heating surface than one square foot for each three pounds of water to be evaporated can effect but little gain in economy for power boilers, because their temperatures do not allow the gases to cool much below 450 degrees.

CHAPTER VII.

COMBUSTION OF FUELS AND BOILER EFFICIENCY.

The efficiency of a furnace and boiler is found when the heat imparted to water or steam from a certain amount of fuel is divided by the number representing the total amount of heat that this fuel can develop on perfect combustion. Perfect efficiency which is not attainable implies that complete combustion takes place with all the fuel used and that all the heat of this combustion is transferred to the water or steam of the boiler. One pound of pure carbon completely burned to carbonic acid yields 14,500 heat units. As one pound of water evaporated from and at 212 degrees absorbs 966 units of heat, the pound of pure carbon consumed with a furnace and boiler of perfect efficiency will evaporate 14,500 ÷ 966 = 15 pounds of water under these conditions. Experiments have shown that an efficiency of 80 per cent. is about the highest that can be reached with the best boilers and furnaces, so that an evaporation of 15 × .80 = 12 pounds of water from and at 212 degrees may be had per pound of pure carbon.

None of the ordinary fuels consist entirely of carbon, but coke contains about 90 per cent. of carbon and 10 per cent., sulphur, moisture and ash. One pound of good coke, therefore, when burned under a boiler of the highest efficiency, evaporates 12 × .90 = 10.8 pounds of water from and at 212 degrees. If the efficiency of the furnace and boiler is at the more common figure of 65 per cent., one pound of coke yields an evaporation, under the conditions named of 15 × .65 × .90 = 8.77 pounds of water.

If the combined efficiency of furnace and boiler drops to 50 per cent., the water that may be evaporated from and at 212 degrees by the combustion of one pound of coke is only 15 × .90 × .50 = 6.75 pounds. The weight of water evaporated with furnaces and boilers of various efficiencies when other fuels than coke are used may be readily calculated from the figures for the heating powers of these fuels per pound.

The combined efficiencies of furnaces and their boilers are less than unity, because of imperfect combustion of the fuels, excessive air supplies which reduce the temperatures of the gases, the escape of gases from the boiler surfaces at high temperature, the heat absorbed by the evaporation of water in the fuels, and the radiation and conduction of heat from the boiler, furnaces and settings.

As a boiler and its settings are much above the surrounding air in temperature while in operation, a constant loss of heat takes place from all their external surfaces. The extent of this heat loss varies with the extent to which the boiler covering or setting provides a good heat insulation, with the temperature of the boiler room and with the arrangement of the boilers. All losses of heat not otherwise accounted for are frequently charged to radiation and conduction from the exterior surfaces. This is only a rough way to determine the losses in question, as it covers up all errors from the analysis of the fuel to the temperature of the escaping chimney gases. The heat lost from the exterior surface of a boiler and its setting may be determined directly if a small portion of the grate surface is bricked off and provided with just enough fire to maintain steam at the desired or usual pressure, while none is drawn from the boiler. A record of the coal burned per hour to simply maintain the steam pressure while no steam is taken from the boiler represents the consumption due to losses from the exterior surfaces and settings. After the efficiency of the boiler has been determined the actual loss in heat units from its exterior surfaces can be found by means of the recorded consumption of coal to simply maintain the steam pressure. All water contained in the fuel necessarily reduces the combined efficiency of the furnace and boiler, because this water must be converted into steam and raised to the temperature of the fire. Coal and coke that is kept under cover often contains 3 to 5 per cent. of water by weight, and if exposed to the weather the proportion of water may rise to 10 per cent. or more. The loss of efficiency through the use of wet coal or coke may be serious, as the following figures show: In the case of coke containing 10 per cent. of moisture, and also 10 per cent. of ash, as before mentioned, the total heating power per pound on perfect combustion amounts to 14,500 × .80 = 11,600 units. To evaporate one pound of water in the coke from and at 212 degrees requires 966 heat units, and about 250 units per pound are necessary to raise the water to 212 degrees, and also the resulting steam to the temperature of the fire, a total of 1,216 units of heat. The 10 per cent. of moisture contained in one pound of this coke thus absorbs 121 ÷ 11,600 = about 10 per cent. of its heating capacity and lowers the efficiency by this figure.

If wet coal or coke is purchased there is thus a loss not only of the weight of fuel represented by the contained water, but also a further loss to evaporate this water. Aside from their contained steam, chimney gases represent two distinct kinds of losses—those due to the temperature of these gases, and those that result from incomplete combustion. In order to determine how much energy the chimney gases represent, it is thus necessary not only to take their temperature, but also to determine their composition by chemical analysis. Where bituminous coal is the fuel, its volatile portion is rapidly driven off as gas before its combustion, and if this gas escapes unburned a large portion of the total heating power of the coal is lost. If the combustible portion of the fuel used consists entirely of pure carbon, as is nearly the case for anthracite coal, as well as for coke, gas is formed only as the oxygen of the air unites with the carbon to form carbonic acid. One pound of carbon combines with two and two-thirds pounds of oxygen to form three and two-thirds pounds of carbonic acid gas. If the supply of air to the furnace is insufficient, the carbonic acid in contact with the incandescent solid carbon combines with an additional quantity of carbon to form carbonic oxide. The carbonic oxide contains carbon and oxygen in the proportion of two pounds of carbon to two and two-thirds pounds of oxygen; or, in other words, three and two-thirds pounds of carbonic acid unite with one pound of carbon to form four and two-thirds pounds of carbonic oxide. The space occupied by the three and two-thirds pounds of carbonic acid is just equal to the space required for the two and two-thirds pounds of oxygen that enters it; but when three and two-thirds pounds of carbonic acid unite with one pound of carbon to form four and two-thirds pounds of carbonic oxide, this oxide expands to twice the volume of the carbonic acid entering into it. One pound of carbon yields 14,500 heat units when it unites with two and two-thirds pounds of oxygen to form carbonic acid, and this is the maximum heating effect that can be got by the combustion of carbon. If, owing to an insufficient supply of air, the carbonic acid unites with a weight of carbon equal to that which it already contains, carbonic acid is formed, in which one pound of carbon is combined with one and one-third pounds of oxygen, and the heat resulting from this combination is only 4,400 units per pound of carbon. It thus appears that if carbonic oxide instead of carbonic acid is the final result of the combustion of carbon, the heat obtained per pound of carbon is less than one-third as great as that available where carbonic acid is the ultimate product.

This difference in heating effects is due to the absorption of energy to expand the gas and convert double the weight of carbon from a solid to a vapor per unit of oxygen consumed in the case of carbonic oxide. If sufficient air is supplied to carbonic oxide, two and one-third pounds of this gas, or the amount containing one pound of carbon, unites with one and one-third pounds of oxygen to form three and two-thirds pounds of carbonic acid, the original product of the combustion. The two and one-third pounds of carbonic oxide on combustion with one and one-third pounds of oxygen yield 10,100 heat units, which, added to the 4,400 heat units liberated by the formation of the two and one-third pounds of carbonic oxide, gives the total heat per pound of carbon consumed as 14,500 units, as before. From the foregoing facts it is evident that complete combustion of the carbon in fuel is of the highest importance for boiler economy. This complete combustion can only be had with an ample supply of air to yield the necessary oxygen. Experience has shown that complete combustion cannot be attained with an air supply that contains only the amount of oxygen actually combining with the carbon burned. It is therefore the practice to admit more air to furnaces than that containing the weight of oxygen to be combined with the carbon of the necessary fuel. This practice may easily be carried too far, however, because all of the air admitted to the fire necessarily lowers the resulting temperature of the gases of combustion, and thus reduces the amount of heat that the boiler surfaces can extract from them. The best practice as to air supply must therefore admit to the fuel just enough air to ensure complete combustion, but no more.

Thus far fuel that consists almost entirely of pure carbon as to its combustible portion has been considered. Anthracite coal contains 3 to 5 per cent. of volatile matter, and this ratio increases through the semi-anthracite, semi-bituminous and bituminous coals up to 40 per cent. or more. This volatile matter consists of compounds composed of carbon, hydrogen and oxygen. These compounds go under the general name of hydrocarbons, and must pass into the gaseous state before they are burned. Where oxygen and hydrogen exist together in a fuel they unite to form steam under the influence of combustion in the proportion of one pound of hydrogen to eight pounds of oxygen up to the point where the supply of either oxygen or hydrogen in the fuel is exhausted. This union of oxygen and hydrogen to form water or steam liberates no heat energy, but each pound of the steam thus formed absorbs about 1,216 heat units from the fire to raise its temperature and supply latent heat. The carbon of the volatile compounds has an equal heating value per pound with that in the solid portion of the fuel. After the oxygen of the volatile compounds has been consumed by combination with their hydrogen to form steam, the remaining hydrogen is available for fuel. One pound of hydrogen, when burned by combination with eight pounds of oxygen, yields 62,032 units of heat, or more than four times the heat that can be generated by the combustion of one pound of carbon. Hydrogen is thus a most energetic fuel, but unless suitable precautions are taken in the use of bituminous coal a large part of the volatile compounds containing the hydrogen escape unburned.

This tendency for the volatile portion of semi-bituminous and bituminous coals to escape to the chimney before combustion can take place is due to the fact that they are converted into the gaseous form at comparatively low temperatures, are often cooled below the point of combustion by mixture with cold air in the furnace, and that the air supply is at times insufficient to furnish oxygen as fast as it is necessary. To avoid the loss of boiler efficiency from the causes just named, the air should be heated before it is supplied to the funrace, and its quantity should be ample for the desired combustion. Moreover, the furnace, where coal with a large percentage of volatile matter is to be burned, should have an arch of firebrick a short distance above the grate in order to make sure that the gases will not fall below the temperature of combustion until after they are burned.

Complete combustion of the fuel is the office of the boiler furnace, while it is the purpose of the boiler surfaces to extract from the gases as much as possible of the heat thus generated. The temperature of the surfaces of a boiler are fairly constant for any given steam pressure, providing the supply of feed water is regular, but the temperature of the gases of combustion is a very variable quantity. Obviously, as the gases pass over the boiler surfaces and give up heat, their temperature is reduced. It has been found in practice that it is not wise to carry this reduction of temperature for the gases much nearer than 150 degrees to that of the steam in the boiler, because of the great extension of boiler surface necessary, due to the slow passage of heat from the gases to the water of the boiler when they are near the same temperature.

The temperature of steam at 100 pounds gauge pressure is 337 degrees, so that the temperature of the gases of combustion cannot well be reduced much below 150 + 337, or about 500 degrees, before they leave the surfaces of a boiler operated at this pressure. With compound engines a steam pressure of 150 pounds gauge may well be used, corresponding to a temperature for the steam of 365 degrees, and leaving the lowest desirable temperature of gases from the boiler surfaces at a little more than 500 degrees. Where a boiler is operated at a low pressure, say, of five pounds, for steam heating, corresponding to a temperature of 227 degrees, or for hot water heating at a temperature of 212 degrees, the gases may well be reduced to a temperature of 375 degrees befor leaving the boiler surfaces.

Taking 500 degrees as about the average temperature of gases escaping from boilers used for steam power purposes, it is evident that, excluding the factor of direct radiation from the bed of fuel on the grate, the heat derived by the boiler from its fuel is measured by the fall in the temperature of its gases from the time they leave the furnace until they escape to the chimney. The greater this fall of temperature the higher will be the efficiency of the boiler, other factors being constant. Before the fall in the temperature of gases can be determined the temperature at which they leave the furnace must be known. In order to determine the initial temperature of the furnace gases it is necessary to know the amount of air entering the furnace per unit of time, as well as the rate at which fuel is consumed and its quality.

Oxygen for the combustion of fuel necessarily comes from the air admitted to the furnace. As pointed out above, two and two-thirds pounds of oxygen are necessary for the complete combustion of one pound of carbon, and eight pounds of oxygen are required to burn one pound of hydrogen. Air is a mechanical mixture of 23 parts of oxygen and 77 parts of nitrogen by weight. It follows that to furnish eight pounds of oxygen to burn one pound of hydrogen the air that must be admitted to the furnace is found from $8 \div .23 = 34.78$ pounds. In like manner the weight of air, 2.66 pounds, necessary to furnish oxygen to burn one pound of carbon is found from $2.66 \div .23 \div 11.6$ pounds. It is evident that at least these proportions of air must be heated to the temperature of the furnace, as must also the fuel consumed. As a matter of practice, a much larger proportion of air is necessary.

As each pound of fuel supplies a definite number of heat units on complete combustion, independently of the amount of air mixed with the gases of combustion, the temperature of the mixture of gases and air evidently depends on the ratio between the weight of air and fuel supplied to the furnace. While it is desirable that the initial temperature of the gases of combustion in the furnace be at a point as high as is possible above their nearly fixed final temperature at the chimney, it is found in practice that to avoid the very serious losses incident to imperfect combustion the actual supply of air in any case must materially exceed in oxygen the chemical requirements of the fuel burned. It is therefore common practice to supply from one and one-half to twice the air to boiler furnaces that their actual consumption of oxygen in combustion with the fuel consumes. To determine the temperature of the products of combustion above that of the air, assuming all the heat to be absorbed by the gases, the total heat units liberated by burning one pound of the fuel should be divided by the sum of the products of each element in the furnace gases by its specific heat. The specific heats of the important gases concerned in combustion are as follows: At constant pressure, air, 0.237; oxygen, 0.217; hydrogen, 3.409; nitrogen, 0.243; steam, 0.475; carbonic acid, 0.217; carbonic oxide, 0.247. The maximum temperature of combustion is obviously attained when just enough air is admitted to the furnace to supply oxygen for the chemical combination. If pure carbon is the fuel used, one pound develops 14,500 heat units. For the perfect combustion of this carbon two and two-third pounds of oxygen are necessary, and this oxygen is contained in air weighing 11.6 pounds. Of this air 11.6 — 2.66 = 8.94 pounds appear as nitrogen in the products of combustion, the remainder of these products with the one pound of carbon being 3.66 pounds of carbonic acid. The multiplication of the weight of each of these gases by its specific heat yields the following results:

Nitrogen, 8.94 × 0.243 =................2.17
Carbonic acid, 3.66 × 0.217................0.79

2.96

Dividing the 14,500 heat units developed from the one pound of carbon by the quantity just found, shows the maximum temperature of combustion to be 14,500 ÷ 2.96 = 4,899 degrees above the temperature of the air and fuel supplied. No such temperature as this can be attained in regular practice, however, and the following figures, based on the admission of 24 pounds of air to the furnace for each pound of carbon burned, are given to represent ordinary results where the gases absorb all of the heat. In this case the figures just found for free nitrogen and carbonic acid remain good, and to them must be added the value for 24 — 11.6 = 12.4 pounds of air. As the specific heat of air is 0.237, the quantity that must be added to the above divisor of the total heat combustion is 12.4 × 0.237 = 2.94, making the divisor for the present case 2.94 + 2.90 = 5.90. The total heat of combustion divided by this last quantity yields 14,500 ÷ 5.90 = 2,457 as the temperature in degrees Fahrenheit of the products of combustion above that of the air. To represent about what might be done in the best practice if the entire heat of combustion went into the gases the following results are computed on the basis of 18 pounds of air admitted to the furnace for each pound of carbon completely burned. In this case 11.6 pounds of air will be separated into oxygen and nitrogen in order to effect the combustion as above, leaving 18 — 11.6 = 6.4 pounds of air to be heated to the temperature of the fire. The weight of this air multiplied by its specific heat amounts to 6.4 × 0.237 = 1.517, which, added to the figure of 2.96 for the free nitrogen and carbonic acid, gives 2.96 + 1.52 = 4.48 as the divisor for the total heat of combustion. The result of this division is 14,500 ÷ 4.48 = 3,236, representing the initial temperature of the gases of combustion in degrees Fahrenheit above that of the air. Taking, then, 3,000 degrees above the air as about the highest initial temperature to be attained in the products of combustion, and 500 degrees above the air as their temperature when they leave the boiler surfaces, the difference, or 3,000 — 500 = 2,500 degrees, indicates the portion of the heat imparted to them that the gases give up to the boiler. If the gases yield their heat in the same ratio that they cool, which is practically true, the fall of temperature from 3,000 to 500 degrees above that of the air corresponds to an extraction of 2,500 ÷ 3,000 = .83 per cent. of the heat that has been imparted to them.

If the total heat of combustion is absorbed by the resulting gases, as has thus far been assumed, the figure of .83 per cent. might represent the boiler efficiency, but this cannot be the case, for two reasons. In no case can all the heat of combustion be absorbed by the gases of combustion, because some of it is absorbed by the ashes and more is lost by radiation from the boiler and furnace. Aside from these losses, a large amount of heat, with many forms of boiler setting, passes directly from the bed of incandescent fuel to the boiler by radiation, and cannot therefore be included in the heat absorbed by the gases of combustion. No satisfactory general rule can be laid down for the proportion of the heat of combustion that passes from the fuel in the furnace to the boiler by direct radiation. In a furnace where the fuel is surrounded on all sides above the grate by firebricks, radiation from the fuel to the boiler, which can only take place on straight lines, is not possible. In this case, therefore, the total amount of heat imparted to the boiler is measured by the fall of the temperature of the gases while they are passing over its surfaces.

For the more common case, where the fuel is surrounded in part by the heating surfaces of the boiler, from two-tenths to four-tenths of the total heat generated by the fuel will pass by direct radiation to the boiler surfaces. Applying suitable figures for losses of heat in the ashes and from boiler settings, it is possible to determine an approximate figure for the maximum initial temperature of the gases, where a part of the boiler surfaces surround the fuel. If a large per cent. of the boiler surface is included in the firebox about the bed of fuel, as in the locomotive type of boiler, a relatively large portion of the total heat of combustion will pass to the boiler surfaces by direct radiation, other things being equal. If, on the other hand, the amount of surface that direct radiation from the fire can reach is relatively small, comparatively little heat will pass to the boiler in this way. Other factors remaining constant, thick fires lower the per cent. of total heat passing to the boiler surfaces by direct radiation, while thin fires increase this per cent., because of the greater radiating surface the fuel offers in proportion to the amount consumed. As a medium figure, 0.3 may be taken as that portion of the total heat developed that passes to the boiler by direct radiation. For the loss of heat in the ashes and from the boiler setting 10 per cent. of the total may be assumed.

With these figures as a basis, the heat remaining to be absorbed by the gases is 100 — 30 — 10 = 60 per cent. of the total amount resulting from combustion. Considering one pound of pure carbon, as before, the heat now available for the gases of combustion is 14,500 × .6 = 8,700 units. Taking the case where 18 pounds of air is supplied to the furnace for each pound of carbon burned, it was found above that the amount of heat available for the gases must be divided by the factor 4.48 to determine the initial temperature of the products of combustion. This division shows that the temperature of the gases will be 8,700 ÷ 4.48 = 1,942 degrees Fahrenheit above that of the air and fuel supplied to the furnace. If now the gases of combustion leave the boiler at a temperature of 500 degrees above that of the outside air, as might well be the case with the outside air at zero temperature, the portion of their contained heat given by the gases to the boiler surfaces is (1,942 — 500) ÷ 1,942 = 74 per cent. As only 60 per cent. of the total heat produced by the combustion of the pound of carbon is imparted to the gases in this case, these gases deliver to the boiler .60 × 74 = 44 per cent. of this total. It was assumed at the start that 30 per cent. of the total heat of combustion went to the boiler as direct radiation, so the efficiency of the boiler and furnace for the present case is the sum of .44 + .30 = 74 per cent. The loss of 26 per cent. is divided between those by radiation from the setting and those in the escaping gases. Ten per cent. was allowed at the start for loss of heat by radiation and in the ashes. The portion that may be lost with the flue gases is therefore 26 — 10 = 16 per cent. This last figure may be arrived at by considering that the gases absorb as a total only 60 per cent. of the heat of combustion, and 26 per cent. of this amount escapes to the chimney, so that the chimney loss of heat must be 26 × .60 = 15.6 per cent.

This efficiency figure for the boiler and furnace, namely, 74 per cent., has been obtained on the assumption that the pound of carbon considered is perfectly burned, but it is hard to obtain perfect combustion of all the fuel in even the best furnaces, so that the figure for efficiency is often lowered 3 to 5 per cent. because the fuel is not completely burned. In order to raise the efficiency in this case from 74 to 80 per cent., or about the highest figure it has thus far been practicable to obtain, the loss by radiation from the boiler and furnace settings must be reduced a little by better heat insulation on these parts. It will also be necessary either to reduce still further the amount of air admitted to the furnace per pound of fuel without causing imperfect combustion, or else to increase the heat extracted from the gases of combustion, as may be done by means of an economizer.

The fuel thus far considered has been assumed to consist, as to its combustible portion, of pure carbon, as is true for coke, and nearly so for the best grades of anthracite coal. Semi-bituminous coal is much more generally used than anthracite for the furnaces of power boilers, and the results obtained with the former fuel differ somewhat from those had with coke and anthracite coal. Take, for example, a dry coal of which the combustible portion contains 82 parts carbon, 10 parts hydrogen and 8 parts oxygen. Under the influence of combustion all the oxygen in this fuel will unite with enough hydrogen to form water. As water consists of 8 parts by weight of oxygen to 1 of hydrogen, the loss of hydrogen in this case will be .08 ÷ 8 = .01 pound, and the hydrogen remaining for combustion is .09 pound. The heating power of this pound of combustible is thus for the carbon 14,500 × .82 = 11,890 units, and for the hydrogen 62,032 × .09 =

5,582 units, a total of 17,472 heat units. The oxygen that must be supplied from the air for the combustion of this fuel is for the carbon 2.66 × .82 = 2.18 pounds, and for the hydrogen 8.0 × .09 = 0.72 pounds, making the total weight of oxygen = 2.90 pounds. As air contains 23 per cent. of oxygen by weight, the amount of air necessary to supply just enough oxygen for the chemical combustion in this case is 2.9 ÷ .23 = 12.6 pounds. Of this air 12.6 — 2.9 = 9.7 pounds is reduced to free nitrogen by the combustion. With good management of the furnace, perfect combustion may be effected by the use of 50 per cent. more air than that necessary to supply oxygen, so that the total air entering the furnace in this case per pound of combustible may be 12.6 × 1.5 = 18.9 pounds. The free air to be raised to the temperature of the products of combustion in this case is thus 6.3 pounds. For each pound of combustible the weight of water formed by the contained oxygen and hydrogen is 0.08 + 0.01 = 0.09 pound, and to this should be added the weight of the hydrogen burnt with oxygen from the air, the total is 0.09 + (8 × .09) = 0.81 pound of steam. To determine the temperature of the products of combustion the weight of air, carbonic acid, nitrogen and steam must each be multiplied by its specific heat, and then the sum of these products used as a divisor for that part of the total heat of combustion that is available for absorption by the gases. The weight of carbonic acid for this case is 0.82 + 2.18 = 3.00 pounds, and the product by its specific heat 3 × .217 = .651; for air the product is 6.3 × .238 = 1.499; for the nitrogen 9.7 × .245 = 2.436; for the steam 0.81 + .48 = 0.388, making a total divisor of 3.974. The total heating capacity for this pound of combustible was found above to be 17,472 heat units, and of this 10 per cent. may be allowed for loss by radiation from the boiler and furnace setting and 30 per cent. for transfer to the boiler by direct radiation. There remain 17,472 × .60 = 10,483 heat units for absorption by the products of combustion. Dividing this last number by the factor 3.97, above found, yields 10,483 ÷ 3.97 = 2,643, representing the initial temperature of the products of combustion above that of the outside air in degrees Fahrenheit. If these gases are cooled by the boiler to 500 degrees above outside air, they represent a loss of 500 ÷ 2,643 = 19 per cent. of the heat imparted to them.

CHAPTER VIII.

HEATING POWERS OF FUELS.

The heating power of the fuel consumed in any case must be known before the efficiency of the boiler with which it is used can be determined. Coal or other fuel may have its heating value per unit of weight determined by chemical analysis or by combustion in a calorimeter. The practical heating value of any fuel may obviously be found by actual trial of it with a boiler, but such a trial shows only the result that may be attained with the particular boiler used, and cannot determine the boiler efficiency unless the total heating value of the fuel is previously known.

A chemical analysis of coal shows the relative proportions of carbon, hydrogen, oxygen, water and ash that it contains. The extent to which the carbon and hydrogen yield heat per unit of weight on perfect combustion is known, and the heating value of a pound of coal containing certain portions of these elements is thus easily calculated. Water and ash, of course, contribute nothing to the heat that may be derived from coal.

A formula may be readily constructed to give the heating value of a certain coal per pound when the chemical analysis of the coal is known. Such a formula expresses what is known as Dulong's law, and is: Heat units $= 14{,}500\,C + 62{,}000\left(H - \frac{O}{8}\right)$, in which C stands for the fraction of a pound of carbon, H the fraction of a pound of hydrogen and O the fraction of a pound of oxygen found in one pound of coal. The numbers 14,500 and 62,000 represent the heat units liberated by the complete combustion of one pound of carbon and of one pound of hydrogen, respectively, as determined by experiment.

A calorimeter consists essentially of a closed iron vessel, adapted to receive a quantity of fuel and oxygen and immersed in a known quantity of water. The fuel whose heating value is to be determined is represented by a small sample of known weight that is placed in the closed vessel. Oxygen gas in this vessel is usually at a pressure of twenty or more atmospheres, and the sample of fuel is burned explosively on ignition by an electric spark. The excess of oxygen present in the closed vessel makes complete combustion certain, and the entire amount of heat liberated is absorbed by the vessel itself and by the surrounding water. As the rise of temperature in the vessel and water are accurately noted, the heat units liberated by the combustion of the known weight of fuel are readily computed. This method of heat determination by the calorimeter is capable of great accuracy, and duplicate tests agree in their results to within less than one per cent. The heat yielded per unit weight of fuel on perfect combustion as determined from chemical analysis and by the calorimeter has been found to be the same in many cases to within less than 1 per cent. Most of the better known varieties of coal have been tested so often that their heating values have become matters of record, and can be readily found when wanted. In order to indicate the range of variation and to show about what may be expected in heating value for the more common varieties of coal, the following figures have been selected from the results of a number of calorimeter tests reported by George H. Barrus, in Volume XIV. of the Transactions of the American Society of Mechanical Engineers:

Anthracite coal, 11 tests; percentage of ash, 9.1 to 10.5; total heat of combustion, 11,521 to 13,189 heat units per pound.

SEMI-BITUMINOUS COAL.

George's Creek, Cumberland, Md., 10 tests; ash, 6.1 to 8.6 per cent.; total heat of combustion, 12,874 to 14,217 heat units per pound.

Pocahontas, Va., 5 tests; ash, 3.2 to 6.2 per cent.; total heat of combustion, 13,608 to 13,922 heat units per pound.

New River, Va., 6 tests; ash, 3.5 to 5.7 per cent.; total heat of combustion, 13,858 to 13,922 heat units per pound.

Welsh, 1 test; ash, 7.7 per cent.; total heat of combustion, 12,182 heat units per pound.

BITUMINOUS COAL.

Yohoghany, Pa., lump ash, 5.9 per cent.; total heat of combustion, 12,941 heat units per pound.

Frontenac, Kansas, ash, 17.7 per cent.; total heat of combustion, 10,506 heat units per pound.

Cape Breton (Caledonia), ash, 8.7 per cent.; total heat of combustion, 12,420 heat units per pound of coal.

Lancashire, England, ash, 6.8 per cent.; total heat of combustion, 12,182 heat units per pound of coal.

With boilers and furnaces of perfect efficiency, the combustion of coal would be complete, and all of the generated heat would be transferred to the contained water and steam. It is interesting to note the evaporation of water per pound of coal that would be possible under such perfect conditions. Take first the case of the anthracite coal given above, having a heating power of 13,189 heat units per pound. As 966 heat units are necessary to change one pound of water at a temperature of 212 degrees to steam at atmospheric pressure, the total heat of combustion for one pound of this anthracite coal is sufficient to evaporate 13,189 ÷ 966 = 13.6 pounds of water from and at 212 degrees.

With a furnace and boiler of 80 per cent. efficiency, about the highest figure attainable in practice, the anthracite coal just mentioned will evaporate 13.6 × .80 = 10.88 pounds of water from and at 212 degrees per pound of the coal burned.

Taking the best result with semi-bituminous coal—that is, 14,217 heat units per pound—it appears that 14,217 ÷ 966 = 14.7 pounds of water may be evaporated from and at 212 degrees by its total heating value per pound. A boiler and furnace of 80 per cent. efficiency with this coal would be able to evaporate 14.7 × .80 = 11.76 pounds of water from and at 212 degrees per pound of the coal consumed.

The bituminous coals named in this test have lower heating powers than those used in the computations just made, so that the possible evaporation with any of them would obviously be smaller.

An essential difference between anthracite, semi-bituminous and bituminous coals is found in the percentage of fixed carbon and volatile matter in each of these varieties. Anthracite coal contains a larger per cent. of fixed carbon and a smaller per cent. of volatile matter than any of the other varieties. In Volume XIV. of the Transactions of American Institute of Mechanical Engineers, a report is given of the analysis of over thirty samples of anthracite coal, each taken from lots of 100 to 200 tons, as sent to market. These samples were all from the coal fields of Pennsylvania, being divided between the Northern field, near Wilkesbarre; the Eastern Middle, or Lehigh; the Western Middle, near Shenandoah, and the Southern field, from Mauch Chunk to Tamaqua. The following table gives the results of some of these analyses for coals of all sizes mixed together:

		Percentage of						
Name of bed.	Name of field.	Water.	Volatile matter.	Fixed carbon.	Ash.	Sulphur.	Volatile matter of total combustible.	Ratio of fixed carbon to volatile matter.
Wharton	East Middle	3.71	3.08	86.40	6.22	0.58	3.44	28.07
Mammoth	East Middle	4.12	3.08	86.38	5.92	.49	3.45	27.99
Primrose	West Middle	3.54	3.72	81.59	10.65	.50	4.36	21.93
Mammoth	West Middle	3.16	3.72	81.14	11.08	.90	4.38	21.83
Buck Mountain	West Middle	3.04	4.13	87.98	4.38	.50	4.48	21.32
Primrose F.	Southern	3.01	3.95	82.66	9.88	.46	4.56	20.93
Seven Foot	Southern	3.41	3.98	80.87	11.23	.51	4.69	20.32
Mammoth	Southern	3.09	4.28	83.81	8.18	.64	4.85	19.62
Mammoth	Northern	3.42	4.38	83.27	8.20	.73	5.00	19.00

As the size of coal grows smaller, the relative amount of contained ash increases. Analyses of several sizes from one mine covered by the above tests gave the results of the following table:

	Screened.		Analyses.	
Size.	Through.	Over.	Fixed carbon.	Ash.
Egg coal	2.5 ins.	1.75 ins.	88.49	5.66
Stove coal	1.75 "	1.25 "	83.67	10.17
Chestnut coal	1.25 "	.75 "	80.72	12.67
Pea coal	.75 "	.50 "	79.05	14.66
Buckwheat coal	.50 "	.25 "	76.92	16.62

These figures plainly show that the fuel value of coal from any given mine decreases with the size of the lumps, since the per cent. of fixed carbon is less and the per cent. of ash greater in the smaller coals.

What are known as the semi-anthracite, semi-bituminous and the bituminous coals.differ from anthracite mainly as to the relative amounts of volatile matter and fixed carbon in each. Just where the lines should be drawn to separate the several varieties is a matter of some difference of opinion, but it is not of great importance as long as the composition of the coal used in any particular case is known.

The sixth volume of the Transactions A. I. M. E., page 430, contains the results of test by Rogers on anthracite, semi-anthracite and semi-bituminous coals, as follows: Sixteen analyses of hard, dry anthracites give fixed carbon a range of 82.47 to 94.10 per cent.; volatile matter, 1.40 to 9.53 per cent., and 4.50 to 8.00 per cent. of ash, water and impurities. The ratio of these tests for carbon to volatile matter thus range from 8.64 to 67.02. For semi-anthracite coal twelve tests gave a range of 74.55 to 90.23 per cent. for fixed carbon, 7.07 to 13.75 per cent. for volatile matter, and for water, impurities and ash, 2.20 to 12.10 per cent. Here the ratio of fixed carbon to volatile matter is 5.41 to 12.75. With ten analyses of semi-bituminous coals the per cent. of fixed carbon ranged from 68.41 to 84.80, of volatile matter 11.2 to 17.28, and for impurities, water and ash 4 to 13.99.

In this last case the ratio of fixed carbon to volatile matter goes from 3.96 to 11.41. Following are given the results of several analyses selected from about fifty in the reports of the Pennsylvania Geological Survey. The figures here given all relate to bituminous coals, as may be seen from the low ratio of fixed carbon to volatile matter: Green county coal, five analyses, fixed carbon, 59.72 per cent.; volatile matter, 40.28 per cent.; ratio carbon to volatile matter, 1.48. Washington county coal, five analyses, fixed carbon, 53.22 per cent.; volatile matter, 46.78 per cent.; carbon ratio to volatile matter, 1.13. Lower Bench, Washington county coal, five analyses, fixed carbon, 50.97 per cent.; volatile matter, 49.03 per cent.; ratio of fixed carbon to volatile matter, 1.04. Jefferson county, Ohio coal, fixed carbon, 61.45 per cent.; volatile matter, 38.55 per cent.; ratio fixed carbon to volatile matter, 1.59.

The figures given from the report last named take no account of the water, ash and impurities in the coal tested, but have been reduced so as to include the combustible portion only. The differences as to contained fixed carbon and volatile matter in coals are of particular importance because of the marked effect on practical heating results, due to variations in the proportions of these elements. With ordinary boilers and furnaces the practical heating value of bituminous coal is much lower than its actual heating value on perfect combustion. This difference is due to the fact that boilers and furnaces, unless especially fitted for the use of bituminous coal, have a decidedly lower efficiency with it than they show when hard anthracite coal is employed. The volatile portion of the bituminous coal is rapidly distilled as gas after the coal is put into a furnace, and this gas is very apt to escape to the chimney unburned. With anthracite coal containing as much as 96 per cent. of the combustible portion in the form of fixed carbon, the boiler efficiency may be as high as 80 per cent. In the best of the grades of coal that have not more than 80 per cent. of fixed carbon, such as Cumberland, it is hard to obtain an efficiency of more than 75 per cent. Where the fixed carbon in coal is as low as 60 per cent., a boiler efficiency of 65 per cent. is seldom exceeded. In the use of coals having little more than 50 per cent. of fixed carbon, the boiler efficiency is most often below 60 per cent.

The rapid falling off in efficiency with an increase in the volatile portion of coals is due not only to the escape of the gases distilled from the coal before they have been burned, but also to the thick deposits of soot that form rapidly on many parts of the boiler heating surfaces where these coals are used.

With coals that contain less than 20 per cent. of volatile matter almost any of the ordinary types of boiler furnaces will give good results if properly proportioned and fired. Where 20 to 40 per cent. of volatile matter is present in the coal, a good form of furnace includes plain grate bars and a rather low arch of firebrick over them, so as to keep the temperature of the combustion chamber at a point sufficiently high to ignite the gases distilled from the coal. If the coal contains more than 40 per cent. of volatile matter, the furnace should have a large combustion chamber surrounded by firebrick to maintain the highest possible temperature.

In connection with this last mentioned furnace, the air necessary for combustion should be raised to a high temperature before it is introduced to the furnace. The best equipment for the use of coal high in volatile matter includes a gas producer, so that the coal gases as well as the air may be brought to a high temperature before their admission to the combustion chamber. The ordinary kind of boiler furnace, where the boiler surfaces are directly above the grate bars and receive the radiant heat of the fire, is especially to be avoided with coals that contain 20 per cent. or more of volatile matter, because the combustion chamber thus formed is sure to have a rather low temperature. A down draft that forces the distilled gases through the bed of coal on the grate, also the feeding of new coal underneath that already on the grate, has been found to increase efficiency where volatile matter is present in large amounts.

While coal is the most important single fuel, there are others that find extensive use in some parts of the country. At particular points certain fuels, such as wood, natural gas and petroleum, may be cheaper than coal for a given heating effect, and are there naturally used on the score of economy. In many large cities there are serious and growing objections to the extensive use of coal. For anthracite coal the most important objection to its use in large buildings and manufacturing plants is that of cost, which is frequently 50 to 100 per cent. greater than that of bituminous coal of equal heating capacity. Bituminous coal, though cheap in price, meets with serious objection for city use because of the smoke resulting from its combustion, so that it is prohibited in some places. Another important hindrance to the use of bituminous coal is found in the fact that efficient combustion with it can only be had in certain special forms of furnace. A further disadvantage that applies to both sorts of coal for most large city plants is found in the expense of hauling coal and in the removal of ashes by teams. Some of the undesirable features of coal are avoided by other kinds of fuel to a greater or less extent.

COKE.

Considered as to first cost, general desirability and the extent of its use, coke ranks next to coal in fuel importance. Coke is made from bituminous coal, either by partial combustion in ovens or by distillation in retorts. The oven coke is generally more desirable for fuel purposes than that made in retorts at gas works. Dry coke varies in composition with the coal from which it is made, as to the proportions of its ingredients, but average figures may be taken as 90 per cent. carbon, 9 per cent. ash and 1 per cent. sulphur. It may be noted from this that the composition of good coke differs but little from that of the best grades of anthracite coal. In the process of coke making the volatile portions of the bituminous coal used are driven off as gas or consumed. The reduction in weight from the coal to the coke by this process is 30 to 40 per cent., leaving 60 to 70 per cent. of the weight of the coal used as coke. The fuel value of coke depends on its contained carbon, and taking this at 90 per cent. of the total weight, one pound of coke on perfect combustion develops $14{,}500 \times .9 = 13{,}050$ heat units, since the heating power of one pound of pure carbon is 14,500 heat units. As the fuel value of coke is thus about the same as that of anthracite coal, and as its price is usually between the prices of bituminous and anthracite, it forms a desirable substitute for these coals in some cases on the score of either greater economy or more desirable qualities. Unlike bituminous coal, coke requires no special form of furnace for its satisfactory combustion, and is as free from smoke as the best anthracite coal. At present gas retorts furnish most of the coke available in cities for general use, but there seems to be a movement toward the substitution of ovens for retorts in gas making.

ILLUMINATING GAS.

Another product from coal that may serve as fuel in some cases is illuminating gas, but it is only available in special cases or where the item of cost is of minor importance. The value of illuminating gas as a fuel is approximately 650 heat units per cubic foot on perfect combustion, so that 1,000 cubic feet of gas yields 650,000 heat units. As one dollar is about the lowest current price for illuminating gas per 1,000 feet, the 650,000 heat units may be taken as the heat available from gas for that sum. If anthracite coal costs five dollars per ton, 400 pounds may be obtained for one dollar, and allowing 13,000 heat units per pound for this coal, the total heating value is 13,000 × 400 = 5,200,000 units. Under these conditions, therefore, the gas is 5,200,000 ÷ 650,000 = 8 times as expensive as anthracite coal.

NATURAL GAS.

In some parts of the country where natural gas is abundant it may and does displace coal as fuel to some extent. The heating power of natural gas is much greater than that of coal gas, and may be fairly taken at 1,000 heat units per cubic foot on an average, so that 1,000 cubic feet yield 1,000,000 units of heat. Comparing natural gas with anthracite coal at five dollars per ton, in which one dollar purchases a heating power of 5,200,000 units, it appears that 5,200,000 ÷ 1,000,000 = 5.2 times 1,000 cubic feet of natural gas must be supplied to obtain as much heat as may be had from coal costing one dollar. Natural gas must therefore sell for 100 ÷ 5.2 = 19.2 cents per 1,000 cubic feet to be equally cheap with anthracite coal for fuel. The absence of smoke and ashes, also the saving of labor, where natural gas is available raise the price at which it really competes with coal somewhat above the figure just found.

WOOD AS FUEL.

Wood continues to be an important fuel for even large establishments in many parts of the United States. Different varieties of wood vary widely as to their heating powers, so that the number of cubic feet or cords alone is no definite indication of the heat that may be obtained from it. The heating power of wood varies in very nearly the same proportion as its weight when it is perfectly dry. Average weights for perfectly dry wood are: White pine, 25 pounds; white oak, 48 pounds; maple, 50 pounds; red oak 40 pounds per cubic foot. One cord of wood occupies a space of 128 cubic feet, but a greater or less portion of this space is actually filled by the wood, according to the size and straightness of the sticks. An average figure for the number of cubic feet of solid wood in one cord is 60. On this basis a cord of maple, perfectly dry, weighs 50 × 60 = 3,000 pounds. Perfectly dry wood is only obtained by some artificial process of drying, and air dried wood contains 20 to 25 per cent. of water at best. It follows that a cord of maple wood, as dry as it can be got in the open air, weighs about 4,000 pounds. Perfectly dry wood of most varieties is nearly uniform in chemical composition, except that some pine wood has more than the usual proportion of hydrogen. Average figures for the composition of wood are:

Carbon, 50; oxygen, 42; hydrogen, 6; nitrogen, 1, and ash, 1 per cent. The nitrogen and ash have no fuel value, and if the figures for the other elements are substituted in Dulong's formula, the result is $(14{,}500)\ .5 + 62{,}000 \left(.06 - \frac{.42}{8}\right) = 7{,}715$ heat units. In the case of air-dried wood having 20 per cent. of water, the heat units per pound are reduced to 7,715 × .8 = 5,929. Even this amount of heat cannot be realized for any useful purpose, because the water in the wood must be evaporated on combustion. It may be assumed that 150 heat units are necessary to raise the temperature of one pound of water in the wood from that of the air to 212 degrees. To evaporate one pound of water at 212 degrees requires 966 heat units, and about 100 more units of heat are necessary to bring the temperature of one pound of steam up to that of the fire, making a total of 1,216 heat units per pound of water in the wood. If each pound of air-dried wood contains 20 per cent. of water, 1,216 × .2 = 243.2 heat units must be expended in its water when the wood is burned, leaving 5,929 — 243 = 5,686 heat units per pound of maple wood for useful purposes.

Allowing anthracite coal a heating power of 13,000 units per pound, it appears that one pound of maple wood will develop 5,686 ÷ 13,000 = 43 per cent. of the heat that may be had from a pound of this coal. As one cord of this wood weighs 4,000 pounds, or two tons, the wood is equivalent to .43 × 2 = 86 per cent. of a ton of the coal in heating power. If the ton of coal costs five dollars, the maple wood will be equally cheap as fuel when it costs $5 × .86 = 4.30 dollars per cord. Hickory has fully as much heating power per cord as maple, white oak has a little less, and white pine only one-half. Wet and green wood may weigh as much as 50 per cent. more than that which is perfectly dry, but the additional water causes a material loss in the available heating power in a given bulk of the wood, because this water must be evaporated when the wood is burned. A furnace for wood should be larger than one for coal to obtain a given heating effect, because of the greater bulk of the former, but no other special features are necessary. With good draft wood burns without much smoke, and the volume of ash is relatively small, so that it is a desirable fuel in these respects.

CHARCOAL.

Charcoal holds something the same relation to wood that coke does to coal; that is, charcoal is the residue, mainly of carbon, left by the partial combustion of wood under conditions where the air is in large part excluded, or by heating wood in closed retorts. With air-dried wood heated to produce charcoal, the weight of the product is two to three-tenths of that of the wood consumed, according to the process employed. Charcoal, as it comes from the furnace, is almost perfectly dry, but it absorbs water rapidly from the air, and its proportion of moisture rises to as much as 10 per cent. after a few days. The compositon of charcoal ordinarily sold may be taken at 85 per cent. carbon, 10 per cent. water, 4 per cent. ash and 1 per cent. hydrogen. As the heating power of carbon is 14,500 units per pound, one pound of ordinary charcoal may be expected to yield $14{,}500 \times .85 = 12{,}325$ heat units on combustion, or 95 per cent. of the heat from one pound of good anthracite coal. It follows that about 2,100 pounds of charcoal will furnish as much heat as one ton of anthracite coal. Charcoal is commonly sold by the bushel, and the weight of this volume is about 15 to 30 pounds, according to the kind of wood from which the charcoal is made. For oak and maple charcoal the weight is about 30 pounds per bushel, so that 2,100 ÷ 30 = 70 bushels are required to equal in heating capacity one ton of good anthracite coal. Because of its small per cent. of ash and freedom from smoke when burning, charcoal is a very desirable fuel, but its price is such that it cannot compete with coal for general use, except in a few localities. Charcoal has, however, an extensive application for special heating purposes, and competes with gas as a fuel for cooking in hot weather. Peat, as well as wood, can be used in the production of charcoal, but wood is much more generally employed for the purpose in the United States.

PEAT.

Peat is extensively used for fuel in some parts of Europe, but has as yet been little applied in the United States. Large deposits of peat are known to exist here, however, and a moderate increase in the average price of coal would probably give them importance as fuel. Peat, after being removed from its natural beds and air-dried, contains about 25 per cent. of water. Perfectly dry peat contains in 100 parts by weight about 58 parts of carbon, 6 parts of hydrogen, 30 parts of oxygen and 6 parts of ash. Applying Dulong's formula to this composition, gives the heating power of one pound of perfectly dry peat as $.58 (14{,}500) + 62{,}000 \left(.06 - \frac{.30}{8}\right) = 9{,}805$ heat units. Where the peat is air-dried and contains 25 per cent. of moisture, the heating power per pound drops to $9{,}805 \times .75 = 7{,}353$ heat units. To evaporate one pound of water from the peat will require, as in the case of wood, about 1,216 heat units, so that the one-fourth pound of water in one pound of air-dried peat absorbs 1,216 ÷ 4 = 304 heat units on combustion. The net available heat per pound of peat is thus 7,353 — 304 = 7,049 heat units, or about 7,049 ÷ 1,300 = 54 per cent. of that for anthracite coal.

PETROLEUM.

Petroleum is sufficiently abundant to be used as fuel to some extent, and it is very desirable for this purpose, as to the absence of smoke and ashes. The approximate chemical composition of 100 parts of petroleum is 85 parts carbon, 13 parts hydrogen and 2 parts oxygen. These values substituted in Dulong's formula give the heating power of one pound of crude petroleum as $.85\ (14{,}500 + 62{,}000\ (.13 - \frac{,02}{8}) = 20{,}230$ heat units. Petroleum is usually quoted by the gallon, of which the average weight is about 6.7 pounds. The heating power per gallon is therefore 20,230 × 6.7 = 135,541 heat units, so that the gallons to equal one ton of anthracite coal in heating power are found from (13,000 × 2,000) ÷ 135,541 = 192. To equal anthracite coal in cost per unit of heating power, when the coal is worth five dollars per ton, the petroleum may therefore cost 500 ÷ 192 = 2.6 cents. per gallon. Compared with coal, petroleum offers some saving in the cost of firing, but in spite of this and its other desirable features, its price is usually such as to prohibit its use for fuel, aside from some special cases.

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