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The Efficiency of Furnaces.

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"Efficiency" may be considered in many various aspects. The most general meaning is the quality of accomplishing the desired purpose at the minimum cost. This is a very complex quantity, and must be discussed from the most general and varied standpoints. Again, one furnace accomplishes a certain work with one-half of the fuel which another furnace uses, and we can therefore speak of the first furnace being *relatively* twice as efficient as the second, as far as fuel consumption is concerned. But, besides relative efficiencies, there is such a thing as *absolute efficiency*, when speaking of thermal efficiency;—that is, the ratio of the net thermal effect produced to the heating power of the fuel.

We will take up the subject first as regards *Thermal Efficiency*, both absolute and relative, and conclude with a discussion of *Efficiency* in its most general meaning, as relates to minimum cost.

THERMAL EFFICIENCY.

A view of efficiency which in many cases leads to the most revolutionary ideas in practice, is to compare the actual net heating effect produced with the total heat used to produce it. To make a comparison, one steam boiler may be 50 per cent. more efficient than another, in regard to coal used per ton of water vaporized, and a third 20 per cent. still more efficient; yet when we learn that these three boilers only return 30, 45 and 54 per cent. of the heating power of the coal, as heat in dry steam, we realize that there is still considerable room for improvement. In short, comparisons of general efficiency are only relative, while the calculation of net thermal efficiency

gives absolute data which are of the highest scientific interest and practical importance.

We must distinguish rather sharply, however, between two classes of operations, which do not allow of the application of the same standards of efficiency. These are (1) those requiring a definite amount of thermal effect to be produced, independent of the time, and (2) those which require the application of a certain temperature for a given time. We will explain more at length.

In operations of class (1) we wish to bring a substance into a given condition by the application of heat, and the *time* factor is sub-ordinate or negligible, the principal or controlling factor being the net amount of heat *absorbed* in the operation. In operations of class (2), the material usually absorbs some heat in being brought up to working temperature (and this part of the operation is identical with the whole of an operation of class 1) but here the material must be kept at this temperature for a shorter or longer period, simply for the physical changes which the temperature produces, and during this period no more heat is absorbed by it.

Thermal Efficiency (Class 1.)

The problem is, having a given substance or mixture of substances in a given physical or chemical condition, to apply heat so as to change it to a different physical or chemical condition, the said change absorbing a definite amount of heat energy in calories. Under such conditions, determine the thermal efficiency of the furnace. Here we must distinguish three cases: (A) when the desired change is merely one of temperature; (B) when the change is a mixed physical and chemical effect; (C) when the change is merely a chemical transposition.

(A) These form the simplest cases for determining thermal efficiency. Examples are as follows: The melting of metals or other substances for the purpose of casting them, the heating of metals to given temperatures for the purpose of working them, such as rolling, forging, etc.,—in short, all operations in which a substance is put into a furnace simply for the purpose of making it hot, or melting it, and then taken away from the furnace to be worked or used in the hot condition. In all these

cases, the thermal efficiency is simply the heat imparted to the body, divided by the total heat available in the furnace.

Illustration 1: An iron-foundry cupola melts 1000 kilograms of pig-iron by the use of 140 kilograms of coke, having a calorific power of 7000 Calories, and yields 980 kilograms of melted iron, ready for casting, containing 275 Calories per kilogram, there being oxidized 15 kilograms of iron and 5 of silicon. What is the thermal efficiency of the cupola?

Solution: The net useful effect is $980 \times 275 = 269,500$ Calories, which has been obtained from burning 140 kg. of coke, with a possible calorific power of 980,000 Calories, and the combustion of 15 kg. of iron and 5 kg. of silicon. The last two items afford

$$\begin{array}{rcl} 15 \text{ kg. Fe to FeO} & = 15 \times 1173 & = 17,595 \text{ Calories.} \\ 5 \text{ kg. Si to SiO}^2 & = 5 \times 7000 & = 35,000 \text{ "} \\ \hline & & 52,595 \text{ "} \end{array}$$

which is in fact increased further by the heat of combination of 19 kg. of FeO formed with the 11 kg. of SiO², to form slag, amounting to

$$\begin{array}{rcl} 11 \times 148 & = & 1,630 \text{ Calories} \\ \hline \text{Total heat of oxidation} & = & 54,225 \text{ "} \\ \text{Calorific power of the coke..} & = & 980,000 \text{ "} \\ \hline \text{Total heat available} & = & 1,034,225 \text{ "} \\ \text{Thermal efficiency} & = & \frac{269,500}{1,034,225} = 0.260 = 26.0 \text{ per cent.} \end{array}$$

Illustration 2: 100 pounds of pure Swedish bar iron and 50 pounds of "washed" pig metal are put into a steel melting crucible and melted down in 2 hours, using 200 pounds of coke, to melted steel containing 315 Calories per unit of steel (pound Calories per pound). Assuming the calorific power of the coke 7000 Calories, what is the thermal efficiency?

$$\begin{array}{rcl} \text{SOLUTION: Heat in steel } 150 \times 315 & = & 47,250 \text{ lb. Calories} \\ \text{Calorific power of the coke } 200 \times 7000 & = & 1,400,000 \text{ " "} \\ \hline \text{Thermal efficiency} & = & \frac{47,250}{1,400,000} = 0.0337 = 3.37 \text{ per cent.} \end{array}$$

Illustration 3: 1000 kilograms of pure Swedish bar iron and 500 kilograms of "washed" pig metal are put into the crucible of an electric melting furnace of the induction type, and are

melted down in one hour to melted steel containing 315 Calories per kilogram, by the expenditure of 1,000 kilowatts of current. What is the thermal efficiency?

$$\begin{array}{lcl}
 \text{SOLUTION: Heat in melted steel } 1500 \times 315 & = & 472,500 \text{ Calories.} \\
 \text{Heat energy of 1 kilowatt second} & = & 0.2389 \text{ " "} \\
 \text{" " " " hour} & = & 0.2389 \times 3600 = 860 \text{ " "} \\
 \text{" " " 1000 " hours} & = & 860,000 \text{ " "} \\
 \text{Thermal efficiency} & = & \frac{472,500}{860,000} = 0.55 = 55 \text{ per cent.}
 \end{array}$$

Such calculations as the above require a knowledge of the calorific power of the fuel used, data for calculating other sources of heat, and the net heat in hot or melted metals,—data such as are given in some of the larger compilations of physico-chemical data, such as Landoldt-Bornstein-Meyerhoff's tables, or the author's "Metallurgical Calculations."

Illustration 4: A regenerative gas furnace heats ten tons of soft steel ingots to 1000° C., using 900 cubic meters of natural gas of the following composition:

Hydrogen, H^2	22.50	per cent.
Methane, CH^4	60.27	" "
Ethylene, C^2H^4	6.80	" "
Carbon di-oxide, CO^2	2.28	" "
Oxygen, O^2	0.38	" "
Nitrogen N^2	7.32	" "

What is the thermal efficiency of the furnace?

Solution: Heat in the hot ingots at 1000° is 166 Calories per kilogram, according to Pionchon's (re-calculated) tests; therefore, to 10,000 kilograms of ingots there are furnished

$$\begin{array}{lcl}
 10,000 \times 166 & = & 1,660,000 \text{ Calories.} \\
 \text{Calorific power of the gas used per cubic meter:} & & \\
 \text{Hydrogen } 0.2250 \times 2,613 & = & 588 \text{ Calories} \\
 \text{Methane } 0.6027 \times 8,598 & = & 5182 \text{ " "} \\
 \text{Ethylene } 0.0680 \times 14,480 & = & 985 \text{ " "} \\
 \hline
 \text{Total.....} & & 6755 \text{ " "} \\
 \text{per 900 cubic meters...} & & 6,079,500 \text{ " "} \\
 \text{Thermal efficiency} & = & \frac{1,660,000}{6,079,500} = 0.273 = 27.3 \text{ per cent.}
 \end{array}$$

Examples could be multiplied almost indefinitely, from the metallurgical and metal-working industries, illustrating the applications of the above principles. They will be found es-

pecially valuable as indicating to the furnace designer and user the considerable room for improvement in thermal efficiency almost universally prevalent.

(B) When a considerable chemical change takes place in the mixture being heated, in order to get a hot product for casting or other hot-working, the heat absorbed or evolved in the chemical reactions must be also counted in. Such cases occur when melted metals are produced from the reaction of metallic ingredients. For example, pure (washed) pig-iron may be put into a crucible with enough pure magnetic iron oxide to burn out its carbon and produce steel. The heat in the resulting steel plus the heat absorbed in the chemical reaction is here the total useful calorific effect, and is to be compared with the calorific power of the fuel consumed.

Illustration 5: A charge put into a hot crucible consists of 100 pounds of "washed" pig-iron, containing 3.5 per cent. of carbon, and 13 pounds of pure magnetite concentrates, Fe^3O^4 . Assuming the oxygen of the magnetite to form CO with part of the carbon of the pig-iron; that the steel resulting contains 315 lb. Calories per pound, and that 200 pounds of coke having a calorific power of 7,000 Calories is used, what is the thermal efficiency of the operation?

Solution: Oxygen in 13 pounds of Fe^3O^4

$$13 \times (64 \div 232) = 3.59 \text{ pounds.}$$

$$\text{Carbon consumed } 3.59 \times (12 \div 16) = 2.69 \text{ "}$$

$$\text{Carbon remaining } 3.50 - 2.69 = 0.81 \text{ "}$$

Weight of steel:

$$96.5 + 0.81 + (13 - 3.59) = 106.72 \text{ pounds.}$$

Heat in melted steel:

$$106.72 \times 315 = 33,617 \text{ Calories}$$

Heat absorbed in chemical reactions:

$$\text{De-oxidation of iron } 9.41 \times 1612 = 15,169 \text{ Calories (absorbed)}$$

$$\text{Oxidation of carbon } 2.69 \times 2430 = 6,537 \text{ " (evolved)}$$

$$\text{Net} = 8,632 \text{ " (absorbed)}$$

$$\text{Total heat absorbed} = 42,249 \text{ "}$$

$$\text{Heating power of coke } 200 \times 7,000 = 1,400,000 \text{ Calories.}$$

$$\text{Thermal efficiency} = \frac{42,249}{1,400,000} = 0.030 = 3.0 \text{ per cent.}$$

Illustration 6: Fifty metric tons (50,000 kg.) of pig-iron containing 3.5 per cent. of carbon, 2 per cent. silicon, and 1 per

cent. manganese is run into an open-hearth furnace, at 1250°C . As its temperature is being raised, red hematite ore is put in to oxidize out its impurities, a corresponding amount of iron being reduced. Heat in the pig-iron 275 Calories, in the finished bath (0.10 per cent. carbon), 350 Calories, per kg. During the heating 6,000 kilos of coal (calorific power 8500 Calories) are used in the producers. What is the net thermal efficiency of the whole plant (producers and furnace considered together)?

Solution: Oxygen needed from added ore:

$$\text{Carbon } 1,700 \text{ kg.} \times (16 \div 12) = 2,267 \text{ kg.}$$

$$\text{Silicon } 1,000 \text{ kg.} \times (32 \div 28) = 1,143 \text{ "}$$

$$\text{Manganese } 500 \text{ kg.} \times (16 \div 55) = 145 \text{ "}$$

$$\text{Total} = 3,555 \text{ "}$$

$$\text{Ore required} = 3,555 \times (160 \div 48) = 11,850 \text{ kg.}$$

$$\text{Fe in ore} = 11,850 - 3,555 = 8,295 \text{ "}$$

Final weight of bath:

$$50,000 - (1,700 + 1,000 + 500) + 8,295 \text{ "}$$

$$= 55,095 \text{ "}$$

$$\text{Heat in original pig iron} = 50,000 \times 275 = 13,750,000 \text{ Cal.}$$

$$\text{Heat in final bath} = 55,095 \times 350 = 19,283,250 \text{ "}$$

$$\text{Heat furnished} = 6,533,250 \text{ "}$$

Heat absorbed in chemical reactions:

$$\text{De-oxidation of iron} = 8,295 \times 1,746 = 14,483,000 \text{ Cal. (Absorbed).}$$

$$\text{Oxidation of carbon} = 1,700 \times 2,430 = 4,131,000 \text{ " (Evolved).}$$

$$\text{" silicon} = 1,000 \times 7,000 = 7,000,000 \text{ " "}$$

$$\text{" manganese} = 500 \times 1,653 = 826,500 \text{ " "}$$

$$\text{Net heat absorbed} = 2,525,500 \text{ "}$$

$$\text{Total thermal effect of furnace} = 9,058,750 \text{ "}$$

$$\text{Heating power of coal used} = 51,000,000 \text{ "}$$

Thermal efficiency of combined producer and furnace:

$$\frac{9,058,750}{51,000,000} = 0.177 = 17.7 \text{ per cent.}$$

(C) If the furnace is merely intended to accomplish a chemical transposition, and the heat in the final product is not a desideratum, but is capable of being utilized for return to the furnace, then the net heat absorbed in the chemical reactions is the only net thermal work accomplished by the furnace.

This is so, because the energy absorbed chemically must be furnished, but the heat carried out by hot products may be more or less perfectly returned to the furnace, i. e., is not final or definitive loss.

A blast furnace reducing iron ore, for instance, reduces the ore by means of carbon, or carbon monoxide, whereby a large amount of chemical work is accomplished. The product is liquid pig-iron, but its sensible heat is in no wise all a necessary loss—a large part of it might conceivably be returned to the furnace as heat in hot blast. Similarly the slag carries out much heat, but some copper blast furnaces already use hot slag for heating their blast, so that this heat is not all a necessary loss. The gases pass out of the furnace hot, and with considerable calorific power, but their sensible heat can be utilized as well as their heat of combustion, for heating blast. Much heat is lost by radiation, but how much of this can be prevented is an unsettled question. In short, some inventor with ideas of economy, might well devise schemes for returning to the furnace a large proportion of the heat ordinarily lost by hot pig-iron, slag, gases and radiation, and the more he succeeded the more efficient his furnace would be, but the irreducible minimum, the absolutely requisite energy required for the chemical reactions, would always remain as the necessary measure of the useful thermal effect of the furnace.

Illustration 7: A blast-furnace produces pig-iron containing 3.5 per cent. of carbon, 2 per cent. of silicon and 1 per cent. of manganese, from red hematite ore, using 1 ton of coke (90 per cent. carbon, calorific power 7,000 Calories) per ton of pig-iron produced. What is the net thermal efficiency?

Solution: Letting the ton be 1000 kilograms, the coke contains 900 kg. of carbon, of which, however, 35 are necessarily required to go into the pig-iron, cutting down the available calorific power of the coke to 865/900 of its theoretical power. The heating power available is therefore:

$$7,000 \times 865/900 \times 1,000 = 6,728,000 \text{ Cal.}$$

Heat used in reductions:

$$\text{Silicon } 20 \text{ kg.} \times 7,000 = 140,000$$

$$\text{Manganese } 10 \text{ kg.} \times 1,653 = 16,530$$

$$\text{Iron } 935 \text{ kg.} \times 1,746 = 1,652,510 \quad 1,809,040 \quad "$$

$$\text{Thermal efficiency} = \frac{1,809,040}{6,728,000} = 0.269 = 26.9 \text{ per cent.}$$

In the above calculation a few refinements have been left out, such as the heat of formation of the slag, which is positive, but usually balanced approximately by the heat required to decompose the flux. Many metallurgists are accustomed to regard the heat in slag and pig-iron as usefully applied heat, but when we consider that this heat may be utilized more or less, and if returned to the furnace would increase the net efficiency of the furnace, we see that it would be illogical to regard it as usefully applied heat. Any loss of heat which may be indefinitely reduced, or any heat, otherwise lost, which can be returned to the furnace, is not net useful thermal work.

Thermal Efficiency (Class 2.)

The second class of operations, which do not admit of calculations of absolute thermal efficiency, are those in which a furnace is kept up to heat for an indefinite time, during which physical or chemical changes take place in the contents of the furnace. Here only relative thermal efficiencies, of one furnace to another, can be calculated. The bases for making these comparisons are either (1) the calorific power expended to keep a given working space (cubical content of the laboratory of the furnace) at a given temperature for unit of time, or (2) the calorific power used to keep a given quantity of material at a given temperature for unit of time.

If the problem is, for instance, to keep a core-oven up to a certain temperature constantly, the fuel necessary to do so, per day, can be best calculated per cubic foot or cubic meter of useful baking space, and thus two ovens compared with each other. If, again, the question is to keep a pot full of metal melted all day, at a certain temperature, while it is being cast, let us say, into small ingots, then the fuel consumed should be calculated per unit of time and per unit of metal kept melted; thus comparisons can be instituted, but no calculations of absolute net thermal efficiency are possible.

It might be thought that in cases such as those just cited a quantity analogous to net thermal effect might be obtained by suddenly drawing the fire and determining the rate at which the melted metal cooled. Multiplying its fall of temperature per minute by its weight and specific heat, a value is obtained representing the heat which the bath must have been receiving

per minute in order to keep it constantly at the required temperature, and therefore the net thermal effect produced per minute by the furnace. But this quantity is not an irreducible minimum, representing net thermal effect, for by putting a thicker non-conducting lid on the pot, the bath would cool much slower, and therefore we would be led to say that the net thermal effect was smaller, whereas the relative effectiveness of the furnace would be thereby increased.

This class of operations cannot be solved by the device of Mr. Queneau, who in his recent book on "Industrial Furnaces" says that the efficiency is to be measured by the ratio of heat radiated by the body of the furnace to the total heating power of the fuel. If that were so, very thin walls, which would increase greatly the heat radiated by the body of the furnace, would increase the efficiency of the furnace (!)

ECONOMIC EFFICIENCY.

This most general aspect of efficiency is a complex quantity; for, granted that the work is properly done, the cost of operation is composed of the following factors:

- (a) Cost of fuel.
- (b) Cost of repairs.
- (c) Cost of labor and superintendence.
- (d) Cost of power, light and general supplies.
- (e) Depreciation.
- (f) Interest on first cost.
- (g) Interest on value of material being treated.
- (h) Rent of necessary ground and building.

We will consider these items *seriatim*.

(a) If a furnace is run continuously the fuel required per unit of time, or if run discontinuously, the fuel required for unit of charge treated, might equally well be supposed to measure the efficiency of the furnace in regard to fuel. The proper basis of comparison, however, between two furnaces must be on the basis of unit amount of material treated or of useful effect produced. Here we must distinguish between the cost of the fuel and the quantity of the fuel. One furnace may need 1 ton of \$5.00 coke to smelt 10 tons of ore, while another may use $1\frac{1}{2}$ tons of \$2.50 coal to do the same work, and the latter be therefore the most efficient of the two, in re-

gard to cost of fuel. The water-jacketted copper blast furnace and the rival reverberatory smelter will well illustrate this point. If two furnaces can use the same fuel, the weights used by each in doing a given work can measure their relative fuel efficiencies.

(b) The cost of repairs per year divided by the tonnage treated per year, yields a figure which is often highly important in determining the efficiency of a furnace. Many moving parts, poor design, too light construction, too heavy walls, too expensive machine work to replace if broken, will all count in making a heavy repair bill. This item of repairs per unit of output should be distributed over a considerable period, so as to cover all kinds of periodically-occurring stoppages due to general inefficiency of the furnace.

(c) Labor forms often the largest single item in the expense account. Two furnaces may accomplish almost exactly similar results, and yet one require twice or even more laborers than the other, or one require highly skilled (and therefore high-priced) attention, while the other requires only moderately skilled labor in order to do just as good work. One of the chief items of economy in modern metallurgical practice is the great increase in the size of furnaces, by which the labor expense per unit of product is almost invariably greatly reduced, —in some cases to a small fraction of its former cost. If one highly-skilled superintendent controls the manufacture of 1000 tons of steel per day, at a yearly salary of \$5000, the cost of this skilled attention is much less per ton of steel than in a mill where a \$2000 man superintends the production of 200 tons daily. Such economies are possible, where, for instance, the first plant possesses 20 50-ton furnaces, and the second 20 10-ton furnaces.

(d) Two furnaces may do equally good work, with the same fuel and cost of repairs, labor and superintendence, and yet cost very differently as requires motive power, light and other supplies, such as oil, belt grease, etc. These all have their bearing on the efficiency of the furnace.

(e) Although constant repairing will keep a furnace together for a long while, yet a time comes sooner or later when it has to be practically rebuilt. Foundations will eventually sink, buck-staves rust where embedded in the ground, the hearth

get past repairing, and the roof *hors du combat*. This general re-building may come once in five years or once in fifteen, but the oftener it does come the less efficient the furnace must be regarded. Charging as depreciation 5 to 20 per cent. per year, on the first cost of the furnace, according to the life of the furnace, and dividing by the tonnage per year, there is obtained the proper depreciation cost per ton of output.

(f) Interest on cost of the furnace, at say six per cent. a year, is a proper charge, because of two furnaces doing equally good work, that one is most efficient which cost the least; and the only way to properly enter this item in the comparison of the two furnaces is to charge the interest cost per ton of material treated. Expensive castings or machine work, high-priced linings or special shapes of bricks, deep excavations, or high chimneys, all add greatly to first cost, and entail high capital charges.

(g) Two furnaces may do work of equally good quality, and turn out practically the same average output per day, and yet one furnace may keep the material in course of treatment only an hour, another a week. Or, putting it another way, one furnace may contain in course of treatment, ten tons of material and another one hundred tons, and yet the average daily output and working charges be the same per ton for each. In such cases, an interest charge on the material under treatment is a proper item in the cost sheet, in order to get a numerical expression for this difference of efficiency of the two furnaces. An ordinary 50-ton open-hearth furnace turns out 100 tons of steel per day; a Talbot continuous furnace turning out the same amount has 200 tons of steel under treatment continuously, so that the interest charge on material under treatment would be twice as great in the second case as in the first. An ordinary reverberatory roasting furnace will turn out say ten tons of roasted ore per day, the ore not being in the furnace over 24 hours; roasting stalls to roast 150 tons in 15 days (an average of ten tons per day) require that the ore be under treatment 15 days. The interest charges on value of ore under treatment is fifteen times as heavy for the stalls as for the reverberatory furnace; and in this regard the latter is much the more efficient style of roasting furnace. Smelters of the more valuable metals, particularly of copper, silver and gold, pay

particular attention to these interest charges, as they sometimes are the main factors in the total efficiency of the furnaces used.

(h) The necessary ground space and building for housing a furnace is often very different for two furnaces of the same output. Where space is at a premium, it is important that a furnace occupy small ground space, and the more compact furnace is the most efficient in this respect. A Stetefeldt furnace for chloridising roasting of silver ores will, for example, roast 80 tons in 24 hours, and occupy a space of 55 square meters; while reverberatory furnaces for the same output would occupy 700 square meters, and need a building of that size to cover them. It is correct, therefore, to add the rent of necessary ground, or ground and building, calculated per ton of output, to the cost sheet, in order to properly compare the efficiencies of furnaces.

(i) To all the above items should be added a term which cannot be expressed in dollars and cents, but only in words; viz., general reliability. The furnace which does the most uniform work, with the least brain fag for the superintendent, and which can be counted on as always doing its work, is preferable, and usually preferred, to the one which may do its work a little more cheaply but is not so reliable.

PRODUCTION OF BISMUTH IN 1905.

The marketed production of bismuth ore in 1905 was 24,405 pounds, valued at \$4,187; in 1904 it was 5184 pounds, valued at \$314. There was no marketed production of bismuth ores in the United States during 1903 or 1902. Interesting features in the bismuth industry in 1905 were the shipment of ore from a new deposit in California, the resumption of mining on the Ballard property in Colorado, and the reduction of 50 per cent. in the price of the metal in London from 10 s. (\$2.43) to 5 s. (\$1.22) a pound.

PRODUCTION OF ZINC IN 1905.

The production of zinc in 1905 showed an increase in quantity as compared with 1904, 1903, 1902 and 1901, the production being 203,849 short tons, as compared with 186,702 short tons in 1904, with 159,219 short tons in 1903, with 156,927 short tons in 1902, and with 140,822 short tons in 1901. The value of the zinc production in 1905 was \$24,054,182, as compared with \$18,670,200 in 1904, with \$16,717,995 in 1903, with \$14,625,596 in 1902, and with \$11,265,760 in 1901.