and that relatively little profit has been found in applying them to other branches of metallurgy. In these other branches it is usually true either that operations are on a relatively small scale, or that the temperature needed is relatively low; and in either case the total value of the heat in the escaping products of combustion is correspondingly small. Thus in copper refining the temperature is so low and hence the escaping products of combustion contain so little heat that no great outlay for recovering it would usually be justified.

Of course, the value of heat is the cost of reproducing it. If fuel is locally very expensive and the value of a unit of heat therefore correspondingly great, then regenerative arrangements for recovering the waste heat of copper refining furnaces might be profitable; they might be profitable in Sweden with its dear coal, though unprofitable in Pittsburgh with its cheap coal.

319. Comparison of Regenerative and Recuperative Furnaces. — Let us recapitulate the essentials of the Siemens and the recuperative systems.

In the regenerative or Siemens system the heat is first filtered out of the escaping products of combustion by passing them through large chambers loosely filled with a checkerwork of brickwork; and it is then transferred to the gas, and to the air used to burn that gas, by passing these, before they come into contact with each other and burn, separately back through these same filtering chambers or *regenerators*. (§ 276.)

In the *recuperative system* the heat is filtered out of the escaping products of combustion by passing them around a system of clay pipes, while through the interior of those pipes the air used for burning the gas is passed, or *vice versa*, (Fig. 113, p. 377).

Comparing these two systems, the Siemens has the advantage of recovering the waste heat of the products of combustion more effectively, chiefly because the heat-filtering surface is kept more efficient, or in other words because it uses the right side of its brickwork to catch the heat, while the recuperative system uses the wrong side of a clay tube.

A second reason why the Siemens system recovers the waste heat more thoroughly is that in it both the air and the gas can be used for that recovery; whereas in the recuperative system the air alone can be thus used. In other words, regeneration can be of both air and gas, while recuperation can be of air only. This advantage, this gas regeneration, of the Siemens system was formerly thought important; but a closer examination, and especially the experience of the last few years, go to show that it is of relatively little weight, and that little is gained by adding gas regeneration to air regeneration. To this we will return in § 321.

In the greater ease and cheapness of repairs the Siemens system probably has a further great advantage, at least when very high temperatures are reached. The plain bricks with which it catches the heat are not only cheap but durable, compared with the clay tubes or their equivalent used in the recuperative system.

320. The Siemens System Catches the Heat on the Right Side. — In the Siemens system the surface of brickwork upon which in one phase the heat is deposited, is the same surface which is exposed to the incoming gas or air during the alternate phase; it is one and the same surface which stores heat in one phase, and restores it in the next: hence this surface is an efficient instrument for thus storing and restoring heat. But in the recuperative system it is to one surface of the pipes that the passing products of combustion are exposed, and to the other surface that the air is exposed; it is one surface of the pipes that stores the heat and the other that restores it; and the storing and restoring surfaces are thus separated by a wall of clay, which, because it is so bad a conductor of heat, very greatly impedes the passage of the heat from the storing surface to the restoring surface, and so lessens the efficiency of the apparatus as an instrument for transferring heat from the escaping products of combustion to the incoming air. That these walls should be of clay seems unavoidable. Metallic pipes would be quickly destroyed, and no other well conducting substance seems available, at least for high temperatures.

Looking at it in another way, only a cold object can be a good heat catcher; the hotter it is the less heat can it take up from the passing products of combustion. In the Siemens system the heat-catching surface of the regenerator bricks begins each phase efficiently cooled by the direct passage over it during the preceding phase of the incoming gas or air; while in the recuperative system this needed cooling of the heat-catching surface is opposed by the bad conduction of the fire-clay walls of the pipes. In short, the Siemens system catches the heat with the right side, the recuperative system with the wrong side, of a clay mass.

321. THE VALUE OF GAS REGENERATION. — I will first explain the reasoning which formerly led to the belief that gas regeneration was very important, and then point out why its real value is probably much less than was formerly supposed.

That a heat-catching system should work implies two things: first that it has an opportunity to catch heat; second that this heat is thoroughly removed from it. No such system can store an indefinite quantity of heat; should the checkerwork of the Siemens system be as hot as the products of combustion passed through it, it could take no heat from them. Only in virtue of its being cooler than they, can it take heat from them. That it shall continue to take heat from them requires that the heat which it takes shall be in turn removed from it; the heat which it receives it must again give out before it can receive more.

Again, the products of combustion cannot heat any system to a temperature higher than their own.

Now the flame and hence the products of its combustion are made up of from two sources, the producer gas itself, and the air with which that gas is burned. In the recuperative system this air alone is used to recover the heat deposited in the recuperative pipes; while in the Siemens system both gas and air are used habitually for this purpose. Since the weight of the gas and air is equal to that of the products of combustion, and since (if we assume for simplicity that the specific heat of all is the same), their capacity for heat (weight $\times$ specific heat) is the same as that of the products of combustion, they are theoretically capable of absorbing all the heat of those products. That is to say, it is theoretically conceivable that were there no losses of heat by conduction through the walls of the regenerators, *etc.*, these regenerators might cool the products of combustion down to the temperature of the incoming air and gas; and might in the following phase, heat up that air and gas to the temperature at which the products of combustion leave the working chamber; in which case the incoming gas and air would, in this sense, recover the whole heat of the products of combustion.

Of course, this result could never be fully attained; it is, however, the limit towards which the system works. But in the recuperative system, since the weight of the air is only about half that of the products of combustion, and since the air alone is used for absorbing their heat, the system is theoretically capable

of absorbing only about half their heat; for manifestly they cannot heat that air hotter than they themselves are, and consequently can give to it only about half their heat.

To illustrate this, let us take a case in which no steam is used in the gas producer, *i. e.*, in which true producer gas unmixed with water gas is made, and let us assume that 120 parts by weight of air are used to burn 100 parts of producer gas:

Let w' = the weight of air used in the producer to gasify the coal, *i. e.*, the gasifying air, per ton of coal,

w'' = that used in the working chamber to burn that gas, or the gas-burning air,

w''' = the weight of the gas itself,

W = the weight of the products of combustion,

T = the temperature at which the products of combustion escape from the working chamber,

Sh = the specific heat of gas, air, and products of combustion, assumed for simplicity to be of the same specific heat,

H = the quantity of heat in the products of combustion as they escape from the working chamber, per ton of coal,

hS = the quantity of heat theoretically recoverable in the Siemens system, and

hr = that recoverable in the recuperative system.

Then from our assumptions

(1) $w''' = w' + 1$,

(2) $W = w'' + w'''$,

(3) $H = W \times T \times Sh$,

(4) $w'' = w''' \times 1.2$.

To simplify the problem let us assume that the gas and air enter each heat-system at the temperature at which the products of combustion escape.

In the Siemens system both the gas itself and the gas-burning air are available for recovering heat; hence

(5) $hS = (w'' + w''') \times T \times Sh$.

In the recuperative system, only the gas-burning air is thus available; hence,

(6) $hr = w'' \times T \times Sh$.

From (4)

(7) $hS = hr\ (1.2 + 1) \div 1.2 = hr\ 1.83$,

or in short, gas regeneration promised to increase the value of the heat-catching system by 83 per cent; it promised to give the regenerative system 83 per cent greater heat-catching power than the recuperative system.

This defect of the recuperative system, that the incoming gas cannot be used to recover the heat of the products of combustion, or in other words that gas-recuperation is impracticable, appears to be inevitable; for we see no way in which the gas can be passed inside the pipes of such a system. The reason for this is that the hydrocarbons of the producer gas break up and deposit carbon when heated; and if passed through these hot pipes they would thus quickly choke them with deposited carbon. In the Siemens system this difficulty does not arise, because any carbon deposited in one phase on the surface of the regenerator bricks is burnt away by the free oxygen always present in the products of combustion passing over that same surface in the next following phase.

The advantage of gas regeneration, however, on further examination turns out to be much less than we have calculated. In the first place, the losses through radiation from the outside of the regenerative system, and the heat needed to give the chimney draught, represent a large fraction of the heat of the products of combustion, and leave in them just so much less heat capable of being caught by any system whatsoever; this reduces correspondingly the margin of heat to be caught over and above that which air regeneration (or for that matter air recuperation), can catch, and thus diminishes the possible gain to be had through gas regeneration. In the second place, as it is only in virtue of entering the regenerators cold or cool that the gas is capable of absorbing heat, in gas regeneration the sensible heat developed in the gas producer is necessarily wasted, or at least it detracts correspondingly from the heat-catching power of gas regeneration.

But, in spite of this, the calculable advantage of gas regeneration seemed so great that no reasonable allowance for these considerations seemed likely to reduce it to an unimportant quantity. Further Siemens reasoned that, since gas regeneration was thus so important, and since any sensible heat brought by the gas from the producer into the regenerative system simply lessened the efficiency of that system proportionally, there was no advantage in trying to save that sensible heat. He therefore set his producers at a convenient and usually great distance from the furnace. The sensible heat was in part utilized by making water gas in the producer as explained in § 326, p. 429, and in part

wasted by radiation from the walls of the producer and of the often very long gas conduits.

If, now, the gas actually issued from the producer at a temperature as high as that to which it is practicable to preheat it in the gas regenerator, and if we first wasted the sensible heat of the gas producer for the purpose of so cooling that gas that it would be capable of absorbing heat in the regenerator from the products of combustion, and then used for that purpose that gas so cooled, we should gain nothing. To waste a calory in order to be able to save another calory is futile. Now, while we may utilize much of the heat generated in the gas producer by making water gas by means of steam introduced along with the blast, yet we are limited in this direction by the fact that the temperature in the producer must be kept up to the point of ignition, lest combustion there cease, and our blast and steam pass through the bed of coal without generating gas. Therefore the gas must necessarily emerge from the top of the bed of coal at a rather high temperature.

If we call the temperature to which it is practicable to preheat the gas in the regenerator, T^h, and the lowest temperature at which it is practicable to have the gas escape from the top of the fuel in the producer, T^p; then all the heat that this gas can really save out of the products of combustion is that represented by the expression $w''' \times Sh \times (T^h - T^p)$.

Just what the temperature difference $T^h - T^p$ really is remains to be proved. Apparently it is not very great. Hence it appears that the real economy of gas regeneration is not very great.

There is a second important consideration tending to lessen the value of gas regeneration. Producer gas from bituminous coal may contain much hydrocarbon which, when highly heated, splits up with the separation of lampblack. If the producer gas is taken straight from the producer with its initial sensible heat into the working chamber of the furnace, *i. e.*, if we do not use gas regeneration, the carbon thus separated immediately burns in that chamber and is thus utilized. If, however, we use gas regeneration, then when the gas enters the hot checkerwork of the regenerator the carbon, which as before separates, deposits on the checkerwork, where it remains inert until the next phase of the furnace, when the products of combustion pass out through this same checkerwork. On meeting this deposited carbon they burn it, and sweep the heat which its combustion generates out to the chimney where it is lost.

It seems to be owing to these two considerations that, in actual large-scale tests lately made, it has proved that gas regeneration saved nothing. That is to say, first the Siemens steel-melting furnaces were worked with gas regeneration, and then in a direct comparative test and with all other conditions constant, the gas was carried direct from the producer to the working chamber. Under these latter conditions no more coal was used per ton of steel ingots made than when gas regeneration was used.

How far this may prove true under other conditions remains to be seen. It may be that in this particular practice the producer had been run needlessly hot, so that the margin $T^h—T^p$ was needlessly small, and that economy might have resulted from introducing more steam into the producer so as to lower T^p and increase the margin.

322. The Progressive Rise in Temperature in Regenerative Furnaces.—In the Siemens system, the combustion in the working chamber is of gas and air preheated to say 1100°. In direct-firing, the combustion close to that working chamber is of coal with initially cold air. Manifestly, starting thus from a higher initial temperature, combustion should generate a much higher temperature in regenerative than in direct-firing. Moreover, each time the direction of the gaseous currents is reversed, the temperature should rise. Thus if we assume that the heat generated by the combustion of a given mixture of gas and air initially at 0° C. evolves enough heat to raise the products of that combustion to 1500°; that the escaping products in passing through the regenerators heat those regenerators themselves to 1300°; and that on reversing the current those regenerators in turn heat the now incoming gas and air to 1100°; and that all other conditions remain constant, so that this new combustion, like the first, generates enough heat to raise its products through 1500°; then it would generate a temperature of $1500° + 1100° = 2600°$. Supposing this process to continue, there should be like elevation of temperature at each reversal.

Not only would any such sequence destroy any furnace quickly, but for obvious reasons the temperature, while it may

quickly rise especially in furnaces provided with large regenerators to a point at which it would destroy the brickwork, yet rises at a rate much less than that just sketched. As the temperature rises, the loss of heat by conduction through the walls of the furnace increases rapidly; in fact, the outflow of heat is so rapid as to suggest the simile of steam or other gas imprisoned at very high pressure in a furnace the very walls of which are porous, so that the steam escapes rapidly, not only through every crevice but through the walls themselves. Indeed this conception of the rapid outrush of heat from our high temperature furnaces and through their walls is an instructive and useful one.*

What actually happens is that the temperature of the regenerators, and through this the temperature of the incoming gas and air and of the working chamber, continue to rise until the rapidly increasing loss of heat through the walls and up the chimney, plus the heat absorbed by the charge of metal under treatment, just balances the heat evolved by the combustion.

It remains quite true, however, that if we wish to raise the temperature of the working chamber suddenly, we can do this by reversing the direction of the gaseous currents at very short intervals, which in some works are at times reduced to 10 minutes, or even less.

323. The Siemens Gas Producer. — As shown in Figs. 98 and 99, p. 352, this consists of an approximately rectangular fire-brick chamber, with a grate, on the rear end of which the coal is dropped from a hopper.

The grate consists of two parts; first, the nearly horizontal bars under the fuel, and, next, the lower part of the inclined wall at the left, which is here made up of iron plates so arranged as to form a kind of grate.

As the object in making a gas producer was to provide a bed of fuel deeper than that of the old direct-firing grates, it is natural that Siemens in this early producer used a grate much like that of a direct-fire, simply providing a deep chamber above

* Again, as the temperature rises the combustion becomes less complete, because dissociation goes the farther the higher the temperature; or rather because the principle which under other conditions would cause dissociation, here correspondingly restricts combustion. But as the products of this combustion thus made incomplete descend through the regenerators and thus cool down, the combustion thus arrested may continue.

it for holding the deeper bed of fuel, together with suitable hoppers, poke-holes, *etc.*

But a serious difficulty arose in trying to remove the ashes from beneath this deep bed of fuel, without letting the fuel itself fall through the grate along with the ashes. This formation and removal of ash is a more serious thing than might be supposed by those unfamiliar with such matters. If a producer gasifies daily three tons of coal containing 10 per cent of ash, with which is mixed, say, 10 per cent more of unburned coal, there are some 750 pounds of hot ash, clinker and unburnt coal to be cared for daily. To remove this from beneath a mass of fuel, which itself is in small lumps, was a difficult matter.

The method of removing the ashes was as follows: First, they were allowed to accumulate in a thick bed. Then a series of flat bars, called "false bars," was driven across the producer through this bed of accumulated ash, so that their further ends rested on the back (or right hand) wall of the producer. They were thus placed at such a height above the true grate bars that most of the accumulation of ashes was beneath them, while above them was the remainder of these ashes and the thick layer of still unburnt fuel. Then the true grate bars were pulled out, so that all the ashes below the false bars, thus deprived of support, fell down into the ashpit. Then the grate bars were replaced and the false bars withdrawn, letting the fuel down upon the grate bars, whereby the producer was restored to working condition.

This method was laborious, especially because the workmen while cleaning the fire were exposed to great heat; and wasteful of fuel, because with the ash thus removed a great deal of unburnt coal was mixed up. If, in order to hasten the work of the producer, the air was forced in under pressure, the disadvantages of the system were all the greater, for two reasons. First, in this case the fire was cleaned only at rather long intervals, because in order to clean it the blast had to be stopped, and the producer thus thrown temporarily out of use, or its gas output, at the best, very greatly lessened; and during these long intervals the accumulation of clinker became all the more serious. Second, the higher local temperature, to which the more rapid combustion led, heated much of the ash so hot that it melted and ran together into large clinkers, very difficult to remove from beneath the overlying fuel.

The formation of clinkers under these conditions was materially lessened by using a steam jet as a means of forcing the air through the producer, for two reasons. First, the steam itself was decomposed by the strongly endothermic reaction

$$(31)\quad H_2O + C = 2H + CO,$$

and the local temperature was so much lowered, by the absorption of heat by this reaction, as to lessen the melting of the ash into clinker. Second, an examination of the ash indicated that the moisture which condensed from this steam in the lower layers of ash, below the level at which combustion was active, itself decomposed some of the clinkers which had formed in the hotter level of active combustion above, when they in turn reached this lower and cooler level.

Further, by thus lessening the formation of clinker and breaking up that which forms, the steam passed through the producer probably lessens materially the quantity of coal which, entangled in that clinker, escapes unburnt, and is thus wasted. The use of steam in the producer has another advantage which can be understood more easily after studying § 326, p. 429.

But, even with the use of steam, the Siemens producer is so troublesome to clean, and the inconvenience of having its gas output so greatly diminished during the long cleaning period is so great, that it has been displaced to a great extent by more modern producers. Among these the W. J. Taylor and the Duff have come into such wide and successful use as to call for description. In each of these the ashes are withdrawn from under the fuel without interrupting the working of the producer. And, though in the Taylor producer their eventual removal from the apparatus may interrupt the gas output, this interruption comes at such long intervals, and is so brief, as to be unimportant.

324. THE TAYLOR GAS PRODUCER.* — The distinctive feature of this is that the column of fuel and ashes rests on a circular plate, which in revolving discharges the ashes over its edge into a sealed ashpit, and thus withdraws them from beneath the overlying fuel without disturbing it or interrupting the work of the producer.

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* U. S. Patent, 399,798, William J. Taylor, R. D. Wood & Co., 400 Chestnut Street, Philadelphia.