blowing engine has just so much less frictional resistance to overcome. The necessary heating surface is given by three high partitions instead of by nine short ones.

Fig. 93 shows the early form of the Whitwell stove. The gas and the air which is to burn enter it at the lower part of the left-hand vertical chamber, which is made wide so as to permit thorough mixing and combustion. Thence, as shown by the arrows, the products of their combustion pass up and down the nine vertical passages at the right of the combustion chamber, giving up their heat to the brickwork partitions. In the next phase, when "on wind," the cold blast is forced in at the right-hand side of the stove, and passes back in the reverse direction, absorbing heat from these same partitions, and escaping from the left-hand side as hot blast.

Fig. 94 may serve to illustrate both the modern Whitwell type, and also the Hugh Kennedy stove which has much in common with it. The modern Whitwell lacks the chimneys shown at the top of Fig. 94, and it has a wide combustion chamber at the left instead of the narrow one here shown.

The Hugh Kennedy stove shown in Fig. 94 is an ingenious modification of older ones. Its working is described in a note to the figure.

The Cowper stove (Fig. 95) differs from the Whitwell (Fig. 94) (1) in having not a series of flat smooth walls, but a great number of narrow vertical flues, for the alternate absorption and emission of the heat, with the consequence that, for given outside dimensions, it offers about one-half more heating surface than the Whitwell stove; and (2) in that the gas and the blast pass only once up and once down through it, instead of twice up and twice down as in the modern Whitwell stoves. As regards frictional resistance, this smaller number of reversals of direction makes up in a measure for the smaller size of its flues. The large combustion chamber *B* permits thorough combustion of the gas.

272. THE INCREASE IN THE RATE OF PRODUCTION per furnace has been extraordinary. In 1863 a daily production of 50 tons per furnace, and in 1880 one of 115 tons, was unusually large; but in 1898 one of the Duquesne furnaces made 711 tons in a day, and the four furnaces there were making regularly between 2200 and 2300 tons daily, a rate as great as that of the whole world in 1800, and half as great as that of all the United States furnaces collectively in 1870. At Rankin a single blast-furnace made 790 tons of pig iron in a single day of 24 hours. The rate of production of a single one of these furnaces is much greater than that of all the United States furnaces in 1830, about ten times that of 1820, and nearly four times that of the 153 furnaces in the United States in 1810. (*Later.* — Ohio No. 2 Furnace at Youngstown, Ohio, has made 806 tons of Bessemer pig iron in 24 hours.)

These Carnegie furnaces of course are exceptional ones, and the common rate of production, especially in case of European furnaces, is much less. For instance, in 1899 the average daily production of the eighty-five existing and projected furnaces of Lorraine and Luxemburg was estimated at only 127 tons, and the greatest estimated daily production for any of those then building was only 200 tons. Indeed, it is questioned whether the rapid driving at Duquesne, with its rich Lake Superior ores, would be economical if applied to the lean Minette ores of Luxemburg and Lorraine.

The remarkable increase since 1880 has been brought about, not chiefly by the use of larger furnaces, although the hearth or crucible is made somewhat wider than formerly, but by providing very powerful engines and hot-blast stoves; and it has almost forced the adoption of simple mechanical arrangements for handling rapidly both the raw materials and the products of the furnace.

Between 1880 and 1901 the importance of anthracite as a fuel for iron smelting decreased greatly, and that of charcoal very greatly; thus of the total United States product of pig iron, the percentage made with anthracite decreased in this period from 42 to 11, and that made with charcoal from 13 to 2.

Conversion into Wrought Iron and Steel

273. MANUFACTURE OF WROUGHT IRON. — That wrought iron, which in 1880 seemed about to be completely displaced by mild steel, remains in very extensive use is due chiefly (1) to the conservatism, often reasonable, of certain consumers, (2) to the great ease with which it welds, and (3) to the great purity which can readily be given to it. Thus wrought iron horse-shoes, bars, *etc.*, are made in great quantities for country smiths and others who have had no opportunity to learn the

slightly different treatment which mild steel needs. Welded steam, gas, and water pipes also are still often made of wrought iron instead of steel, because here thoroughness of welding is of the first importance, and because if steel for pipes is made sufficiently free from carbon to weld readily, special care is needed to prevent cavities called "blowholes" (see § 290, p. 368), due to the escape of gas from the steel when the ingots into which it is initially cast are solidifying. These blowholes are liable either to aggravate the effects of rusting by causing local pitting, or to injure the soundness of the thread which is cut at the end of each length of pipe.

As a material for making the better classes of tool steel by remelting by the crucible process, wrought iron is preferred to mild steel, both because it can be made freer than mild steel from certain elements, especially manganese, which are here undesirable, and because the crucible steel made from it is, in the opinion of the best judges, better than that made from mild steel even if of like composition, though why this is so has not been convincingly explained. For the former of these reasons, too, and perhaps also because of its very defect of being laminated by the presence of cinder, wrought iron is more ductile than mild steel under certain special conditions of use, such as those of rivets and horseshoe nails, many of which are made of it.

While the yearly production of wrought iron in the United States more than doubled between 1870 and 1890, yet since the latter year it has shrunk very much, probably nearly to that of 1870; and between 1870 and 1900 the proportion which the production of wrought iron bears to that of steel diminished very greatly. Of the combined annual production of wrought iron and steel in the United States, that of wrought iron formed 95 per cent in 1870, 63 per cent in 1880, 37 per cent in 1890, and probably not far from 15 per cent in 1899. The corresponding numbers for Great Britain are 34 per cent for 1890, 19 per cent for 1899, and 16 per cent for 1901. In the year 1899 the average number of British puddling furnaces in operation is reported as 1149 out of a total of 1320 in existence. Thus in nineteen years the position of wrought iron changed from that of the chief product to one of secondary importance.

274. THE PUDDLING PROCESS still supplies nearly all the wrought iron made. The numerous mechanical puddling furnaces which in 1875 or thereabouts were offered so prominently as a means of lessening the very severe labor of the puddler, have for the most part disappeared, even the Danks furnace being now almost forgotten, and puddling is now usually done by hand in the old-fashioned furnaces and in the same way as formerly. The novelties in puddling which here need notice are (1) the Pietzka furnace, (2) a tentative increase in the size of charges treated, and (3) the use of "direct metal," *i. e.,* molten cast iron direct from the blast-furnace.

A much lower temperature is needed during the early part of the puddling process, in which the initial charge of cast iron, a relatively fusible substance, is melted down, than towards the end, when the resultant relatively infusible wrought iron must be very highly heated so that its particles may be welded firmly together, and so that the cinder shall be so fluid that the greater part of it may readily be squeezed out of the puddled ball. The *Pietzka furnace* (Fig. 96) is designed to meet this condition, by having two separate "hearths" or working chambers, *A, A,* in the right-hand or cooler of which a new charge is melted down and puddling is begun, while in the left-hand hearth, which is hotter because nearer the fire, another charge is finishing. As soon as this latter charge has been drawn from the furnace and the necessary repairs have been made, the two hearths are made to change places, being lifted by means of the hydraulic plunger *B,* and rotated 180° about this plunger as an axis. This brings to the hot end of the furnace the charge of which the treatment has been begun at the cooler end. To permit this rotation the joints *C,* between the rotating parts of the furnace and the fixed

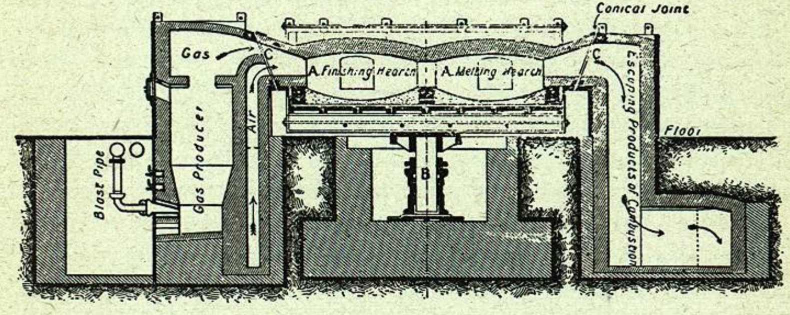

Fig. 96. Diagrammatic Section of the Pietzka Puddling Furnace.

parts, may be made conical. In effect the heat which, in a common puddling furnace, would escape directly from the working chamber into the chimney and thus be lost, is here used in the right-hand or cooler hearth for the early part of the process itself. Beyond this, the heat in the escaping products of combustion may be further recovered by the Siemens regenerative or by the recuperative system. Thus arranged, the Pietzka furnace effects a great saving of fuel.

In common practice the cast iron as it runs from the blast-furnace is allowed to solidify and cool completely in the form of pigs, which are then graded by their fracture, and remelted in the puddling furnace itself. At Hourpes, in order to save the expense of this remelting, the molten cast iron as it comes from the blast-furnace is poured directly into the puddling furnace, in large charges of about 2200 pounds, which are thus about four times as large as those of common puddling furnaces. These large charges are puddled by two gangs of four men each, and a great saving in fuel and labor is effected.

Interesting as are these advances in puddling, they have not been widely adopted, for two chief reasons: First, owners of puddling works have been reluctant to spend money freely in plant for a process of which the future is so uncertain, and this unwillingness has been the more natural because these very men are in large part the more conservative fraction, which has resisted the temptation to abandon puddling and adopt the steel-making processes. Second, in puddling iron which is to be used as a raw material for making very fine steel by the crucible process, quality is the thing of first importance. Now in the series of operations, the blast-furnace, puddling, and crucible processes, through which the iron passes from the state of ore to that of crucible tool steel, it is so difficult to detect just which are the conditions essential to excellence in the final product that, once a given procedure has been found to yield excellent steel, every one of its details is adhered to by the more cautious ironmasters, often with surprising conservatism. Buyers of certain excellent classes of Swedish iron have been said even to object to the substitution of electricity for water-power as a means of driving the machinery of the forge. In case of direct puddling and the use of larger charges this conservatism is reasonable, for the established custom of allowing the cast iron to solidify gives a better opportunity of examining its fracture, and thus of rejecting unsuitable iron, than is afforded in direct puddling. So, too, when several puddlers are jointly responsible for the thoroughness of their work, as happens in puddling large charges, they will not exercise such care (nor indeed will a given degree of care be so effective) as when responsibility for each charge rests on one man.

275. The Open-hearth Process. — In this process, sometimes called the *Siemens-Martin process,* the advances have been more important than those in any other branch of steel making. The chief of these are: (1) the wide use of a basic lining and basic slag, so that the process removes phosphorus from the iron; (2) a great increase in the size of furnaces, from 10 to 50 and even 70 tons' capacity; (3) the use of tilting furnaces; and (4) special modes of procedure.

The American rate of production of the open-hearth process per furnace per week has increased from six heats aggregating 30 tons in 1870 to 22 heats aggregating 1,129 tons, the production of a 50-ton furnace at Duquesne when treating charges composed of 34.3 per cent of molten pig iron, 10.5 per cent of cold pig iron, and 55.2 per cent of scrap iron.

In 1880 the radical defect of the open-hearth process, like that of the Bessemer process, was that it did not remove phosphorus, a most hurtful element, of which nearly all pig irons contain more than is desirable, and most of them more than is permissible, in steel. The essence of both these processes as we have seen is the removal, by oxidation, of the impurities, carbon, silicon, manganese, etc., which the molten cast iron contains.

The carbon oxidizes to carbonic oxide gas which escapes; the silicon oxidizes to silica, and the manganese to manganous oxide, and the resultant silica and manganous oxide unite with the slag, which floats in a thin layer on the molten metal, like cream on simmering milk.

The condition of things in the open-hearth process is sketched in Fig. 97. The right-hand half of this figure shows the charge in a state of violent boiling, due to the reaction between the oxygen of the dark lumps of iron ore which have been thrown in, and now lie floating between metal and slag, and the carbon of the molten metal, $C + O = CO$. The resultant carbonic oxide gas escapes in great volumes and converts the slag into a thick frothing mass. The condition of things at the end of this process, when

Half Section
Showing condition of charge when boiling very gently.

Half Section
Showing condition of charge when boiling violently during ore-ing

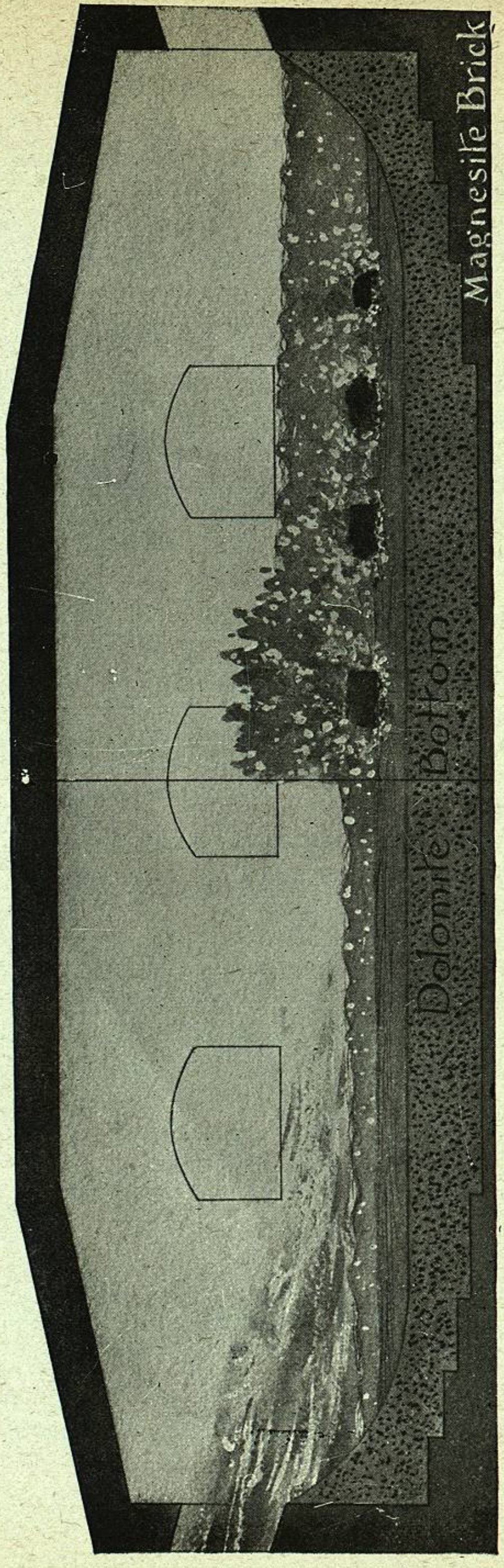

Fig. 97. The Open-hearth Process.

ebullition has nearly ceased, is shown in the left-hand part of this sketch. Naturally we have to draw somewhat upon our imagination for our conception of what takes place within an opaque mass like this.

Phosphorus also, like carbon, silicon and manganese, may be oxidized by means of iron oxide, forming phosphoric acid, which separates from the molten metal and combines with lime, iron oxide and other bases in the molten slag. Phosphoric acid, however, is here so unstable that it tends strongly to be again deoxidized as fast as it is formed, by the carbon and silicon of the molten iron beneath, or even by the molten iron itself, and, when so deoxidized, it immediately reunites with that iron, so that in effect dephosphorization is wholly prevented. This strong tendency to instantaneous and complete "rephosphorization" must be counteracted if the removal of phosphorus is to be effective, and to make that possible the slag must be made strongly retentive of phosphoric acid. But in order to be retentive of phosphoric acid, it must contain an excess of powerful bases, such as lime and iron oxide, for these, so long as they are in excess, form with the phosphoric acid salts so stable as to resist the deoxidizing action of the molten metal beneath.

Silica, or silicic acid, here plays the part of an acid so powerful that, if there is more than some 20 per cent of it in the slag, it enfeebles the hold of these bases on the phosphoric acid, with the result that much of this substance is reduced by the carbon, silicon or iron to phosphorus, and consequently reabsorbed by the molten metal. To exclude silica the furnace walls, which under other conditions are usually made of sand or clay, are here made either of a neutral substance, chromite (FeO, Cr_2O_3), or of a basic and yet infusible one, such as magnesia or the mixture of magnesia and lime which results from calcining dolomite $(Ca, Mg)CO_3$. This, when mixed with some 10 per cent of dehydrated coal tar, is coked by the heat of the furnace into a hard ringing mass, which is much more resistant than a silicious lining, so that the basic process is actually easier to conduct than the older or "acid" process with its acid, *i. e.*, silicious, walls and slag. The basic variety has reached great importance in Germany, and in 1901 in the United States, 77 per cent of the total of open-hearth steel was made by it, though in Great Britain the proportion (in the first half of 1902) was only 13.6 per cent.

Furnaces, each treating a charge of fifty tons — five times the weight common in 1880 — have proved so economical that two of 70 tons' capacity have been built. No special difficulties have arisen in the use of these enormous furnaces. The gas and the air each enter the furnace through a single port, yielding a flame so great and long as to fill the whole melting chamber.

Many of these large furnaces are tilted at the end of each charge, as shown by the arrows in Fig. 100, so as to pour the molten steel into the casting-ladle, and the molten slag into its receptacle; thus the troublesome operation of pouring is brought under much better control. This and the other incidental advantages of tilting are much more important in the basic than in the acid process, but even in the former case it is not generally conceded that the tilting system has yet been so perfected that its advantages considerably outweigh its greater cost for installation and repairs.

276. THE SIEMENS FURNACE. — Figs. 98 to 101 are intended to explain not only the tilting furnace, but the general principle of the Siemens furnace. The charge of metal is melted and brought to the desired composition and temperature in the working chamber or body of the furnace, *G*, a long quasi-cylindrical vessel of brickwork, heated by burning within it preheated gas with preheated air. This working chamber is the furnace proper, in which the whole of the open-hearth process is carried out, and the function of all the rest of the apparatus, apart from the tilting mechanism, is simply to preheat the air and gas, and to lead them to the furnace proper and the products of their combustion thence to the chimney.

How this is done may be understood more easily if Figs. 98 and 99 are regarded for the moment as forming a single diagrammatic figure instead of sections in different planes. The unbroken arrows show the direction of the incoming gas and air, the broken ones the direction of the escaping products of their combustion. The air and gas, the latter coming from the gas producers or other source shown at the left of Fig. 99, arrive through *H* and *J* respectively, and their path thence is determined by the position of the reversing valves *K* and *K'*. In the position shown in solid lines, these valves deflect the air and gas into the left-hand pair of "regenerators," the air into and through the extreme left-hand regenerator, the gas into and through that immediately on its right. Before considering the further path of the gas and air let us turn aside for the moment to ask what these regenerators are.

The Regenerators. It is for the purpose of highly preheating the air and gas before they mix and burn that they are passed separately into and through these regenerators. These are large rectangular chambers, in each of which is a great mass of "checkerwork," *i. e.*, firebricks piled loosely in such a way as to leave abundant free but zigzag passage for the passing air or gas, and by this very act to cause the air and the gas separately to come during their passage into extensive contact with the preheated surfaces of this checkerwork. How this preheating is done we shall shortly see; suffice it for the moment that the gas and air are separately exposed in them to an enormous extent of roughened and highly preheated firebrick surface, so that in this passage the gas becomes heated very highly, say to a light yellow heat, 1100° C. (2012° F.), in one regenerator, and the air simultaneously becomes highly heated in the other.

Let us now return to the itinerary of the gas and air, which we have now followed as far as the left-hand pair of regenerators, which in the present phase are the inlet regenerators. The gas and air next ascend, still as two separate streams, through the uptakes (Fig. 101), and they first mix at the moment of entering the working chamber through the ports *L* and *L'* (Fig. 98). As they are so hot at starting, their combustion of course yields a very much higher temperature than if they had been cold before burning, and they form an enormous flame, which fills the great working chamber. The products of combustion are sucked by the pull of the chimney through the farther or right-hand end of this chamber, out through the right-hand ports which in this phase are the exit ports, as shown by the dotted arrows, down through the right-hand pair of regenerators, heating to perhaps 1300° C. the upper part of the loosely-piled masses of brickwork within them, and thence past the valves *K* and *K'* to the chimney-flue *O*.

During this phase the incoming gas and air have been withdrawing heat from the left-hand regenerators, which have thus been cooling down, while the escaping products of combustion have been depositing heat in the right-hand pair of regenerators which have thus been heating up. After some thirty minutes this condition of things is reversed by turning the valves *K* and *K'* 90°, into the positions shown in broken lines, when they deflect