piston makes its down-stroke (in the actual engine the working cylinder was double-acting, another heating vessel, precisely like A, being connected with the cylinder B above the piston); this com­presses the air isothermally, the heat produced by compression being taken up by C. Finally the plunger is raised, and the working air again passes through the regenerator, taking up the heat it left there, and rising to τ1. The theoretical indicator diagram has been given in fig. 13.

245. The actual forms in which Stirling’s engine was used are described in two patents by R. & J. Stirling (1827 and 1840@@1). An important feature in them was that the air was compressed (by means of a pump) to a pressure greatly above that of the atmo­sphere. Stirling’s cycle is theoretically perfect whatever the density of the working air, and compression did not in his case increase what may be called the theoretical thermodynamic efficiency. It did, however, very greatly increase the mechanical efficiency, and also, what is of special importance, it increased the amount of power yielded by an engine of given size. To see this it is sufficient to consider that with compressed air a greater amount of heat was dealt with in each stroke of the engine, and therefore a greater amount of work was produced. Practically it also increased the thermodynamic efficiency by reducing the ratio of the heat wasted by external conduction and radiation to the whole heat.

A double-acting Stirling engine of 50 I.H.P., used in 1843 at the Dundee foundry, appears to have realized an efficiency of 0·3, and, notwithstanding very inadequate means of heating the air, con­sumed only l·7 lb of coal per I.H.P. per hour.@@2 This engine re­mained at work for three years, but was finally abandoned on account of the failure of the heating vessels. In some forms of Stirling’s engine the regenerator was a separate vessel ; in others the plunger D was itself constructed to serve as regenerator by filling it with wire-gauze and leaving holes at top and bottom for the passage of the air through it.

246. Another mode of using the regenerator was introduced in America by Ericsson, in an engine which also failed, partly because the heating surfaces became burnt, and partly because their area was insufficient. In Ericsson’s engine the temperature of the working substance is changed (by passing through the regenerator) while the pressure remains constant. Cold air is compressed by a pump into a receiver, from which it passes through a regenerator into the working cylinder. In so passing it absorbs heat from the regene­rator and expands. The air in the cylinder is then further expanded by taking in heat from a furnace under the cylinder. The cycle is completed by the discharge of the air through the regenerator. The indicator diagram approximates to a form bounded by two isother­mals and two lines of constant pressure.@@3

247. Externally-heated air-engines are now employed only for very small powers—from a fraction of 1 H.P. up to about 3 H.P. Powerful engines of this type are impracticable on account of their relatively enormous bulk. Those that are now manufactured resemble the original Stirling engine very closely in the main features of their action, and comprise essentially the same organs.@@4

248. *Internal-combustion* engines form a far more important class of motors. The earliest example of this class appears to have been the hot-air engine of Sir George Cayley,@@5 of which Wenham's@@6 and Buckett's@@7 engines are recent forms. In these engines coal or coke is burnt under pressure in a closed chamber, to which the fuel is fed through a species of air-lock. Air for combustion is supplied by a compressing pump, and the engine is governed by means of a distributing valve which supplies a greater or less proportion of the air below the fire as the engine runs slow or fast. The products of combustion, whose volume is increased by their rise in tempera­ture, pass into a working cylinder, raising the piston. When a certain fraction of the stroke is over the supply of hot gas is stopped, and the gases in the cylinder expand, doing more work and becoming reduced in temperature. During the return stroke they are discharged into the atmosphere, and the pump takes in a fresh supply of air. Fig. 142 is a diagram section of the Buckett engine. A is the working piston, the form of which is such as to protect the tight sliding surface (at the top) from contact with the hot gases ; B is the compressing pump, C the valve by which the governor regulates the rate at which fuel is consumed, and D the air-lock through w’hich fuel is supplied.

249. In engines of this class the degree to which the action is thermodynamically efficient depends very largely on the amount of cooling the gases undergo by adiabatic or nearly adiabatic expansion under the working piston. Without a large ratio of expansion the thermodynamic advantage of a high initial tem­

perature is lost ; but, as the gases have to be discharged at atmo­spheric pressure, a large ratio of expansion is possible only when there is much initial compression. Compression is therefore an

essential condition, without w’hich a heat-engine of this type can­not be made efficient. It is also, as has already been pointed out, essential in all air-engines to the development of a fair amount of power by an engine of moderate bulk.

250. Internal-combustion engines using solid fuel have hitherto been little used, and that only for small powers. Several small engines employ liquid fuel (namely, petroleum) injected in a state of spray, or even vaporized before entering the combustion-chamber. In some forms, of w’hich the Brayton petroleum engine is a type, combustion occurs as the fuel is injected ; in others the action approaches closely that of *gas-engines,* that is to say, of engines in which fuel (generally coal-gas) is supplied in a perfectly gaseous state, and is burnt in a more or less explosive manner. These last are the only heat-engines that have as yet entered into serious competition with steam-engines.

251. The earliest gas-engine to be brought iuto practical use was that of Lenoir (1860). During the first part of the stroke air and gas, in proportions suitable for combustion, were drawn into the cylinder. At about half-stroke the inlet valve closed, and the mixture was immediately exploded by an electric spark. The heated products of combustion then did work on the piston dur­ing the remainder of the forward stroke, and were expelled during the back stroke. The engine was double-acting, and the cylinder was prevented from becoming excessively heated by a casing through which water was kept circulating. The water-jacket has been re­tained in nearly all later gas-engines.

An indicator diagram from a Lenoir engine is shown in fig. 143.@@8 After explosion the line falls, partly from expansion, and partly from the cooling action of the cylinder walls ;

on the other hand, its level is to some extent

maintained by the phenomenon of after-burn­

ing, which will be discussed later. In this

engine, chiefly because there was no compres­

sion, the heat removed by the water-jacket

bore an exceedingly large proportion to the whole heat, and the efficiency was comparatively low ; about 95 cubic feet of gas were used per horse-power per hour. Hugon’s engine, introduced five years later, was a non-compressive engine very similar to Lenoir’s. A novel feature in it was the injection of a jet of cold water to keep the cylinder from becoming too hot. These engines are now obsolete ; the type they belonged to, in which the mixture is not compressed before explosion, is now represented by one small engine—Bischoffs—the mechanical simplicity of which atones for its comparatively wasteful action in certain cases where but little power is required.

252. In 1866 Otto and Langen introduced a curious en­gine,@@9 which, as to economy of gas, was distinctly superior to its predecessors. Like them it did not use compression. The explosion occurred early in the stroke, in a vertical cylinder, under a piston which was free to rise without doing work on the engine shaft. The piston rose w’ith great velocity, so that the expansion was much more nearly adiabatic than in earlier engines. Then after the piston had reached the top of its range the gases cooled, and their pressure fell below that of the atmosphere ; the piston consequently

@@@1 The 1827 patent is reproduced in F. Jenkin’» Lecture on Gas and Caloric Engines, *Inst. Civ. Eng.,* Heat Lectures, 1883-84. See also *Min. Proc. Inst. C.E,* 1815 and 1854.

@@@2 See Rankine’s *Steam, Engine,* p. 367. The consumption per brake H.P. was much greater.

@@@3 For a diagram of Ericsson’s engine see Rankine’s *Steam Engine,* or *Proc. Inst. Mech. Eng.,* 1873.

@@@4 For description of Robinson's, Bailey’s, and Rider’s hot-air engines see F. Jenkin’s lecture, *loc. cit.*

@@@5 *Nicholson’s Art Journal,* 1807.

@@@6 *Proc. Inst. Mech. Eng.,* 1873.

@@@7 F. Jenkin, *loc. cit.* Fig. 142 is taken from this paper.

@@@8 Slade, *Jour. Franklin Inst.,* 1866.

@@@9 *Proc. Inst. Mech. Eng.,* 1875.