Oct. 10, 1961 D. B. SPALDING 3,003,315

COMPRESSION IGNITION PRESSURE EXCHANGER

Filed Oct. 24, 1956 2 Sheets-Sheet 1

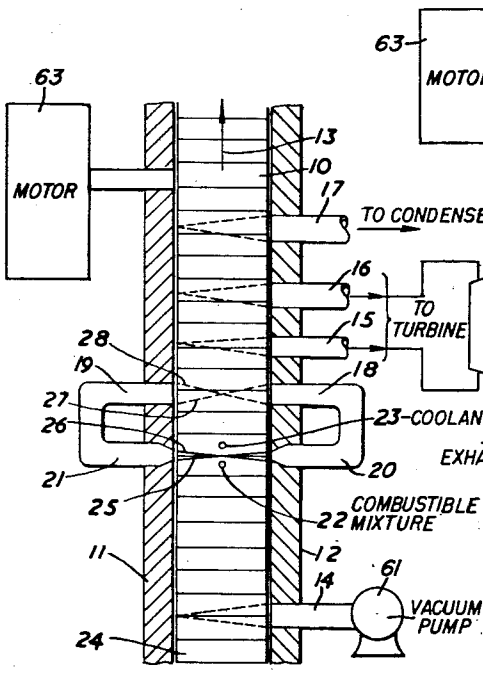



FIG. 1.

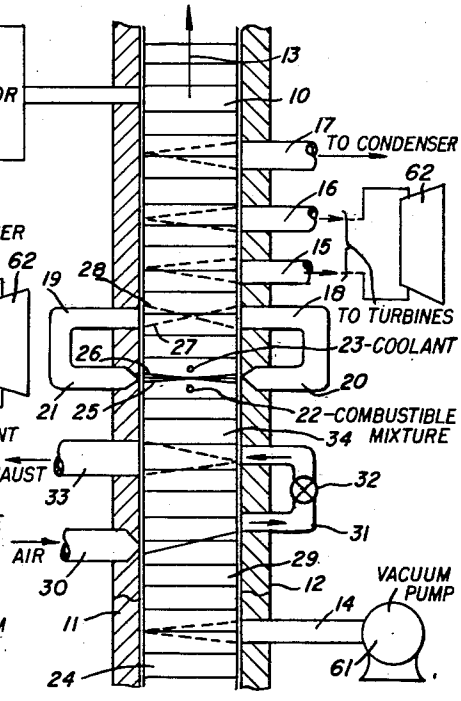



FIG. 2.

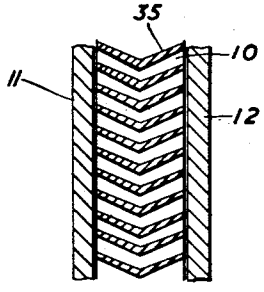



FIG. 3.

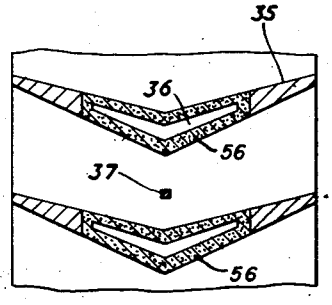



FIG. 4.

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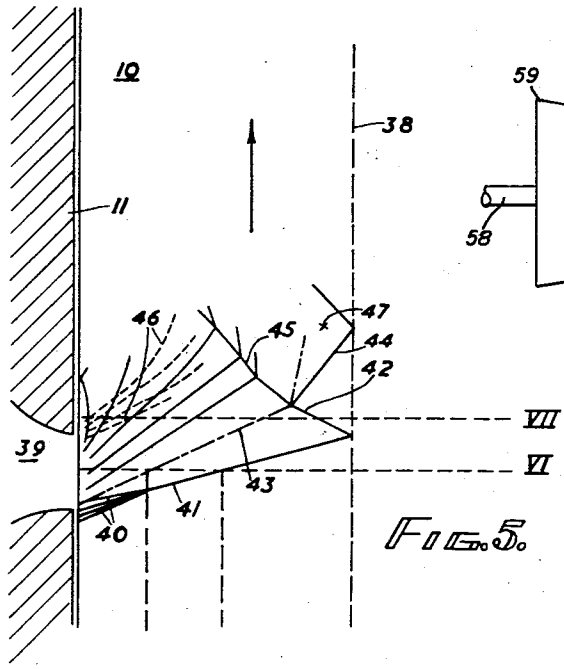



FIG. 5.

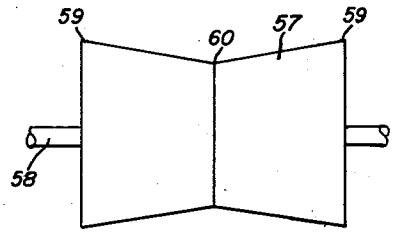



FIG. 8.

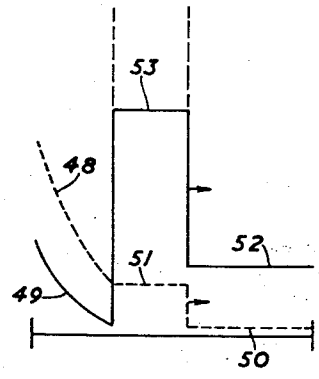



FIG. 6.

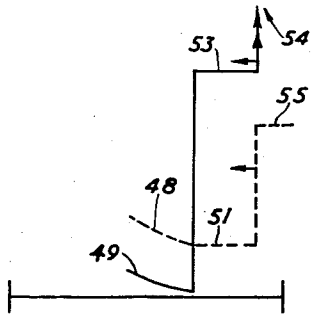



FIG. 7.

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# 3,003,315
# COMPRESSION IGNITION PRESSURE EXCHANGER

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12 Claims. (Cl. 60—39.45)

This invention relates to systems for the continuous production of power from controlled explosions. The apparatus employed comprises a pressure exchanger which enables explosions to take place within the confines of the individual cells and moreover to occur in rapid sequence in successive cells.

The invention provides apparatus for the continuous production of power from controlled explosions comprising a pressure exchanger arranged in operation to compress, by means of a compressible fluid introduced into each cell in turn, an explosive medium separately introduced into the pressure exchanger cells thereby sufficiently increasing the temperature of said medium to effect an explosion in each cell and means for removing explosion products from the cells.

The removal means may incorporate a fluid outlet duct positioned to communicate with each cell following an explosion therein and in which said duct leads to a nozzle communicating with the cells at a position reached by each cell as it approaches the explosion stage.

Preferably a liquid is introduced into each cell immediately following an explosion therein. The liquid is heated by the cooling of the explosion products and can be employed to assist in the compression of the explosive medium.

Specially shaped and arranged cells may with advantage be employed as will be explained below and the explosions are best localized in a central cell region.

A compressible fluid may be admitted to each cell before said explosive medium is introduced and means may be provided for establishing an irreversible expansion process for the contents of each cell immediately after such fluid admission thereby raising the temperature of the cell contents without a proportional increase in the pressure.

Following an explosion in a cell, the latter may communicate with one or more outlet ducts leading say to a turbine.

Embodiments of the invention will be described with reference to the accompanying drawings in which:

FIGURE 1 shows a diagrammatic peripheral development of a pressure exchanger operable to produce high pressure steam supplies from controlled continuous explosions;

FIGURE 2 shows part of a pressure exchanger in which the fluid content of a cell can undergo a considerable temperature rise without a corresponding pressure rise;

FIGURE 3 illustrates an arrangement of tapered cells in a pressure exchanger cell ring;

FIGURE 4 shows how the walls of the tapered cells illustrated in FIGURE 3 may be arranged for internal cooling and for coolant introduction into the cells;

FIGURES 5, 6 and 7 provide diagrammatic illustration of the expected pressure wave pattern and its effect in the high temperature zone of a pressure exchanger arranged to operate in the manner described with reference to FIGURE 1. FIGURES 6 and 7 show pressure and temperature distribution in the cells at positions indicated at VI and VII respectively in FIGURE 5; and

FIGURE 8 is a side elevation of a radially waisted pressure exchanger cell rotor.

In FIGURE 1 there is shown diagrammatically a circumferential development of a pressure exchanger cell ring. Cells **10** are arranged around the circumference of a rotor which is rotated by an electric motor **63** between end plates **11** and **12** in the direction of an arrow **13**. In one end-plate there are arranged four outlet ducts **14–17** and another duct system symmetrically arranged in both end plates comprising outlet ducts **18** and **19** connected to inlet ducts **20** and **21** respectively. In addition to these duct arrangements by which fluid enters and leaves the cells of the rotor, there are two other inlet ports **22** and **23** positioned to allow fuel and a cooling fluid respectively to enter, e.g. through holes in the casing, the cells near their mid-points as they pass the inlet ducts **20** and **21**.



The operation of the pressure exchanger will now be described as the cells in turns pass the various ports at the end of the ducts. A cell initially in the position **24** will be considered. In this cell during operation there is at least some fluid at a low pressure. The pressure is further lowered by the application of a vacuum pump **61** to the evacuating duct **14**. After leaving the duct **14** and before reaching the explosive fuel inlet port **22** the cell contents may be subjected to a heating process and one such process will be described below. As shown in FIGURE 1 however, the cells pass on their way until they encounter the port **22** through which an explosive fuel is admitted at low pressure but at as high a temperature as is permissible. Immediately after this fuel has been admitted in the central region of the cell, the contents thereof are compressed by two shock waves **25** and **26**, due to the cell being opened to the compressed gas inlet ducts **20** and **21**, the first shock wave being an incident wave and the second a reflected wave. This causes the contents to be compressed to a very high pressure because the fluid entering through the ducts **20** and **21** is itself at a high pressure, considerable pressure difference obtaining between it and the cell contents. The compression of the cell contents through the high pressure ratio necessarily means that the high temperature ratio is forthcoming. The explosive medium ignites and yet higher temperatures are immediately experienced. The cell is, however, continuing to move and water is injected through the liquid coolant inlet port **23** into the region of the explosion. The water has the effect of cooling the explosion products and forming high pressure steam. The cycle continues and expansion waves **27** and **28** pass through the cell because it comes into communication with the higher pressure explosion products outlet ducts **18** and **19**. Because the expansion wave follows the shock waves quickly, the pressure at the point of the explosion is rapidly reduced and some of the high pressure steam and explosion products evolved passes out through the ducts **18 and 19** to be recirculated so that it enters the cells again through the ducts **20** and **21**. Thus in this the preferred embodiment it is the explosion itself which provides for the compression of the contents of a following cell. As each cell passes on its way from the ducts **18** and **19** it encounters lower pressure explosion products outlet ducts **15** and **16** through which some of the mixture of steam and explosion products can be taken away for useful purposes, for example it may be expanded through a power producing turbine **62**. Finally through the lower pressure outlet duct **17** some of the remaining low pressure mixture is taken to a condenser and the cell passes on its way again to meet the evacuating duct **14** and to recommence the cycle.

One arrangement for heating the cell contents between duct **14** and port **22** with little or no increase in the pressure thereof is shown in FIGURE 2 in which the contents of the cell initially in the position **29** are compressed by the shock waves due to the entry of compressible fluid through the additional compressed gas inlet duct **30**. This compressible fluid may conveniently be atmospheric air.

Some of the heated and compressed cell contents are then removed through the additional gas outlet duct **31** as the cell continues on its way and their pressure is reduced irreversibly by passage through a throttle **32**. While this part of the cell contents is being expanded through the throttle another expansion takes place in the cell itself due to the cell coming into communication with a duct **33** which allows the pressure of the cell contents to drop to near the original value. In this way, when the cell reaches a position **34** its contents are at or near the pressure existing in the cells at the position **29** but at a higher temperature. A number of such stages can be arranged in succession and incorporated in the apparatus of FIGURE 1 between the evacuating duct **14** and the fuel inlet port **22**.

It will be noted in the arrangements described above that the ports through which compressible fluid enters are convergent so that sonic velocities are attained in the entering fluid at the point of entry. After entry, of course, the entering fluid attains supersonic velocity.

In order to concentrate the shock waves and positively to locate as far as possible the point of explosion it is preferable that the cells should be tapered towards a central point and this desirable feature may be combined with an inclination of the cell walls to the axial direction to give better velocity triangles for the entering fluid. A suitable arrangement is diagrammatically shown in FIGURE 3. It will be noted that the cells in this figure are tapered by having their walls **35** thicker towards the middle of the cells than they are at their ends.

An additional advantage which may be obtained by having the centrally thicker cell wall construction, is indicated in FIGURE 4. The walls have a central cavity **36** through which cooling medium flows. In one such arrangement with water as the coolant, the cell walls are porous (as at **56**) at least in the region of the internal cavity **36**. The water seeping through the walls evaporates through cooling them; the steam rapidly moves away from the cell wall towards its interior so giving rise to additional shock waves directed towards the mid-point of the cells. Some parts of the cell walls especially towards the ends of the rotor may be highly polished in order to reflect radiant heat falling upon them. With the porous wall arrangement of FIGURE 4 it may not be necessary to have the additional water coolant inlet as shown at **23** in FIGURE 1. The water continually seeping through the walls may well suffice for cooling both the walls and the explosion products and for providing the steam and combustion products for compressive purposes. An anvil post **37** may be mounted in the central region of the cell in order to locate the point of origin of the explosion. The explosion will occur immediately and a shock wave is reflected from the anvil post.

FIGURES 5, 6 and 7 are intended to provide an illustrative picture of the wave pattern in one half of a cell passing through the entry port for the compressible fluid flowing through the ducts **20** and **21** in FIGURE 1. In FIGURE 5 the cell walls have been omitted but the rotor **10** has been shown adjacent an end wall **11**. The axially central plane of the rotor has been shown dotted at **38**, and it will be appreciated that with compressible fluid entering through both ends of the cell the wave pattern in the ends of the cells not indicated in FIGURE 5 is a mirror image of that actually shown. As the high pressure fluid enters at sonic velocity through the convergent nozzle **39** into a cell whose contents are at a low pressure, a group of shock waves **40** advances into each cell as it becomes open to the nozzle **39**. There is a group of such shock waves because of the finite cell size in relation to the inlet. The waves of the group combine into one strong shock wave **41** which continues through the cell to be reflected at the mid-point by contact with an anvil post as described above or by meeting a similar shock wave advancing from the opposite end of the same cell. The reflected shock wave is shown at **42**. The initial contents of the cell are compressed by these waves and the entering fluid passes into the cells, an idealized line of demarcation between the initial and entering contents being shown by the chain dotted line **43**. There is a further reflected shock wave **44** caused by the intersection of the shock wave **42** with the line of demarcation **43**. The complicated shock wave pattern also follows along the line **45** due to interaction between the initial reflected shock wave **42** and the waves fanning out from the nozzle inlet **39** through which fluid continues to enter at sonic velocity. As each cell is closed by its wall from the inlet a group of expansion waves **46** fan out from the closing edge of the nozzle and these help to slow down the movement of the fluid in the end of the cell. The explosive fuel is introduced into the cell towards its mid-point before the first incident shock wave **41** is reflected and it will be seen that before the contents of the middle region of the cell have reached the point indicated by a cross **47**, the explosive medium has passed through three immediately successive shock waves. Each shock wave raises pressure and temperature and at about the point **47** the explosion will have started. The temperature then will be very high and a further shock wave due to the explosion will advance from the middle of the cell towards each end. The water or cooling medium introduced into the cells in order to limit the highest temperature reached and cool the explosion products also results in the formation of a high pressure vapor used as explained above in relation to FIGURE 1 to effect the necessary compression.

FIGURES 6 and 7 show in a simplified form the pressure and temperature distribution that can be expected in one end of a cell as it passes from the section VI to VII of FIGURE 5. In both figures, the pressure distributions have been shown by dotted lines **48** while the temperature distributions are shown by the full lines **49**. In FIGURE 6 the effect of the advancing shock wave on the initial cell contents can be seen by the increase of pressure from the level **50** to the level **51** and by the increase of temperature from the level **52** to the level **53**. FIGURE 7 shows in part the pressure and temperature distribution in the mid-region of the cell after the incident shock wave **41** has been reflected once. The condition is that the reflected shock wave **42** is travelling from the middle towards the end of the cell. The temperature has been raised to a much higher level indicated diagrammatically by the arrow **54** and the pressure to a level **55**. It will be realized that with a shock wave pattern of the kind explained above, very considerable temperature ratios can be achieved by the time a cell reaches the point indicated at **47** in FIGURE 5.

Reference has been made above to the desirability of concentrating the shock waves and one construction has been illustrated and described with reference to FIGURE 3 which assists in achieving this aim. FIGURE 8 illustrates another rotor construction which also facilitates the concentration of shock waves. In this construction the rotor **57** is mounted for rotation on a shaft **58** and has a larger diameter at each end **59** than at its center **60**. By the use of this construction the individual cells have cross-sections which progressively diminish from the ends of the rotor **59** to the center of the rotor **60**.

No detailed reference has been made above to the fuels that may be employed in systems such as have been described. This is because many fuels may be so employed, and for instance a conventional explosive such as nitro-glycerine could be introduced as the fuel. In general it is desirable that the cells before reaching the point of fuel introduction should contain a low pressure gas (compressible fluid) having a high ratio of specific heats. Gases with such a high ratio of specific heats are argon or helium. The fuel can then be intro-

duced as a mixture with that gas or it may be suspended in it. The compressible fluid should preferably have a low specific heat. Again water has been mentioned as a convenient cooling medium for introduction immediately after the explosion has taken place and a liquid is preferred for this purpose as the pumping energy required is small but it will be realized that the cooling medium has to be chosen in relation to the fuel used and the limit that has to be set to the maximum temperature.

I claim:

1. Pressure exchanger apparatus including a rotatable ring of open-ended substantially axially-extending cells for the compression and expansion of fluid, two stationary end-plates positioned one adjacent each end of the cells and at least one of the end-plates having ports therein to control fluid flow through the cells, driving means to rotate the ring of cells relatively to the end-plates, an inlet duct to admit an explosive combustible mixture to the cells, a compressed fluid-carrying duct communicating with the cells through one of the ports in the end-plates positioned, considered in the direction of relative rotation, after the port to introduce the combustible mixture, means to supply compressed fluid to the compressed fluid-carrying duct, an outlet duct communicating with one of the ports in one of the end-plates which, considered in the direction of relative rotation, follows the compressed fluid inlet port, and power production means communicating with the said outlet duct.

2. Pressure exchanger apparatus according to claim 1, wherein the means to supply compressed fluid to the compressed fluid duct comprises one of the said ports in one of the end-plates which is arranged to communicate with the cells between the compressed fluid inlet duct and the said port of the outlet duct.

3. Pressure exchanger apparatus according to claim 1, wherein a second inlet duct is provided to admit a coolant to the cells at a position, considered in the direction of relative rotation, after the region at which the combustible mixture is ignited.

4. Pressure exchanger apparatus as claimed in claim 1, wherein there is provided an additional compressed fluid-carrying duct in communication with a port in the other end-plate which is arranged opposite the port of the first-mentioned compressed fluid duct.

5. Pressure exchanger apparatus according to claim 1, comprising a further compressed fluid-carrying inlet duct communicating with the cells through one of the ports in the end-plates positioned, considered in the direction of relative rotation, before the duct to introduce combustible



mixture to the cells, a passage communicating through one of the ports in the end-plate after the port in communication with the further compressed fluid-carrying inlet duct and through another one of the ports in the end-plates after the first-mentioned port in communication with the passage, a throttle in the passage, and an outlet duct to remove substantially all of the compressed fluid introduced by the further compressed fluid inlet duct communicating with the cells through one of the ports in the end-plates positioned, considered in the direction of relative rotation, after the second-mentioned port in communication with the passage but before the combustible mixture inlet duct.

6. Pressure exchanger apparatus according to claim 1, wherein one of the ports in one of the end-plates is in communication with a duct communicating with a vacuum pump to scavenge the cells of combustion products.

7. Pressure exchanger apparatus according to claim 1, wherein the ring of cells has the form of a rotor with a larger diameter at each end than at its center.

8. Pressure exchanger apparatus according to claim 1, wherein the cells have a larger cross-sectional area at their ends adjacent each end-plate than at their centers.

9. Pressure exchanger apparatus according to claim 8, wherein each cell has an anvil secured substantially at the center thereof.

10. Pressure exchanger apparatus according to claim 9, wherein the cells are bounded by walls of chevron formation, the apex portions of the walls being thicker than the ends thereof.

11. Pressure exchanger apparatus according to claim 10, wherein the walls of chevron formation have internal passages to permit coolant flow.

12. Pressure exchanger apparatus according to claim 11, wherein the said walls are at least partly porous.

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