June 7, 1955 R. BIRMANN 2,709,893

GAS TURBINE POWER PLANT WITH HEAT EXCHANGER AND COOLING MEANS

Filed Aug. 6, 1949 4 Sheets-Sheet 1

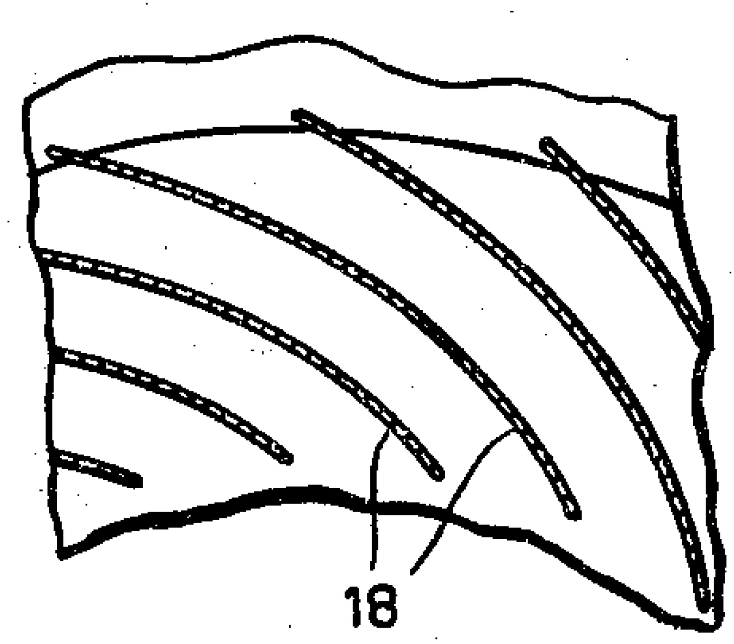

FIG. 2.

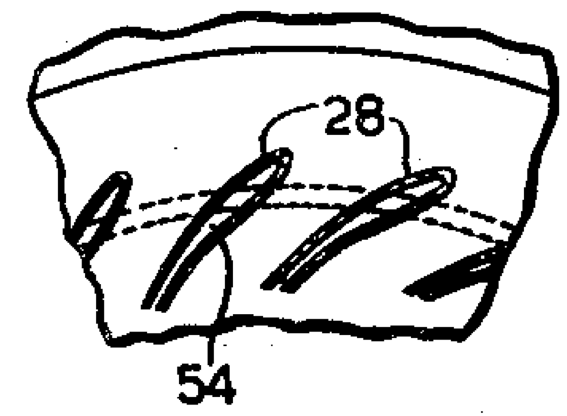

FIG. 3.

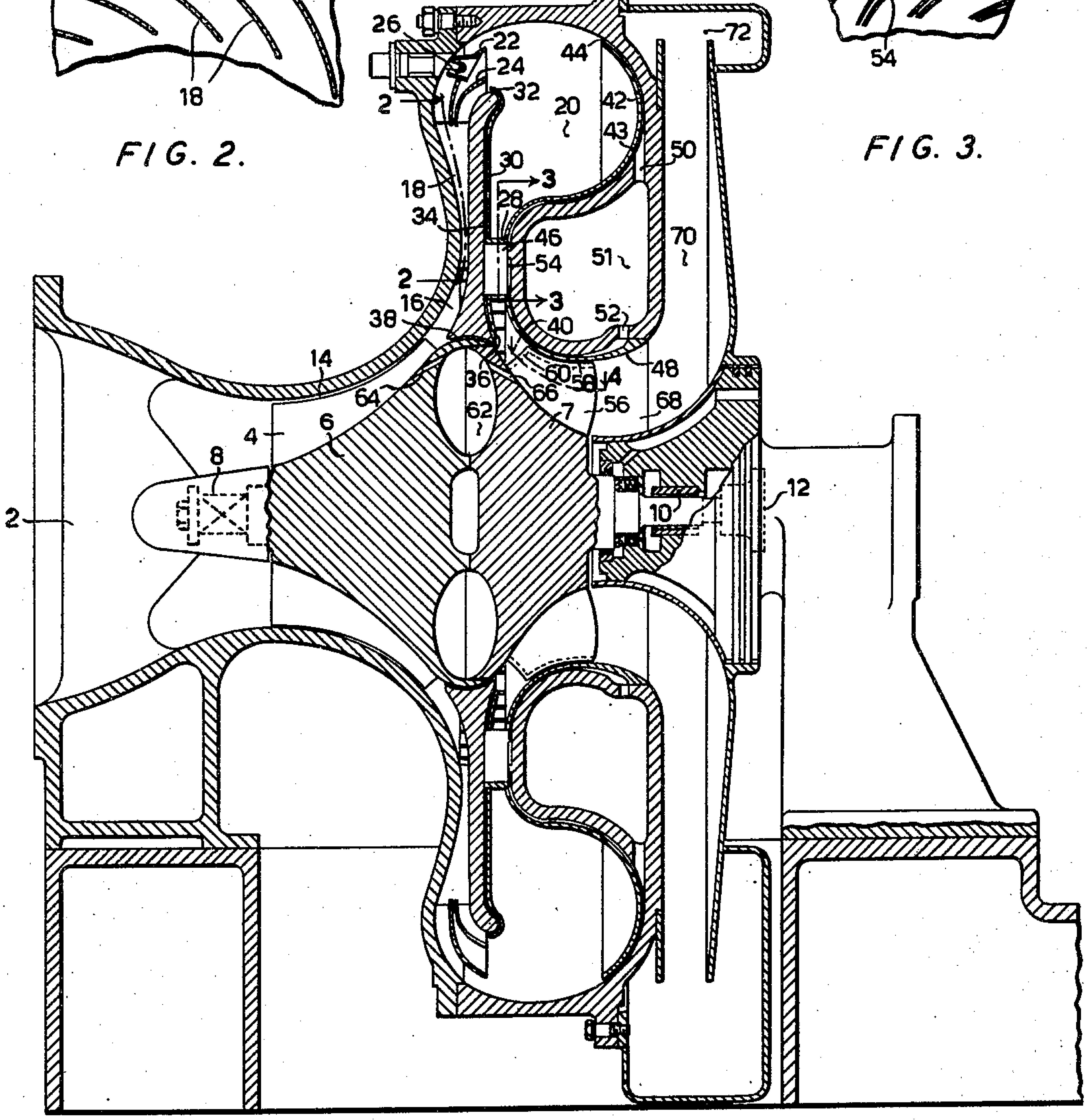

FIG. 1.

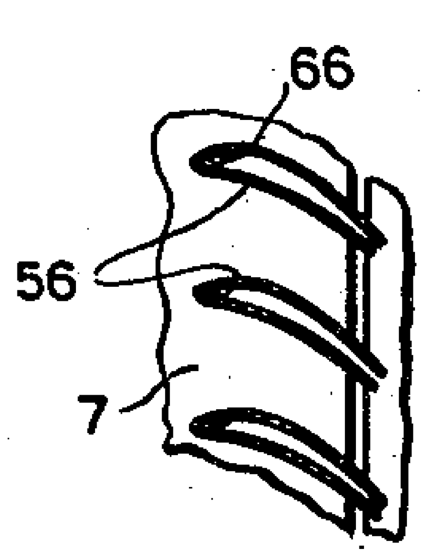

FIG. 4.

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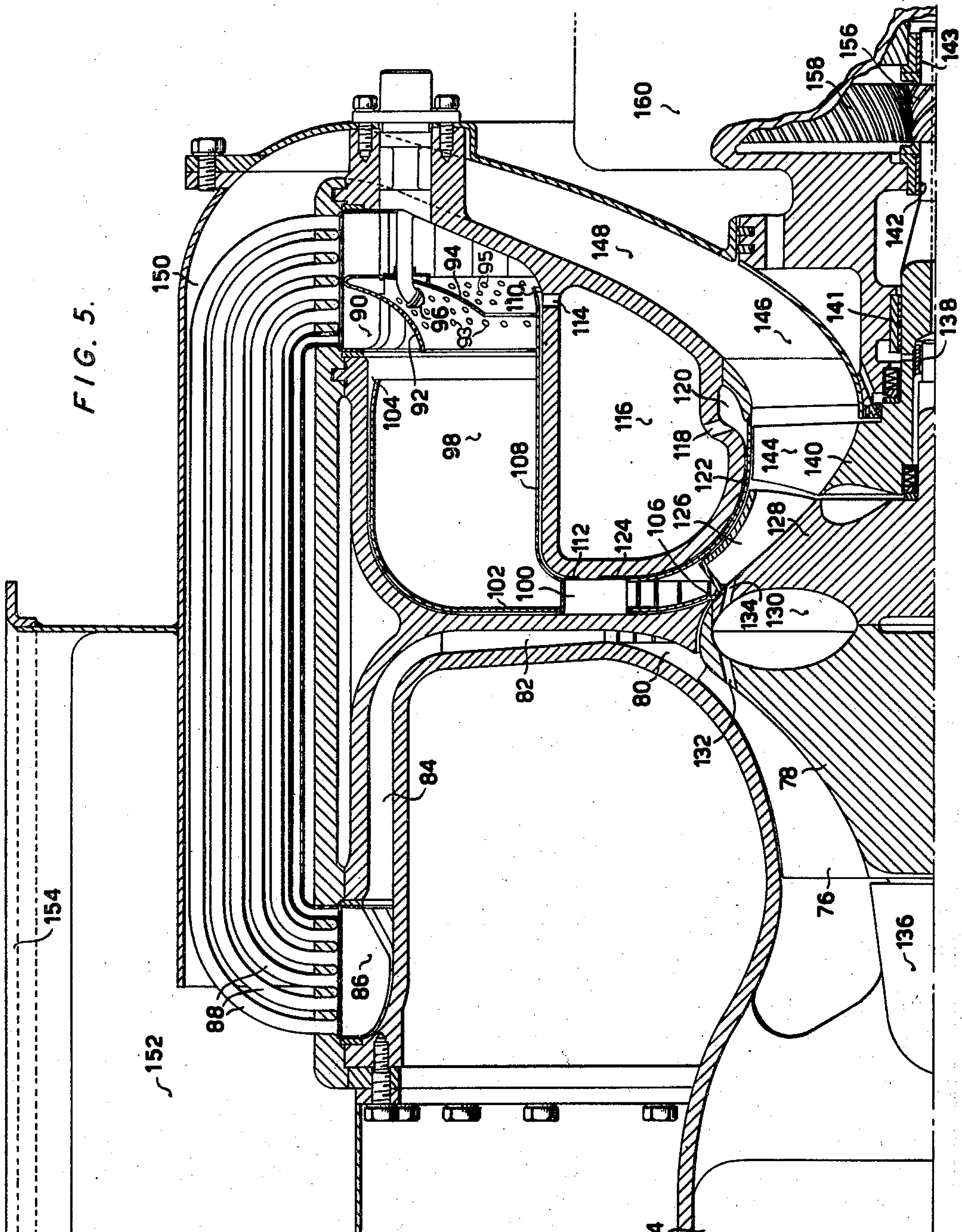
GAS TURBINE POWER PLANT WITH HEAT EXCHANGER AND COOLING MEANS

Filed Aug. 6, 1949 4 Sheets-Sheet 2



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GAS TURBINE POWER PLANT WITH HEAT EXCHANGER AND COOLING MEANS

Filed Aug. 6, 1949 | 4 Sheets-Sheet 3

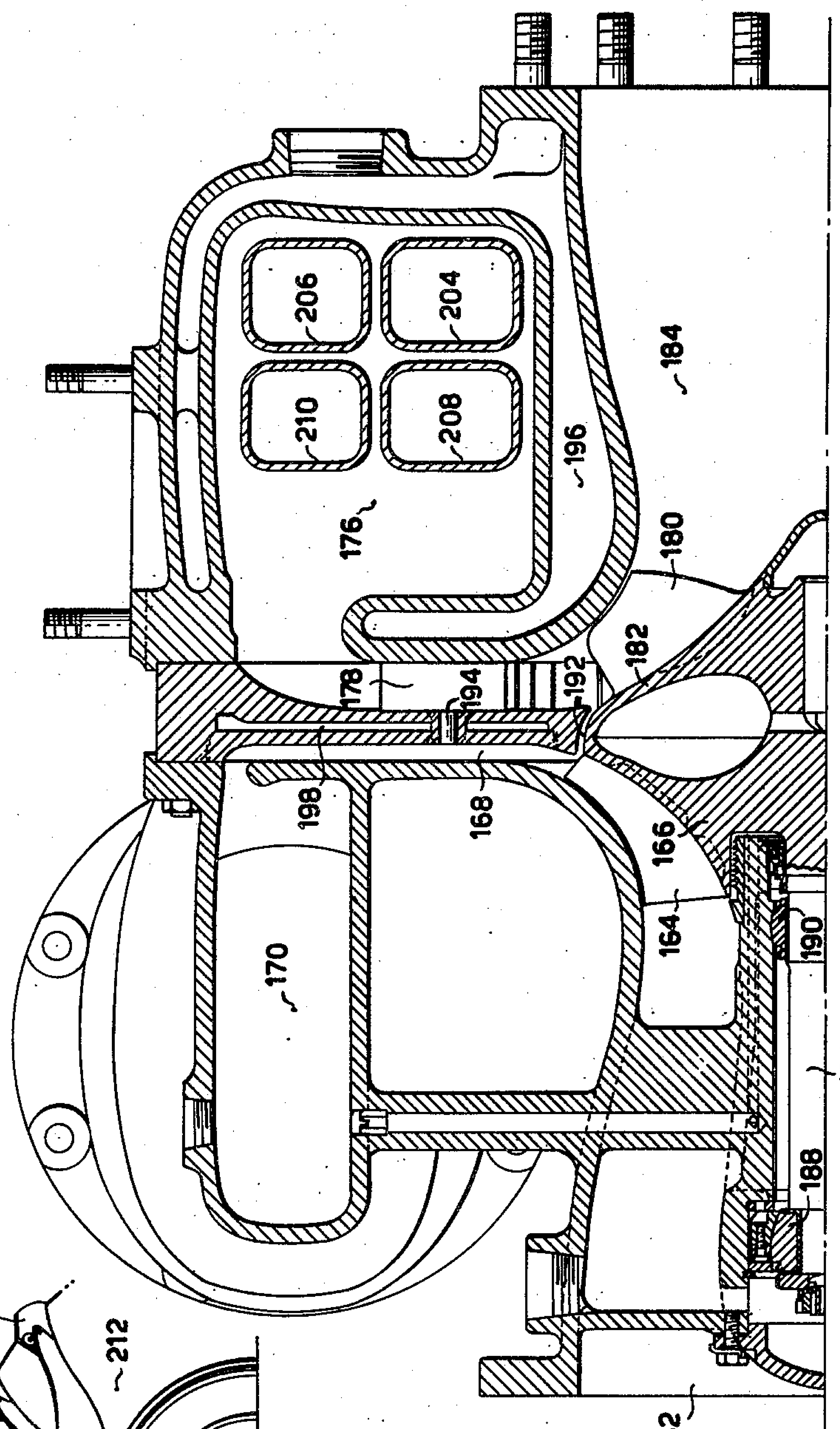

FIG. 6.

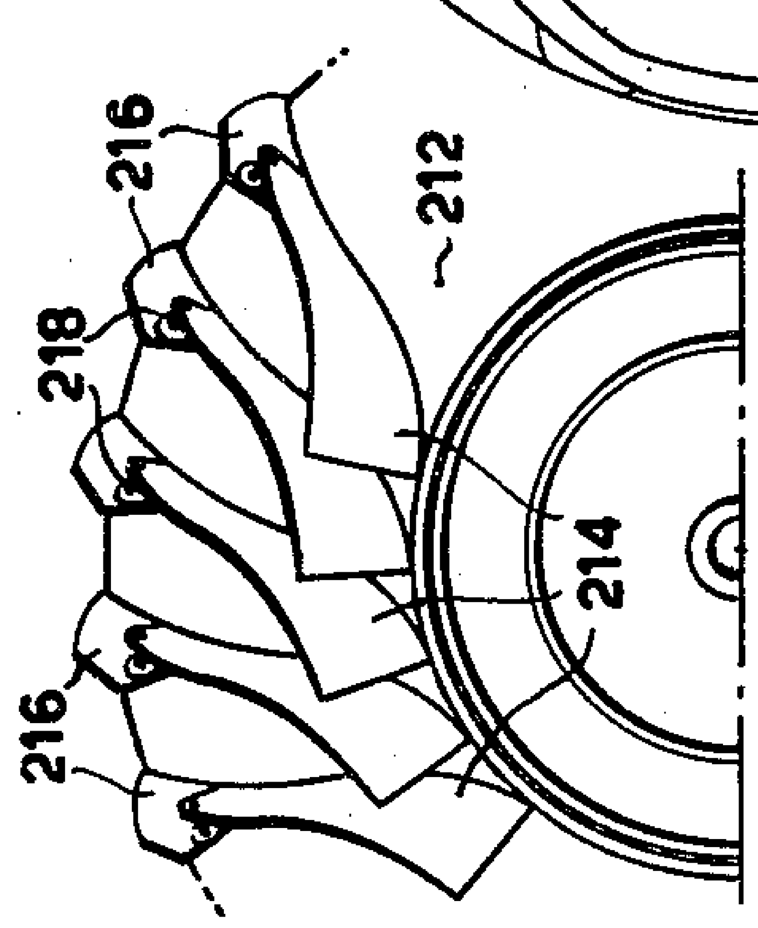

FIG. 8.

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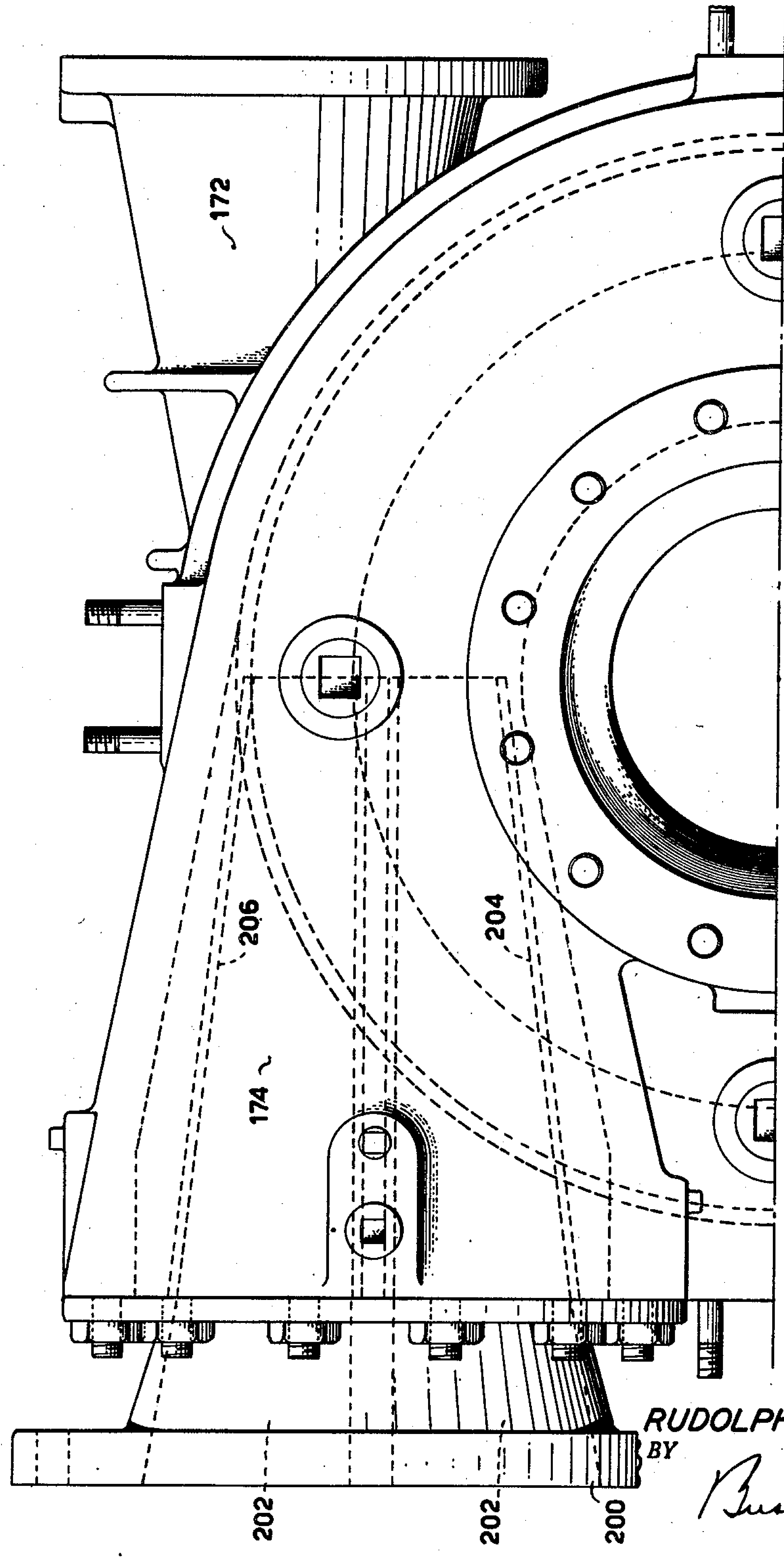

FIG. 7.

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GAS TURBINE POWER PLANT WITH HEAT EXCHANGER AND COOLING MEANS

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Application August 6, 1949, Serial No. 108,975

27 Claims. (Cl. 60—39.51)

This invention relates to gas turbine power plants and has particular reference to such plants of relatively small power outputs though it will become apparent that certain aspects of the invention are applicable to gas turbine power plants of larger sizes.

Claims hereof are directed to certain inventions disclosed in my application Serial No. 38,995, filed July 16, 1948.

It has been known theoretically that gas turbine power plants utilizing the turbine or turbines for the production of useful power must involve exceptionally good compressor efficiency and very high turbine efficiency and must have various parts constructed of alloys highly resistant to heat in combination with other ways and means for making possible safe operation at very high initial temperatures. Only during recent years have these requirements been met to the extent that gas turbine power plants capable of competing with other prime movers could be constructed. But still, at the present time, it has been only possible to construct gas turbine power plants having relatively large power outputs. For small power outputs, such as those ranging from 100 to 500 horsepower, it has been difficult to achieve component efficiencies which result in acceptable performance of the power plant. The difficulties arise from the facts that in small sizes the Reynolds numbers are low, adversely affecting component efficiencies, and that certain parasitic losses, such as windage, friction and leakage, are disproportionately large, resulting in relatively low compressor and turbine efficiencies.

One of the objects of the present invention is to provide a gas turbine power plant in which these parasitic losses are reduced or eliminated and in which the compressor and turbine efficiencies are substantially increased over those obtainable with constructions heretofore used. Another object involved is the provision of a design for the entire hot gas path and particularly a design for the turbine blading which permits operation with exceptionally high initial gas temperatures without anywhere exceeding safe and conservative metal temperatures. This is in contrast to conventional designs of the present date wherein high initial temperatures have been associated with excessive metal temperatures.

Further in accordance with the present invention a gas turbine power plant is achieved which is comparatively simple in construction, eliminating a great number of the parts which cause the conventional gas turbine to be unduly complex structurally in spite of its relatively simple principle of operation.

In brief, these ends are achieved by the utilization of a common rotor for the compressor and the turbine provided for drive of the compressor and possibly for the additional delivery of useful power. As will hereinafter appear, the same general principles are involved in two types of gas turbine power plants having different characteristics of operation. In the case of a gas turbine power plant which is to operate at constant speed a single rotor is involved carrying compressor and turbine blading as just indicated and directly delivering the useful power output. In the case of a variable speed gas turbine power plant two rotors are involved, the first carrying the compressor blading and the turbine blading constituting the turbine for driving the compressor, and a second rotor constituting a second turbine for providing the useful power output, this second turbine receiving its gases directly from the first turbine and being arranged coaxially with the first turbine.

While heretofore there has been discussed a gas turbine power plant of the type utilizing a stationary combustion chamber it will become apparent that various aspects of the present invention are applicable to power plants including an internal combustion engine supercharged by a compressor driven by a gas turbine operating on the exhaust gases from the engine. The provision of a power plant of this type is also one of the objects of the invention. Here also an advantageous construction is achieved by the use of a single rotor carrying the compressor blading for supercharging and the turbine blading for the drive of the compressor. In connection with this type of power plant it is a further object of the invention to provide an arrangement for securing the efficient drive of the turbine by the exhaust gases of the engine despite the intermittent nature of the engine exhaust.

The foregoing objects, together with objects of the invention relating to features of construction and operation, will become apparent from the following description read in conjunction with the accompanying drawings in which:

Figure 1 is a vertical axial section through an improved gas turbine power plant of the type designed for operation at substantially constant speed;

Figure 2 is a fragmentary section taken on the surface, the trace of which is indicated at **2—2** in Figure 1;

Figure 3 is a fragmentary section taken on the plane, the trace of which is indicated at **3—3** in Figure 1;

Figure 4 is a fragmentary developed section taken on the surface of revolution, the trace of which is indicated at **4** in Figure 1;

Figure 5 is a vertical axial section taken through a gas turbine power plant designed to deliver useful power at varying speeds of its output shaft;

Figure 6 is a vertical axial section taken through a turbo-compressor assembly constituting a supercharger for an internal combustion engine;

Figure 7 is an elevation looking at the right of Figure 6; and

Figure 8 is a fragmentary elevation, looking in the direction of the axis of rotation, of an arrangement of compressor blading suitable for use where the axial length of the compressor is relatively short.

Referring first to the power plant illustrated in Figures 1 to 4, inclusive, the power plant therein disclosed comprises a casing provided with an air inlet passage **2** through which air enters the passages between compressor blades **4** carried by the left-hand portion **6** of a rotor, the right-hand portion of which is indicated at **7**. This rotor is mounted in bearings **8** and **10** and is arranged to deliver useful power through its output shaft and coupling **12**.

The housing at **14** provides an outer boundary for the compressor air passages and the compressed air is, in major part, delivered into the vaneless diffuser **16** wherein the direction of flow of the air is smoothly changed to enter the radially extending vaned diffuser **18** wherein a substantial portion of the kinetic energy of the air is converted into pressure. Most of the air leaving the diffuser **18**, however, is permitted to retain a considerable amount of whirl which is carried into the annular combustion chamber **20** under the guidance of annular vanes **22** and

24. The space between these vanes is of diverging form in the direction of spiral flow and, consequently, a relatively minor portion of the air entering between these vanes is slowed down and has injected into it fuel through a series of fuel nozzles 26 arranged in a circle about the axis of rotation.

From the combustion chamber 20 the whirling gases enter nozzles defined by hollow blades 28 which direct gases radially inwardly to the vaneless expansion space 40 from which the gases enter the turbine passages defined by the hollow turbine blades 56 carried by the right-hand portion 7 of the rotor. The gases are discharged with a residual whirl but without substantial radially component of motion into the annular space 68 from which they are directed into the radially extending diffuser 70 which communicates with an annular discharge volute 72 having a tangential outlet (not shown) to the atmosphere.

The major flow has now been described. Certain portions of the compressed air, however, are caused to flow in other paths.

A sheet metal wall 30 is positioned in spaced relationship with the wall constituting the left-hand boundary of the combustion chamber, the nozzle passages and the space 40 to provide a space 34 into which some of the compressed air enters annularly at 32 for inward flow. This compressed air is directed by the nozzle blades 28, which extend through the wall 30 across the space 34, so that the air leaves the passages between these blades in a whirling direction corresponding to that of the combustion gases which are also directed by these blades. The air then leaves the space 34 at 36 where it forms a layer between the combustion gases and additional air which is bled through the passage 38 over the periphery of the hub from the discharge region of the compressor, and along the periphery of the hub and through the portions of the turbine passages adjacent to the hub.

A second sheet metal wall indicated at 42 is spaced from the right-hand wall of the combustion chamber to provide an air space 43 which receives air annularly at 44 and guides it to flow at 46 into the hollow interiors of the nozzle blades 28. Some of the air which enters the space 43 passes through openings 50 into the hollow chamber 51 and thence through openings 52 into a space which is defined outwardly by the wall of the chamber 51 and inwardly by a thin spun wall 48 which provides the right-hand and upper boundary of the space 40 and the gas passages between the turbine blades 56. The air passing outwardly of this wall 42 also enters the hollow nozzle blades at 54. The hollow portions of the nozzle blades are open at the discharge edges of these blades so that the air is discharged to mix with the combustion gases passing through the nozzle passages.

The turbine blades 56 are hollow and the separate portions which form their parts are welded together at the periphery 58 and at the inlet edges 60 of the turbine blades. The interiors of the blades open at the discharge edges thereof.

Passages 64 communicating with the compressor passages serve to bleed air from these passages into the hollow space 62 in the rotor hub and the air passes from this space through passages 66 into the interior spaces of the blades 56 and is discharged into the gas stream issuing from the turbine passages.

The general construction and the flow paths having now been described there may now be referred to the details of what is accomplished.

The hub comprising the portions 6 and 7 and involving the hollow space 62 is in the form of a solid of revolution having the catenoid characteristics referred to in detail in said application Serial No. 38,995. Briefly stated, this construction is such that the thinner portions of the hub flanking and exterior to the space 62 are substantially only in tension under the load of their own material and the blades which they carry with the result that bending stresses are practically eliminated and maximum utilization of the strength of the hub material is attained to the end that the hub may be made relatively light particularly at those portions thereof which are at maximum radius. Very high peripheral speeds are thus attainable with minimum stresses.

The compressor is of the mixed flow type, so called because the flow through its impeller blading is partly axial and partly radial. In contrast with axial flow compressors, mixed flow (and also centrifugal) compressors are distinguished by the fact that a considerable portion of the total pressure rise is the direct result of the centrifugal effect. Since this portion of the total pressure rise, which can amount to as much as 60% or more of the total, is achieved with 100% compression efficiency it could be expected that mixed flow compressors would show a higher overall efficiency than the axial flow type. However, this efficiency can only be achieved by proper aerodynamic design of the passages defined by the impeller blades 4. Accordingly, the compressor passages are designed in accordance with the principles disclosed in detail in said application Serial No. 38,995 to take into account the maintenance of radial stability of the flow, as is accomplished preferably by maintaining free vortex flow throughout. The blade shapes are such that an equal amount of energy is imparted to every air particle regardless of the stream surface along which it travels. The blade form is further characterized by proper aerodynamic loading of the blades and correct load distribution. Specifically the local lift coefficients gradually increase from zero at the inlet edge, reach a permissible maximum at some region between the inlet and discharge edges and from there on smoothly drop off to zero at the discharge edges of the blades. As pointed out in said prior application the blades may be designed to achieve these results and if sufficient axial extent is permissible, as is the case in the present design, the deviations of the blades at all portions thereof from radial condition may be maintained sufficiently small to avoid bending stresses which might result in failure. Under some conditions, however, the blades may have to be made of several sections as will be referred to hereafter. Reference may be made to the application referred to above for details of design considerations involved in the shaping of the compressor blades.

Structurally the blades can be produced by die-forming from sheet metal stock. The blades formed in this manner are inserted in suitable shallow slots milled in the surface of the rotor hub and fastened therein by furnace copper brazing. A construction is thereby achieved which will withstand the centrifugal stresses which are encountered in high speed operation.

The vaneless diffuser 16 in part achieves the conversion of energy into pressure and this conversion is further carried out in the passages defined by the diffuser blades 18. However, in the present construction this conversion is only partially achieved and the air entering the combustion chamber still retains a very high proportion of its energy in kinetic (whirl) form. The diffuser is desirably designed in accordance with the principles set forth in said application Serial No. 38,995.

The condition of maintaining residual whirl is in contrast with what has occurred in hitherto known gas turbine power plants. Usually in such plants the entire air flow has been completely decelerated and then delivered through pipe connections to a combustion chamber. At the sacrifice of pressure there then had to be artifically produced in this combustion chamber violent turbulence by means of baffles and other devices for the purpose of achieving complete combustion and mixing the products with diluting air. After the heated mixture was conveyed at low velocity through ducts to the turbine it was reaccelerated in the turbine nozzles and blading for the purpose of converting the heat and pressure energy of the gases into mechanical energy.

In the present case, however, the conversion of kinetic energy is carried out in the diffusers only to a limited extent. The air which enters the combustion chamber from the passage exterior to the turning vane **22** and interior to the turning vane **24** has a high whirl velocity and spirals inwardly, with increase of whirl component, to enter the nozzle passages which are so directed as to receive the gases at entrance angles corresponding to the direction of the absolute velocity. (In here speaking of the air there is, of course, referred to the elastic fluid which is originally air but by combustion of fuel is transformed in the combustion chamber into a high temperature mixture of air and combustion gases.) The relatively small portion of the air which passes between the vanes **22** and **24** is decelerated to some further extent so that combustion of the fuel entering from the nozzles **26** may be initiated and maintained. It has been found that if air is whirling in a spiral course it is not necessary, to maintain a flame, that the absolute velocity of the flow should be reduced below the velocity of flame propagation. Rather when a spiral path of the air is maintained in a suitable annular chamber it is only necessary that the meridian velocity should be maintained below the flame propagation velocity. Since this last velocity may be considerably less than either the absolute velocity or its whirl component, it will be evident that for the maintenance of a flame the absolute velocity need be reduced to a much less extent than would be required if combustion was to be maintained in a stream of air flowing in a straight line. The present construction takes advantage of this and, as pointed out heretofore, high whirl velocities may be maintained in the combustion chamber thereby avoiding the transition losses which are entailed if the air must be almost completely decelerated at the outlet of the stationary compressor blading and then reaccelerated at the turbine.

While referring to the combustion chamber it may be noted that the entrances **32** and **44** into the spaces behind the lining walls are located in such positions that they are out of the region of the flame and accordingly only the relatively cool air will enter these spaces. Where these entrances exist the products of combustion will not yet have spread outwardly. Beyond these entrances the whirling condition existing in the combustion chamber will affect substantially complete admixture of the combustion gases with the air so that homogeneous high temperature gases enter the nozzle passages.

The fact that the flow approaching the turbine nozzles already possesses a considerable kinetic energy means that there is a considerable reduction of the acceleration which must take place in the turbine nozzles and there is practically eliminated any turning of the flow in these nozzles. The gases discharged from the turbine nozzles enter the space **40** where vortex flow is properly maintained for entrance into the turbine gas passages.

The turbine blading is also constructed in accordance with the principles set forth in the above mentioned application Serial No. 38,995. As in the case of the compressor vortex flow is maintained, with maintenance of radial stability and with proper loading of the turbine blades so as to secure a transformation of the gas energy into mechanical power under conditions of maximum efficiency. Centripetal action here occurs with its attendant advantages in securing the transformation of energy in an efficient fashion similar to that in which a reverse transformation is attained in the mixed flow compressor. Each turbine blade consists of two separate halves both of which are die-formed from thin tapered sheet stock. These two halves are joined into a single blade by a continuous seam weld along the entrance edge and the entire tip contour thus enclosing a thin hollow space for the passage of internally flowing cooling air. These hollow blades are provided with enlarged base portions fitting into slots milled into the rotor hub surface and copper brazed thereto.

The cooling air which enters the passages **64** and thence passes into the space **62** and through the passages **66** into the interior of the turbine blades is heated in such passage and by virtue of inward flow and discharge at the discharge edges of the turbine blades has its heat energy converted into thrust energy which may be shown to involve complete recovery of the work of compressing the cooling air and partial recovery of the heat absorbed from the blades during its cooling action. In other words, the cycle of this cooling air involves compression, heating (by cooling the blades) and then expansion to produce a net power output.

The flow of air over the periphery of the hub through the space **38** serves not only for cooling the periphery of the hub but also for the cooling of the hub and turbine blades at the bases of these blades since this air flows along the hub and serves to isolate from the hub the turbine driving gases. This air also partakes of a cycle which involves compression, heating and expanding so as to provide a substantial recovery of the energy expended in its compression.

The air entering at **32** serves to cool the thin wall **30** and to provide isolation of the heavier wall between the combustion chamber and the diffuser from the high temperature existing in the combustion chamber. This air is directed by the nozzle blades and where it emerges at **36** it provides a second cooling flow exterior to the flow of air from passage **38** and between this flow and the combustion gases. Accordingly, it also serves to effect cooling of the roots of the turbine blades. It may be noted that this air also is involved in a cycle of compression, heating and expansion to provide recovery of the energy involved in its compression and at least partial recovery of the heat absorbed during its cooling action.

The air behind the wall **42** and exterior to the wall **48** is also involved in a similar cycle, being merged with the combustion gases flowing from the nozzles and then passing through the turbine blading.

The air cooling of the walls of the combustion chamber and the use of heat resisting alloys for the thin walls **30**, **42** and **48** serves for the protection of the portions of the casing bounding the combustion chamber so as to minimize difficulties which would otherwise arise from intense heating of the casing. To summarize, it will be noted that the entire path of the hot gases is effectively bounded by cooling air except for the nozzle and turbine blades themselves which are internally cooled. Accordingly, the difficulties which have hitherto been encountered in handling high temperatures are thoroughly eliminated.

As is well known the power output of a turbine rises rapidly with the lowering of the pressure into which the turbine exhausts. In the present design the gases which are discharged from the turbine enter the vaneless diffuser **70** wherein residual kinetic energy is converted into pressure. Since the diffuser communicates with the atmosphere the final pressure obtained must be atmospheric pressure and the result is that in operation there exists in the region **68** at the discharge from the turbine a subatmospheric pressure with a resulting effective lowering of pressure at the discharge of the turbine as contrasted with the pressure which would exist if the turbine discharged directly into the atmosphere. The efficiency of the cycle is thus augmented.

The power plant so far described is adapted for a substantially constant speed operation of the output shaft since for proper operation the turbo-compressor should operate at approximately constant speed. The plant is therefore suitable for the driving of generators, pumps, compressors, or the like. For applications where the power output speed varies within wide limits as, for example, in the drive of locomotives or road vehicles the power turbine must be independent of the turbine which drives the compressor. An embodiment of the invention which is suitable for such use is illustrated in Figure 5.

In this figure the casing is provided with an air inlet **74** for flow of air to the compressor blading **76** carried by the left-hand portion **78** of a primary rotor. As in the case of the previous modification the air is delivered from the compressor to a vaneless diffuser **80** followed by a vaned diffuser **82** which discharges the air into an annular space **84**, the diffuser **82** in this case serving to substantially reduce the spin of the air. Vanes **86** receive the air and deflect its flow radially outwardly into the heat exchange tubes **88** which are arranged annularly around the axis. These tubes, in turn, deliver the air to the spaces between vanes **90** which impart a whirl to the air in the direction of rotation of the rotor and into the combustion chamber **98**, annular guide vanes **92** and **94** serving to turn the air into the chamber and also serving to define a space into which fuel is discharged from fuel nozzles **96**, which space receives air for combustion through the holes **93** and **95** in the vanes **92** and **94**. From the combustion chamber the air flows through hollow nozzle blades **100** similar to those described in the previous modification. As in the previous modification the combustion chamber wall has located in spaced relation to it a thin metal wall **102** defining an air space receiving air at **104** and discharging it at **106** following its deflection by the blades **100** which extend across the space between the two walls. A sheet metal wall **108** lines the inner portion of the combustion chamber being spaced from its boundary wall and receiving air at **110**, discharging it at **112** into the hollow spaces in the nozzle blades. Some of the air is passed through opening **114** into annular chamber **116** from which it passes in turn into the space **120** behind a wall **122** which forms an outer boundary for the gas passages through the two turbines. The space **120** discharges at **124** into the openings in the blades **100** from which openings the air discharges at the inner ends of the blades to mix with the driving gas stream. Turbine blades **126** forming a high pressure stage are carried by the right-hand portion **128** of the rotor. The space **130** in the rotor hub receives air at **132** from the compressor passages and this air is discharged through passages **134** into the hollow spaces in the turbine blades **126** which discharge the air at the discharge edges of these blades.

It will be noted from the foregoing that so far as described and except for the heat exchanger the construction closely resembles that of Figure 1 and similar considerations apply to the corresponding elements which need not be described in further detail, there being involved the same aspects of design of the impeller and turbine blading, of the rotor hub, and of the cooling arrangements which are provided. There is, of course, a loss of pressure through the heat exchange piping.

The high pressure turbine-compressor rotor is provided with a bearing at **136** and has a right-hand bearing at **138** within the hub **140** of a low pressure turbine rotor which is supported in bearing **141** and, through its shaft, in bearings **142** and **143**. The low pressure turbine is provided with blading **144** designed for proper vortex flow in accordance with the same principles as the high pressure blading and as described in said prior application Serial No. 38,995. The low pressure turbine discharges its gases into the annular region **146** communicating with the vaneless diffuser **148** which transforms residual spin of the gases into pressure delivering the gases into the casing region **150** surrounding the heat exchange tubes **88** from which region discharge takes place into the exhaust collector housing **152** which discharges the gases to atmosphere through the outlet **154**. The shaft of the rotor **140** delivers its useful power through reduction gearing indicated at **156** and **158** within a gear housing **160** which may be of usual construction.

Except for the maintenance of whirl of the air through the combustion chamber and into the turbine nozzles the advantages of the high pressure stage and compressor arrangement are similar to those described above. The gases are discharged from the first stage turbine directly to the blading of the low pressure stage turbine and since vortex flow takes place in both stages the transfer of gases from one stage to the other may be accomplished with a minimum of losses since there is no necessity for any redirection of the gases. Furthermore, when the low pressure power output turbine is running at rated speed the relative speed of rotation of the two turbines will be a minimum and losses at such time are correspondingly at a minimum. As in the previous modification the use of the diffuser **148** permits the low pressure stage to discharge its gases to subatmospheric pressure.

While the use of the heat exchanger necessitates removing the whirl from the compressed air the advantages of utilizing heat exchange more than compensate for this disadvantage and it is desirable, accordingly, to provide heat exchange. In fact, it will be evident that in the modification illustrated in Figure 1 the arrangement could also involve heat exchange in the same fashion though heat exchange must be avoided where the unit is to remain of small size and Figure 1 is intended to show a power plant of minimum size.

The low pressure power turbine can operate at any speed from zero to maximum while the compressor-drive turbine can continue to operate at full speed permitting the compressor to operate under the conditions of flow and pressure ratio at which peak power and best thermal efficiency can be obtained. If applied to the propulsion of a vessel, locomotive or road vehicle the power turbine is not rotating when the vehicle stands still whereas the compressor and its driving turbine can run at full speed, which results in development in the power turbine of a torque which may be about 2.3 times its full-load torque. Once the vehicle is in motion and operating normally both the compressor-drive turbine and the power turbine rotate in the same direction and there is little or no differential speed between the two. It may be noted that the low pressure turbine requires no special cooling since the temperature of the gases will have been substantially lowered by the passage through the high pressure stage.

The arrangement of the heat exchanger annularly around the turbine axis keeps to a minimum the flow path of the compressed air and results in extreme simplicity and compactness of the entire power plant.

As mentioned above most of the features of design of the gas turbine power plants utilizing stationary combustion chambers may be applied to a supercharger for a reciprocating internal combustion engine either of diesel or spark ignition type. Figures 6 and 7 illustrate such a supercharger.

Air enters the housing at **162** and after flowing past bearing-supporting struts, enters the compressor blading at **164** carried by the left-hand portion **166** of a hub of catenoid construction such as previously described. In this case a vaneless diffuser **168** receives the air from the impeller and passes it to the volute **170** from which the air is discharged through outlet **172** to the engine. The engine may be of any suitable type capable of utilizing supercharging air.

From the engine the exhaust gases enter the annular gas chamber **176** in fashions which will be described in greater detail hereafter. The gases are delivered from the chamber **176** to nozzles **178** which impart vortex motion to the gases to deliver them to the passages between turbine blades **180** which, in turn, discharge the gases through the tail passage **184**. The rotor is mounted in overhung fashion through the medium of a shaft **186** mounted in bearings indicated generally at **188** and **190**. For the cooling of the hub some of the compressed air is bled across the periphery of the hub at **192** to provide a layer of cooling air passing through the root portions of the turbine passages. The gas chamber **176** is jacketed as indicated at **196** and **198** to receive cooling water from the cooling water system of the engine. The nozzle guide vanes are mounted on tenons **194** so that they may be adjusted to conform the turbine to different engines.

It will be evident from what has been described that this supercharger embodies many of the features of the power plants previously described and structural details, as for example of the compressor and turbine blading, may be precisely as previously described. In view of the fact, however, that the gas temperatures are much lower than those in the previous systems it is unnecessary to resort to wall cooling arrangements and the turbine blades may be made solid instead of hollow since they are subjected only to temperatures which may be readily tolerated by ordinary heat resisting alloys.

Reference may now be made to the special considerations involved in the delivery of the engine exhaust gases to the turbine. As is well known, proper operation of a turbine requires feed thereto of gases at uniform velocity, temperature and pressure. Accordingly, it is common to employ between an internal combustion engine and a turbine to be driven by its exhaust gases a chamber in which the pulses resulting from exhaust of the engine cylinders are smoothed out to provide gas at substantially constant pressure. If such an arrangement is used the gases may be directly delivered through the tangential inlet **174** to the gas chamber **176**.

However, in many cases the use of such a constant pressure producing device represents substantial losses and it is one of the objects of the present invention to provide an arrangement in which the pulses are efficiently smoothed out by the provision of a gas "fly wheel" which acquires a substantially constant kinetic energy despite the delivery thereto of intermittent pulses of gas from the engine. To attain this end an adapter indicated generally at **200** is bolted to the inlet **174** and is provided with a group of passages **202** extended as nozzles **204**, **206**, **208** and **210** which discharge tangentially into the annular chamber **176** at a region axially remote from the location of the nozzle blades **178**. These various nozzles are connected to groups of cylinders which are not simultaneously exhausted. For example, in the case of an eight cylinder engine four nozzles such as illustrated may be utilized with a resulting avoidance of interference with the operation. These nozzles receive the pressure waves of the engine exhaust and expand and discharge the exhaust gases at high velocity into the chamber **176** with the resulting setting up of high speed rotation of the mass of gas therein which, as it progresses toward the turbine nozzles, acquires a uniform velocity so that the nozzles are fed uniformly despite the pulsations produced by the engine. By reason of the use of the nozzles **204**, **206**, **208** and **210** such high velocities are set up as will produce a suction action on the nozzles during their intermittent idle periods with the result that the arrangement, instead of increasing back pressure on the engine will actually produce a reduction of pressure with the result that engine cylinders exhaust to a pressure below the total pressure (static plus dynamic) necessary for driving the turbine; in other words, below the pressure which would exist in the exhaust manifold without the use of the pulse-converter system described. In fact, such high velocities are set up in the chamber **176** that the velocity of approach to the turbine nozzles is in excess of that for proper approach to the turbine blading. The turbine nozzles are accordingly somewhat misnamed in that instead of functioning as nozzles they function rather as diffusers, i. e., the nozzle passages expand in the direction of flow so as to slow down the gases for their approach to the turbine. The result is that the static pressure at the inlet to the turbine blades exceeds the static pressure at the inlet to the turbine nozzles.

While the nozzles **204**, **206**, **208** and **210** are shown as discharging in the same general region it will be evident that, if convenient, they may be equally or otherwise spaced about the axis so as to discharge at different points in the gas fly wheel chamber **176**.

The blades **178** are so oriented that their passages are tangential to the circulating flow of the gas "fly wheel" with the result that the kinetic energy of the gases is to a large extent not transformed in passage through the turbine nozzles.

It was pointed out that in accordance with the principles set forth in my prior application Serial No. 38,995 compressor blades could be made in single sections provided a sufficient axial length was permissible. Where axial length is restricted, however, the blades may be required to depart sufficiently from radial condition in some portions thereof as would result in the setting up of destructive stresses during high speed operation unless a split construction is adopted. Figure 8 illustrates a form of blades which may be utilized when a split construction is required. A hub surface **212** similar to the hub surfaces previously described has brazed thereto pairs of blade sections **214** and **216** which are continuous at their junctions with the hub. Each blade portion **214** is substantially radial over a large extent of its inlet region and each blade section **216** is radial in the vicinity of the discharge. However, the trailing portion of the first section **214** and the leading portion of the second section **216**, when proper design for vortex flow is adopted in accordance with said application, substantially depart from radial condition and to effect neutralization of the bending these portions of the two blade sections are connected by a strut **218**. The connecting strut acts as a vibration damper and the slit which exists serves to bypass air from the pressure side to the suction side of the blade bringing about an energization of the boundary layer of air in accordance with the principle of the slotted wing such as used in aircraft construction. The two sections have a common hub stream line while all other stream lines are displaced peripherally by a distance corresponding to the width of the slit at their location. By the adoption of this type of construction the axial extent of the compressor may be substantially shortened wherever required.

What is claimed is:

1. A power plant comprising a housing, a rotor within the housing carrying blades providing air compressor passages and hollow blades providing turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, and means for bleeding air from the compressor passages to the interiors of said turbine blades to effect cooling thereof.

2. A power plant comprising a housing, a rotor within the housing carrying blades providing air compressor passages and hollow blades providing turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, and means for bleeding air from the compressor passages to the interiors of said turbine blades to effect cooling thereof, said hollow turbine blades discharging the air from their interiors to mingle with the discharged driving gases.

3. A power plant comprising a housing, a hollow rotor within the housing carrying blades providing air compressor passages and hollow blades providing turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of

motion, means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, and means for bleeding air from the compressor passages into the interior of said rotor and thence to the interiors of said turbine blades to effect cooling thereof.

4. A power plant comprising a housing, a hollow rotor within the housing carrying blades providing air compressor passages and hollow blades providing turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, and means for bleeding air from the compressor passages into the interiors of said rotor and thence to the interiors of said turbine blades to effect cooling thereof, said hollow turbine blades discharging the air from their interiors to mingle with the discharged driving gases.

5. A power plant comprising a housing, a rotor within the housing carrying blades providing both air compressor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, and a second rotor adjacent to the first mentioned rotor and rotatable relatively thereto and provided with turbine blading arranged to receive directly the gases discharged from the first mentioned turbine passages.

6. A power plant comprising a housing, a rotor within the housing carrying blades providing both air compressor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, a second rotor adjacent to the first mentioned rotor and provided with turbine blading arranged to receive directly the gases discharged from the first mentioned turbine passages, and a heat exchanger to effect heating of air compressed in said compressor passages by gases discharged from the turbine passages of the second mentioned rotor.

7. A power plant comprising a housing, a rotor within the housing carrying blades providing both air compressor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, an annular combustion chamber surrounding said rotor, guiding means for directing into said combustion chamber air compressed by said compressor with a substantial tangential component to provide rotation of air in the combustion chamber in the direction of rotation of the rotor, means for introducing and burning fuel in the air rotating in the combustion chamber, and nozzles directed to receive smoothly from said combustion chamber gases having a substantial tangential velocity component and directing said gases to said turbine passages to drive the rotor.

8. A power plant comprising a housing, a rotor within the housing carrying blades providing both air compressor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, an annular combustion chamber surrounding said rotor, means including a diffuser for directing into said combustion chamber air compressed by said compressor with a substantial tangential component to provide rotation of air in the combustion chamber in the direction of rotation of the rotor, means for introducing and burning fuel in the air rotating in the combustion chamber, and nozzles directed to receive smoothly from said combustion chamber gases having a substantial tangential velocity component and directing said gases to said turbine passages to drive the rotor.

9. A power plant comprising a housing, a rotor within the housing carrying blades providing both air compressor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, an annular combustion chamber surrounding said rotor, means including a diffuser followed by directing vanes for directing into said combustion chamber air compressed by said compressor with a substantial tangential component to provide rotation of air in the combustion chamber in the direction of rotation of the rotor, means for introducing and burning fuel in the air rotating in the combustion chamber, and nozzles directed to receive smoothly from said combustion chamber gases having a substantial tangential velocity component and directing said gases to said turbine passages to drive the rotor.

10. A power plant comprising a housing, a rotor within the housing carrying blades providing both air compressor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, an annular combustion chamber surrounding said rotor, means for directing into said combustion chamber air compressed by said compressor with a substantial tangential component to provide rotation of air in the combustion chamber in the direction of rotation of the rotor, means for introducing and burning fuel in the air rotating in the combustion chamber, nozzles directed to receive smoothly from said combustion chamber gases having a substantial tangential velocity component and directing said gases to said turbine passages to drive the rotor, and thin metallic wall members providing air passages bounding major internal areas of said combustion chamber, said air passages having communication with the interior of the combustion chamber to receive relatively cool air therefrom to cool the combustion chamber walls.

11. A power plant comprising a housing, a rotor within the housing carrying blades providing both air compressor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, an annular combustion chamber surrounding said rotor, means for directing into said combustion chamber air compressed by said compressor with a substantial tangential component to provide rotation of air in the combustion chamber in the direction of rotation of the rotor, means for introducing and burning fuel in the air rotating in the combustion chamber, nozzles directed to receive smoothly from said combustion chamber gases having a substantial tangential velocity component and directing said gases to said turbine passages to drive the rotor and thin metallic wall members providing air passages bounding major internal areas of said combustion chamber, said air passages having communication with the interior of the combustion chamber to receive relatively cool air therefrom to cool the combustion chamber walls, said air passages discharging their air into the combustion gases approaching the turbine passages.

12. A power plant comprising a housing, a rotor within the housing carrying blades providing both air compres-

sor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, an annular combustion chamber surrounding said rotor, means for directing into said combustion chamber air compressed by said compressor with a substantial tangential component to provide rotation of air in the combustion chamber in the direction of rotation of the rotor, means for introducing and burning fuel in the air rotating in the combustion chamber, nozzles directed to receive smoothly from said combustion chamber gases having a substantial tangential velocity component and directing said gases to said turbine passages to drive the rotor, said nozzles being defined by hollow blades having their interior spaces arranged to discharge in the direction of flow through the nozzles, and a thin metallic wall member providing an air passage bounding an internal area of said combustion chamber, said air passage having communication with the interior of the combustion chamber to receive relatively cool air therefrom to cool said area of the combustion chamber and communicating with the interior spaces of said hollow blades to provide internal cooling of the blades.

13. A power plant comprising a housing, a rotor within the housing carrying blades providing both air compressor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, an annular combustion chamber surrounding said rotor, means for directing into said combustion chamber air compressed by said compressor with a substantial tangential component to provide rotation of air in the combustion chamber in the direction of rotation of the rotor, means for introducing and burning fuel in the air rotating in the combustion chamber, nozzles directed to receive smoothly from said combustion chamber gases having a substantial tangential velocity component and directing said gases to said turbine passages to drive the rotor, said nozzles being defined by hollow blades having their interior spaces arranged to discharge in the direction of flow through the nozzles, and means for directing air compressed by said compressor into the interior spaces of said blades to provide internal cooling of the blades.

14. A power plant comprising a housing, a rotor within the housing carrying blades providing both air compressor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine pasages receiving a flow of gas having a substantial inward component of motion, means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, and a diffuser receiving gases discharged from said turbine passages and discharging to the atmosphere so that the pressure at the discharge from said turbine passages is subatmospheric.

15. A power plant comprising a housing, a rotor within the housing carrying blades providing both air compressor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, and a vaneless diffuser receiving gases discharged from said turbine passages and discharging to the atmosphere so that the pressure at the discharge from said turbine passages is subatmospheric.

16. A power plant comprising a housing, a rotor within the housing carrying blades providing both air compressor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, a second rotor adjacent to the first mentioned rotor and provided with turbine blading arranged to receive directly the gases discharged from the first mentioned turbine passages, and a diffuser receiving gases discharged from the blading of said second rotor and discharging to the atmosphere so that the pressure at the discharge from the second rotor is subatmospheric.

17. A power plant comprising a housing, a rotor within the housing carrying blades providing both air compressor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, a second rotor adjacent to the first mentioned rotor and provided with turbine blading arranged to receive directly the gases discharged from the first mentioned turbine passages, and a vaneless diffuser receiving gases discharged from the blading of said second rotor and discharging to the atmosphere so that the pressure at the discharge from the second rotor is subatmospheric.

18. A power plant comprising a housing, a rotor within the housing carrying blades providing both air compressor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, a second rotor adjacent to the first mentioned rotor and provided with turbine blading arranged to receive directly the gases discharged from the first mentioned turbine passages, a heat exchanger to effect heating of air compressed in said compressor passages by gases discharged from the turbine passages of the second mentioned rotor, and a diffuser between said second mentioned rotor and said heat exchanger for delivering the gases from the former to the latter.

19. A power plant comprising a housing, a rotor within the housing carrying blades providing both air compressor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, and a heat exchanger to effect heating of air compressed in said compressor passages by gases discharged from said turbine passages.

20. A power plant comprising a housing, a rotor within the housing carrying blades providing both air compressor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, and a heat exchanger to effect heating of air compressed in said compressor passages by gases discharged from said turbine passages prior to the passage of the air to said means for adding heat.

21. A power plant comprising a housing, a rotor within the housing carrying blades providing both air compressor

passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, a heat exchanger to effect heating of air compressed in said compressor passages by gases discharged from said turbine passages, and a diffuser between said turbine passages and said heat exchanger for delivering the gases to said heat exchanger.

22. A power plant comprising a rotor carrying blades providing both air compressor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough a substantial outward component of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, and means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, said rotor being in axial section convex at its central portion and concave through portions of substantial axial extent flanking said central portion, the concave portions of the surface carrying, respectively, the compressor blades and the turbine blades and providing outwardly concave passage walls, the convex central portion of the rotor having clearance with a surrounding housing for bypass of compressed air from the compressor passages to the inner portions of the turbine passages adjacent to the rotor to provide cooling of the region of attachment of the turbine blades to the rotor, the convex central portion of the rotor and the surface of the surrounding housing providing said clearance being directed, in axial section, substantially tangential to the turbine side of the rotor to direct the bypassed air tangentially into the flow through said turbine passages.

23. A power plant comprising a housing, a rotor within the housing having a periphery which is convexly rounded in axial section and carrying blades on one axial side of said periphery providing air compressor passages and carrying blades on the other axial side of said periphery providing turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough substantial outward components of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, and means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, said rotor periphery having a small clearance with an adjacent portion of the housing to provide for bleeding of air from the compressor passages to the turbine passages, the rotor periphery and said adjacent portion of the housing providing said clearance being directed, in axial section, substantially tangential to the turbine side of the rotor to direct the bled air tangentially into the flow through said turbine passages.

24. A power plant comprising a housing, a rotor within the housing carrying blades having skew directions with respect to the axis of the rotor and providing both air compressor passages and turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough substantial outward components of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, means beyond the outlets of the compressor passages for reducing the meridianal component of flow of the air, and means for adding heat to air after passage through the last mentioned means to provide heated gases for flow through said turbine passages, said rotor being provided with an internal space having interconnection with and receiving air from said compressor passages.

25. A power plant comprising a housing, a rotor within the housing having a periphery which is convexly rounded in axial section and carrying blades on one axial side of said periphery providing air compressor passages and carrying blades on the other axial side of said periphery providing turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough substantial outward components of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, and means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, said rotor being provided with an internal space having interconnection with and receiving air from said compressor passages.

26. A power plant comprising a housing, a rotor within the housing having a periphery which is convexly rounded in axial section and carrying blades on one axial side of said periphery having skew directions with respect to the axis of the rotor and providing air compressor passages and carrying blades on the other axial side of said periphery providing turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough substantial outward components of motion and the turbine passages receiving a flow of gas having a substantial inward component of motion, and means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, said rotor being provided with an internal space having interconnection with and receiving air from said compressor passages.

27. A power plant comprising a housing, a rotor within the housing having a peripheral portion in the form of a hollow metallic shell constituting a solid of revolution, which shell is convexly outwardly rounded in axial section in the region of its maximum radius, carries blades on one axial side of said peripheral portion providing air compressor passages and carries blades on the other axial side of said peripheral portion providing turbine passages, the walls of the air compressor passages imparting to the flow of air therethrough substantial outward components of motion, means for directing into said turbine passages a flow of gas having a substantial inward component of motion, and means for adding heat to air after compression in said compressor passages to provide heated gases for flow through said turbine passages, said shell having a minimum thickness in the region of its maximum radius and increasing smoothly in thickness with decrease of radius on opposite axial sides thereof so that the metal of said hollow shell is substantially only in tension during high speed rotation.

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