R. H. HOUGH.

METHOD OF IMPARTING, CONVERTING, AND UTILIZING ENERGY IN CONNECTION WITH A COMPRESSIBLE FLUID MEDIUM AND APPARATUS FOR EMPLOYING SAID METHOD.

APPLICATION FILED FEB. 12, 1917.

1,256,231.

Patented Feb. 12, 1918.

4 SHEETS—SHEET 1.

FIG. I.

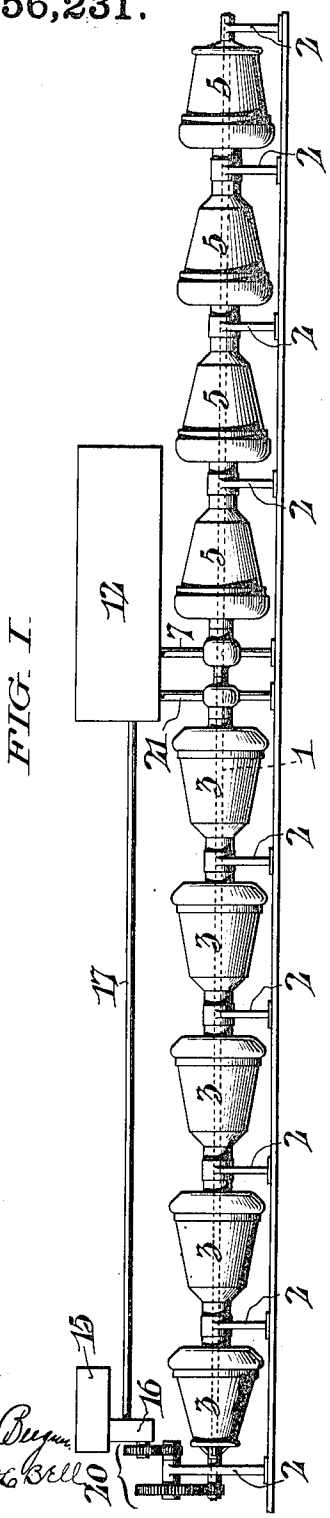


FIG. V.

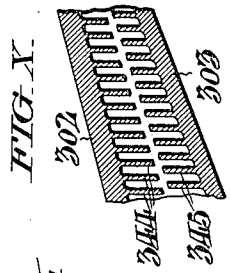


FIG. VII.

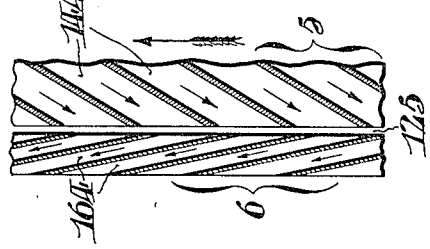


FIG. VIII.

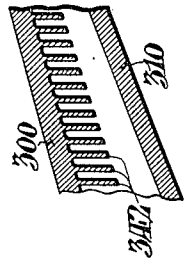


FIG. IX.

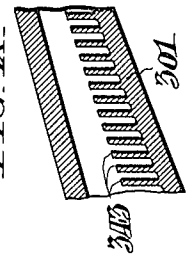
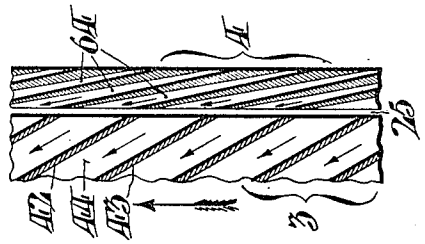


FIG. VI.



Witnesses
John C. Bergen.
James H. Bell

Inventor
Robert H. Hough,
By Raley & Paul.
Attorneys.

R. H. HOUGH.

METHOD OF IMPARTING, CONVERTING, AND UTILIZING ENERGY IN CONNECTION WITH A COMPRESSIBLE FLUID MEDIUM AND APPARATUS FOR EMPLOYING SAID METHOD.

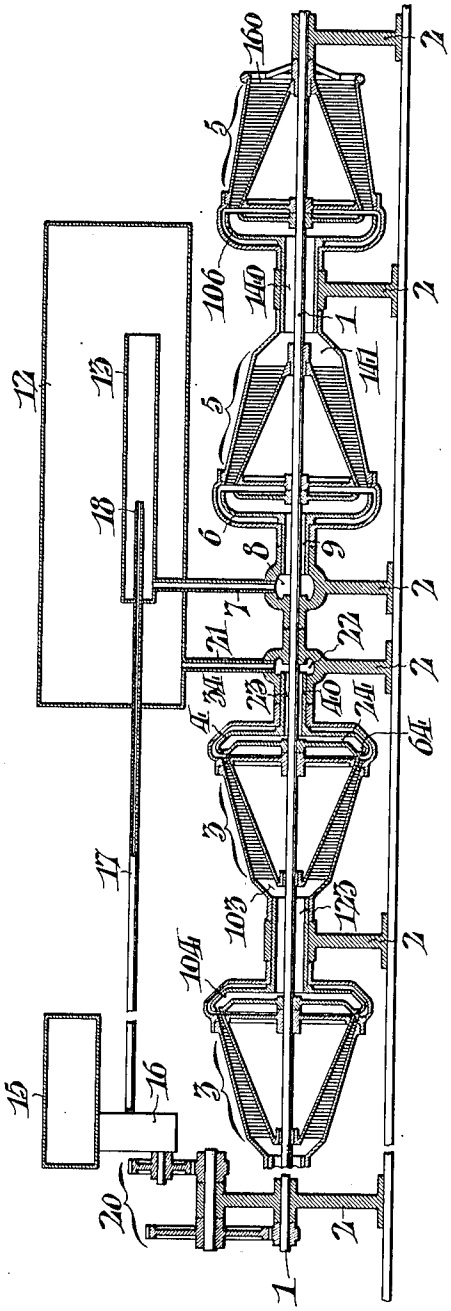
APPLICATION FILED FEB. 12, 1917.

1,256,231.

Patented Feb. 12, 1918.

4 SHEETS—SHEET 2.

FIG. II.



Witnesses
John C. Bergner.
James E. Bell.

Inventor
Robert H. Hough,
By Raley & Paul
Attorneys.

R. H. HOUGH.

METHOD OF IMPARTING, CONVERTING, AND UTILIZING ENERGY IN CONNECTION WITH A COMPRESSIBLE FLUID MEDIUM AND APPARATUS FOR EMPLOYING SAID METHOD.

APPLICATION FILED FEB. 12, 1917.

1,256,231.

Patented Feb. 12, 1918.

4 SHEETS—SHEET 3.

FIG. III.

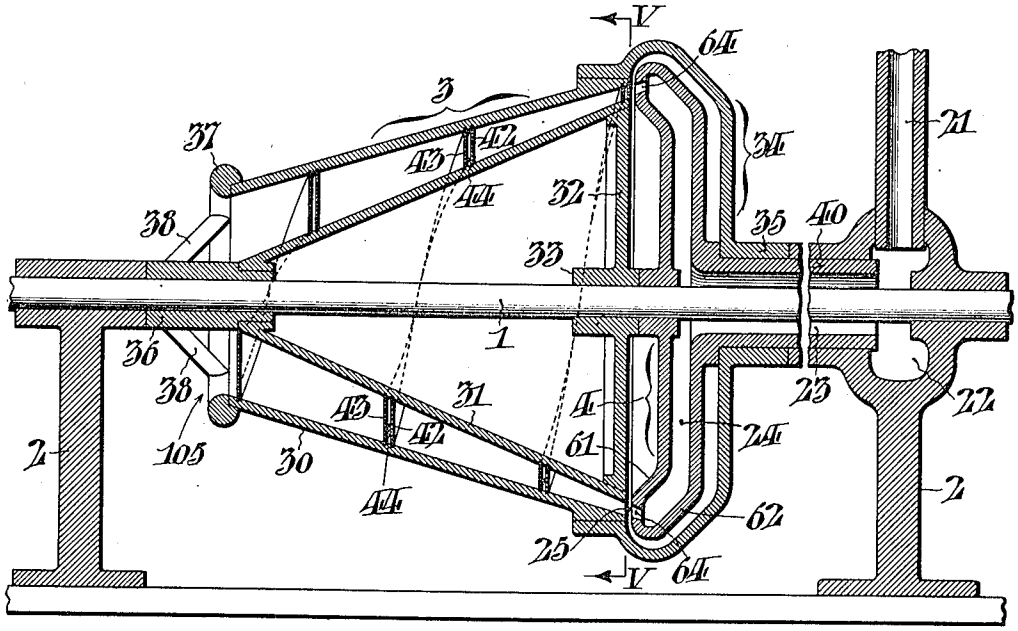


FIG. IV.

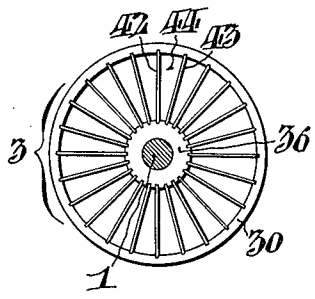
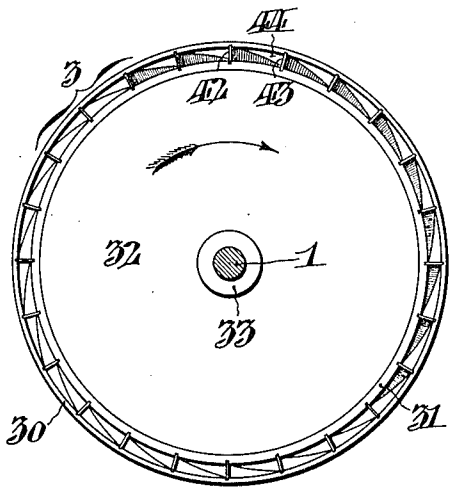


FIG. V.



Inventor

Robert H. Hough,

By Raley & Paul

Attorneys.

Witnesses

John C. Bergner.

James H. Bell.

R. H. HOUGH.

METHOD OF IMPARTING, CONVERTING, AND UTILIZING ENERGY IN CONNECTION WITH A COMPRESSIBLE FLUID MEDIUM AND APPARATUS FOR EMPLOYING SAID METHOD.

APPLICATION FILED FEB. 12, 1917.

1,256,231.

Patented Feb. 12, 1918.

4 SHEETS—SHEET 4.

FIG. XII.

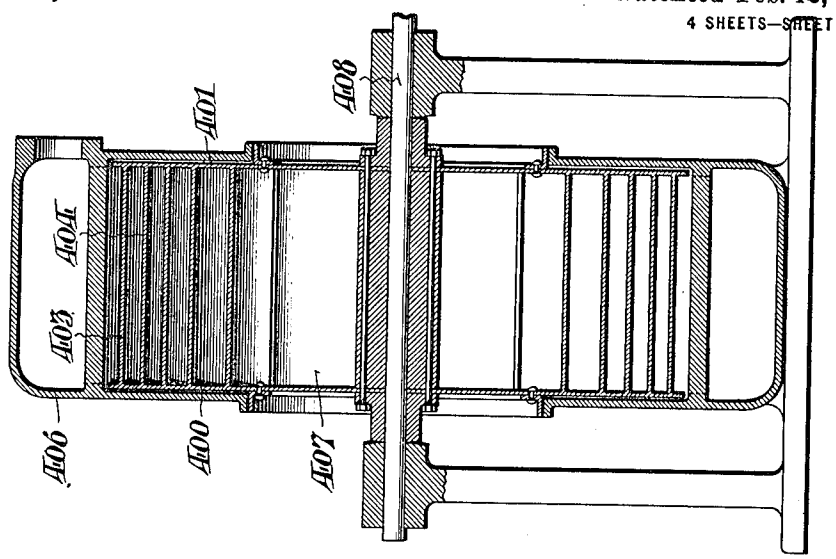
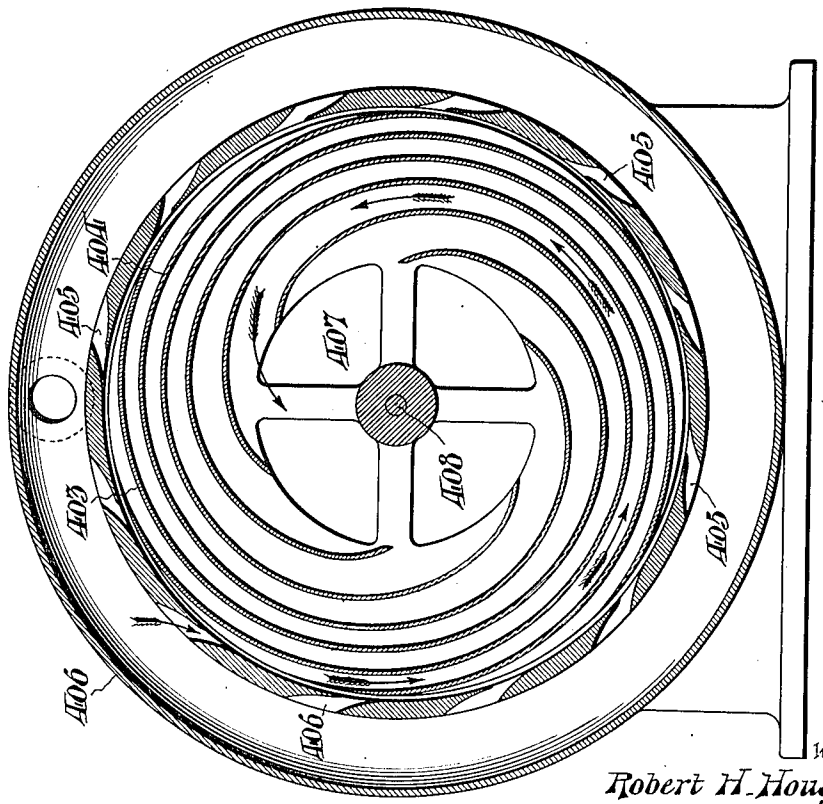


FIG. XI.



Inventor

Robert H. Hough,

By Ridley & Paul

Attorneys.

Witnesses

John C. Bergner.

James C. Bell

UNITED STATES PATENT OFFICE.

ROBERT H. HOUGH, OF PHILADELPHIA, PENNSYLVANIA.

METHOD OF IMPARTING, CONVERTING, AND UTILIZING ENERGY IN CONNECTION WITH A COMPRESSIBLE FLUID MEDIUM AND APPARATUS FOR EMPLOYING SAID METHOD.

1,256,231. Specification of Letters Patent. Patented Feb. 12, 1918.

Application filed February 12, 1917. Serial No. 148,179.

To all whom it may concern:

Be it known that I, ROBERT H. HOUGH, of Philadelphia, in the county of Philadelphia and State of Pennsylvania, have invented a certain new and useful Method of Imparting, Converting, and Utilizing Energy in Connection with a Compressible Fluid Medium and Apparatus for Employing said Method, whereof the following is a specification, reference being had to the accompanying drawings.

Before setting forth the underlying principle and general characteristics of my improved method, I will describe an embodiment of apparatus adapted for the conduct thereof, showing said apparatus in a highly developed form, whereby the advantages of my invention are attained in a high degree, but with the understanding that such showing is typical and not restrictive, for it will be manifest that the method as about to be described in such full development, comprises what may be called subordinate method features, each of which is adapted to obtain specific new and advantageous results.

The apparatus adapted for carrying out my method belongs to the turbine class, and the individual turbine elements are of such general character that the turbine unit can be utilized either as a motor, or, by inversion, as a pumping device, since certain features of novelty in the apparatus lend themselves to either employment, for like reasons.

In the accompanying specification and drawings, I have described and shown the apparatus as embodying both forms, and have illustrated them as united in a single organization, adapted to develop and utilize the advantages of both for a common ultimate purpose. It will be understood, however, that my invention is not limited to such a complete organization, nor to a structure capable of the alternative uses indicated.

Furthermore, I have selected air and vaporized oil as typical thermodynamic reagents for producing energy, the air, vaporized oil and products of combustion being referred to comprehensively as the gas, or the thermodynamic substance. It is to be noted, however, that the invention is not restricted to any particular fuel, or thermodynamic substance.

Referring to the drawings, Figure I, represents in side elevation, the exterior of an organization comprising five turbine motors arranged in series relation to one another, and four turbine air pumps, also arranged in series relation to one another, both of the said series being mounted upon a common rotatable shaft. Combined with the turbine devices proper, the figure indicates the position of a combustion chamber, provided with an oil feeding system, and connections between said chamber and the turbine and pump series respectively.

Fig. II, represents, in vertical axial section, a generally similar organization, showing, however, only two of a series of turbine motors and a series of only two turbine air pumps, mounted upon the common shaft.

Fig. III, represents a vertical axial section through a turbine unit embodying my invention, indicating diagrammatically the position of only two adjacent vanes, out of the total series with which the rotor element is equipped. This method of representation of the vanes is adopted for the sake of clearness and to avoid the complication which would attend upon the production of a complete sectional view. The turbine shown in said Fig. III, is to be considered either as typical of an instance where only a single unit is employed, or as showing the construction of the last motor device at the left hand end of the series shown in Fig. I.

Fig. IV, is a diagrammatic view, in elevation, showing the terminals of the vanes of a rotor element and their relation to the conical walls of the casing, at what may be termed the apex extremity of said walls; and

Fig. V, is a similar view showing the corresponding features at the base extremity of said walls, or as they would appear if viewed on the plane of the section V—V in Fig. III.

Fig. VI, is a sectional view developed upon a plane illustrating diagrammatically the relation of the conduits formed by the vanes, at the intake end of the rotor element, to the adjacent delivery channels of the stator element, when the device is employed as a motor turbine.

Fig. VII, is a similar sectional view, showing the relation of the corresponding parts, when the rotor is employed, inversely,

as a turbine pump. In each of these last two mentioned figures the large single arrow indicates the direction of rotative motion of the rotor element, and the smaller arrows indicate the direction of progressive movement, or flow, of the actuating medium, in the case of Fig. VI, and of the pumped medium, in the case of Fig. VII.

Figs. VIII, IX, and X, are fragmentary sectional views illustrating some of the alternative forms which may be employed for the conduits or passage-ways of the rotor element.

Figs. XI and XII, are sectional views illustrating diagrammatically a rotor element embodying certain features of my invention, but omitting others which are comprised in the preferred general form shown in Figs. I to VII, inclusive.

Referring now to Figs. I, and II, as indicative of the general organization, 1, represents an elongated shaft rotatably mounted in suitable supports 2. Said shaft carries a plurality of turbine motors, whose rotor elements are indicated respectively at 3, and whose stator elements are indicated respectively at 4, and 104, and also carries a plurality of turbine pumps, whose rotor elements are indicated respectively at 5, and whose stator elements are indicated at 6, and 106. At the region intermediate between the motor and pumping groups, conduits 7, and 21, are provided, the conduit 7, leading from the axial chamber 8, at the delivery end of the pumping series, which chamber in turn communicates with the axial tubular extension 9, of the stator 6, of the adjacent pumping turbine, which is the last of the pumping series. The said conduit 7, leads into a combustion chamber, or furnace 12, where it terminates in an enlarged discharge pipe 13. The conduit 21, leads from the furnace 12, to the axial chamber 22, and communicates through the axial passage 23, in the tubular extension 40, of the stator element 4, with the annular chamber 24, of the first turbine motor of the series.

Referring to Fig. II, it will be noted that the intake end 160, of the rotor of the right hand pump (which is the first of the pumping series), is open to the atmosphere, and that the stator 106, of said pump, communicating with the discharge end of the rotor, is connected by means of a tubular axial extension 140, with the intake extremity 141, of the next rotor member of the series, said intake passage being closed to the outer air, as indicated. The stator element 6, of said second device is provided with the axial tubular extension 9, before referred to.

It will also be noted that the discharge extremity 103, of the first (or right hand) rotor element of the motor series is inclosed, and communicates with the axial tubular extension 123, of the stator 104, of the next rotor unit in the series, whose outlet communicates with the stator of the next motor, not shown in Fig. II, but similar to those just described. The last, or extreme left hand unit of the motor series is represented in Fig. III, where it will be noted that its discharge end is open to the atmosphere, as indicated at 105. The details of the rotor and stator elements of the respective units will be described later on, it being understood that the general structure shown in Fig. III, is to be taken as typical of either the motor unit at the discharge extremity of the series, or the pumping unit at the intake extremity of the series, and that Figs. III, IV and V, are also illustrative of the arrangement of vanes in all the rotor elements and the general relation of the rotor casing to the stator casing in all the members of each series. It is to be noted, however, that Fig. III, represents a terminal unit, as stated, and that in the cases of intermediate units, the outer shell or casing of the rotor element is prolonged to form a closed channel leading to or from the next unit in the series, as distinguished from being open to the air in the manner indicated in Fig. III.

An oil tank 15, is mounted at a point adjacent to the furnace, said tank being provided with a fuel pump located at 16, whose discharge pipe 17, leads into the interior of the furnace, and terminates in a nozzle 18, centrally arranged within the discharge pipe 13. The pump 16, is represented as driven by a train of gearing actuated from the shaft 1, and comprehensively indicated by 20.

Turning now from the general organization, as a whole, to the particular details of construction of the turbine elements themselves, attention is directed to Figs. III, IV, V, VI, and VII.

It will be noted that the rotor element comprises an external frusto-conical casing 30, and an internal frusto-conical casing 31, of more obtuse pitch than the external one, the walls of said casings being arranged, as shown, to form an annular funnel-shaped interspace, which progressively varies in radial extent in correspondence with the difference in pitch of the respective cone frusta, which latter, for the sake of brevity, will be referred to as cones. The base of the conical casing 31, is closed by the imperforate diaphragm 32, which has at its center a boss 33, secured to the shaft 1. The base of the external conical wall 30, is closed by the cap or cover 34, secured thereto, said cap being provided at its central region with an extended bearing 35, adapted to be rotatably mounted upon the external surface of the tubular extension 40, of the stator element 4, which will be described later on. The apex extremity of the inner conical wall 31, is closed by the sleeve 36, which is secured

to the shaft 1, and the apex extremity of the outer-conical wall 30, is in this instance provided with a circular rim or band 37, which is supported by means of the spokes 38, upon said sleeve 36. It will, therefore, be seen that the rotor element, comprising the above connected parts, and the shaft 1, rigidly connected thereto, rotate as a whole, with relation to the stator element 4.

The rotor element is provided, in the annular interspace between the two cones 30, and 31, with a plurality of similar tapering helical vanes, such as 42, and 43, symmetrically arranged around the axis.

In order to facilitate the understanding of the arrangement of these vanes, I have illustrated diagrammatically in Fig. III, the course of two thereof, which may be considered as immediately adjacent to one another, the cross-sectional representation of this pair of vanes, showing them as their turns recur in the vertical axial plane, while the dotted lines partly indicate the positions of intermediate portions of their contour.

The characteristic of the tapering helix described by each vane is that the successive complete turns, or angular components, thereof, occupy similar intervals of axial distance but since the edges of the vanes are respectively applied against the external periphery of the cone 31, and against the internal periphery of the cone 30, it follows that as the cross-sectional diameter of the helix, as a whole, taken upon an axial plane, diminishes progressively from the base toward the apex, the cross sectional areas of the individual turns increase progressively as they proceed in that direction. The conditions thus set forth will be further appreciated by noting the representations of the apex and base extremities, shown respectively in Figs. IV, and V.

The result of these structural features is that the rotor of the turbine comprises a plurality of similar conical helical conduits each completely inclosed and having an extended wall surface, said conduits progressively increasing in cross-sectional area from the base toward the apex, and also progressively approaching the axis, so that assuming the base to be the intake end for the passage of a motive medium, said medium will be received at the region of most rapid linear travel of rotation of the cone and discharged at a region of less rapid linear travel, the angular velocities of rotative travel in both instances being identical.

Referring now to the stator element 4, it comprises a hollow disk, as shown in the sectional view of Fig. III, whose walls near the periphery, are dished, as shown at 61, and 62, forming an annular projection inclined toward the base 32, of the rotor, said projection being provided with a series of conduits 64, which correspond, in radial distance from the axis, with the radial position of the intake ends of the conduits 44, in the rotor element. It will be noted, however, that there is a slight interspace 25, between the proximate faces of the rotor base 32, and the annular projection of the stator.

When the turbine device is to be employed as a motor, the relation between the stator conduits and rotor conduits is of the character indicated diagrammatically in Fig. VI, where it will be noted that the stator conduits are inclined at a very oblique angle with relation to the rotor conduits at the base extremity of the latter. The factors which determine this angular relation between the pitch of the conduit walls in the delivery element (in this instance the stator), and the pitch of the conduit walls in the receiving element (in this instance the rotor), are the intended normal velocity of rotative movement of the rotor element and the intended normal velocity of progressive movement, or flow, of the stream of actuating medium. In other words, assuming a given pitch of the helical walls 42, of the rotor conduits 44, and a given progressive velocity of the actuating medium, the pitch of the walls of the stator conduits 64, should become more acute with relation to that of the motor conduits as the intended velocity of rotation is higher.

The object of this difference of pitch is to minimize the resistance attendant upon the passage of the gas currents from the conduits of the delivery element, into the conduits of the receiving element, so that taking as factors the velocity of progressive flow of the moving gaseous medium, and velocity of rotative travel of the rotor, the resultant flow of the medium into the conduits of the receiving element shall take place in a direction which, as nearly as possible, coincides with what may be considered as the average of direction of the successive relative positions of the conduit walls in a given time interval. For convenience of description, I shall characterize the desired resultant direction of flow as being substantially tangential to the conduit walls of the receiving element, which, in this instance, is the rotor.

Ignoring for the present the general operation of the organization as a whole, and considering simply the behavior of the individual turbine as a motor device, the characteristic action is as follows:

A steady volume of moving gaseous medium under pressure flows from the furnace chamber into the stator element and is thence discharged in a plurality of subdivided streams in an angular direction with relation to the axis of the rotor, the immediate region of discharge being the annular interspace 25, between the proximate surfaces of the stator and of the rotor base.

The condition in said interspace may be theoretically considered as a whirling annulus of gas, whose particles are forcibly impelled progressively in an angular direction across the radial plane of the annulus. Owing to the definite relation between the pitch of the stator conduits and rotor conduits, assuming that the predetermined velocities of the rotor and of the gas flow have been attained, the result will be that the transversely moving stream of gas will be continuously delivered into the intake ends of the rotor conduits without direct impulse, and hence without appreciable loss of kinetic energy developed as heat. The moving mass of gaseous medium traverses the inclosed conduits of the rotor element in frictional contact with their extended surfaces, and a two-fold result follows, viz: the velocity of the gas stream is retarded and its pressure is reduced adiabatically.

In correspondence with said retardation and with said adiabatic reduction of pressure, the moving mass imparts kinetic energy to the rotor element, this transfer of energy being effected substantially by what is termed "skin friction" reaction alone, as distinguished from direct impulse, or from reactive pressure exerted in a direction transverse to the general direction of flow.

Since the gaseous medium flows continuously through and out of the rotor conduits, there is necessarily some difference between the velocity of movement of the gaseous stream, as a whole, and the velocity of movement of the surface to which it imparts motion. This difference is termed the slip, and, being attended with friction, a waste of energy necessarily occurs which is manifested as heat. The power thus lost in heat is a function of the slip, and hence it is important to maintain the slip, as a whole, at the lowest ratio which is fully efficient for imparting movement by skin frictional action, and to render the slip, to the extent to which it must exist, as uniform or constant as possible.

As the volume of moving gas progresses through the conduits of the rotor and looses velocity by imparting energy thereto, its frictional slip against the walls would necessarily vary if the actual speed of travel of the conduit walls in contact with the gas stream remained constant.

By my invention the diminution of actual velocity of the moving gas, through transmission of its energy to the rotor, may be substantially compensated by the general approach of the controlling walls of the conduit toward the axis of rotation, whereby a constant angular rotative movement is attended by a diminishing rate of linear travel, the cross sectional area of the conduit also progressively increasing as it approaches the axis of rotation. The slip is measured by the relative velocities of movement of the gas stream, and of the contacting surface of the rotor at each instant of travel. Under the conditions that the axial component of the velocity of the gas stream is constant and that the radial plane component is proportional to the radius, the ratio of the radial plane component of the slip, to the radial plane component of the velocity of the gas will be constant. This is one of the factors which determine the efficiency of conversion, the other factor being that the constant ratio of slip thus attained should be the lowest which affords the proper skin frictional contact.

Therefore, since the slip is a known function of the velocity of the gas, it should have a predetermined value in order that the cross section on the gas stream shall be properly determined. Under these circumstances the ratio of the power lost in heat through undue or irregular friction of the gas stream, to the power developed by the rotor, is very small, and a high efficiency of conversion is attained.

In illustrating the preferred embodiment of my invention so far as the same relates to the structure and mode of operation of the rotor, I have sought to combine in the highest degree certain desiderata.

Thus, the underlying feature resides in providing the rotor element with a structural feature or features of such physical configuration as to impose upon the gas stream a definitely controlled path, and definitely varying cross-sectional area, in its passage between regions of operative contact having different velocities of linear travel, or, in other words, the path of operative contact which affords the desired conditions, is substantially delimited by positive guiding members internal to the rotor casing, as distinguished from permitting the gas stream to select a path automatically in a confined chamber lacking such guiding means, and in which the resultant path of the gas particles would be determined by their re-active effect upon one another and upon the inclosing walls of the chamber, in their effort to follow lines of least resistance between the inlet and outlet openings thereof.

Preferably, the desired control for the purposes of my invention is effected by means of conduits whose walls completely inclose each gas stream on all sides, but a similar mode of operation can be attained to an efficient degree by means of walls or ridges which do not afford complete inclosure, or which are not even continuous throughout, provided that they are sufficient in shape and dimensions to positively impose a substantially definite path for the gas stream, and substantially control the cross sectional area thereof. Instances of

such alternative forms of rotor passage are indicated in Figs. VIII, IX, and X. Thus, in Fig. VIII, the outer casing 300, is provided with internally projecting helical walls 342, which extend only part way across the annular interspace between said outer casing and the inner casing 310.

In Fig. IX, the converse arrangement is shown, in which partial walls 343, are provided on the inner casing 301, only; and in Fig. X, the outer casing 302, and inner casing 303, are respectively provided with oppositely projecting helical walls 344, and 345, whose edges do not meet and which may be staggered, as shown.

In my claims hereinafter made I shall apply the term "delimited" as a convenient one to designate a positively defined passage-way having the characteristics above set forth, and which are common to all the forms shown.

It will also be noted that the spiral form adopted for the conduits is a tapering helical spiral, as distinguished from what may be called a flat spiral. In Figs. XI, and XII, however, I have illustrated a rotor in which one principle of construction characteristic of my invention is embodied, though in what I consider a less desirable form than that described above in detail; Fig. XI, being a section on a plane transverse to the axis of rotation, and Fig. XII, being a section on an axial plane.

Here it will be seen that the walls 400, and 401, of the rotor compartment, are annular disks, the interspace being provided with spiral walls 403, and 404, etc., forming passage-ways of varying pitch and cross-sectional area, whose outer extremities are arranged in proper relation to the conduits 405, of an annular stator 406, which surrounds the chamber formed by said disks.

The inner extremities of the conduits communicate with an axial passage-way 407, to which the gas stream is delivered when the apparatus is operated as a motor device, and obviously a plurality of similar disks with intervening spiral walls may be mounted upon a common axial shaft 408. In this structure the definite control of the gas stream, both as to its progress from the region of highest linear velocity, to that of a lower linear velocity, and of its cross-sectional area in proceeding from one region toward the other, is effected in a manner similar to that above described in connection with my preferred embodiment.

Owing, however, to the disposition of the spiral conduit, in a flat form, as distinguished from a tapering helical form, only the minimum length of passage is obtainable, and hence the period of operative contact of a gas stream having a given velocity is relatively brief.

By extending the conduit axially, and hence disposing it in the form of a tapering helix, as distinguished from a flat spiral, the length of the path, and consequently the period of operative contact of a gas passing at a given velocity, is greatly increased, with corresponding advantages.

Thus the preferred embodiment above set forth in detail affords a degree of freedom which permits the designing of a varying cross-sectional area, such that,—first, any desired variation of the velocity and expansion of the thermodynamic substance may be obtained as it progresses through the rotor element from the point of intake to the point of exit; the preferred condition being that of a substantially uniform retardation of velocity and adiabatic expansion between the intake and exit pressures; and, second, the length of path can be such that retardation of velocity and the expansion may take place at any desired rate, preferably that determined by the relation existing between force per square foot of the skin frictional reaction of the contacting surface to the stream of gas moving at the predetermined slip and the quantity of kinetic energy of mass velocity to be converted.

Hence, while I desire to comprehend within my claims the construction and mode of operation characteristic of a rotor having flat spiral passages of the proper character, I deem it proper to point out that I consider this a less desirable embodiment than one in which the spiral is a helical one.

I would further point out that in order to afford relatively simple structural conditions for a rotor having helical conduits, it is desirable that the inner and outer walls of the rotor element should be approximately frusto-conical. It is obvious, however, that this specific geometrical form is not essential even when a tapering helical type is to be employed, but it may be comprehensively stated that for the preferred embodiment, the outer and inner walls of the rotor element should be surfaces of revolution whose proximate faces are so related to one another as to afford an annular interspace, the radial extent of which increases as it approaches the axis. A further desideratum is that in determining the character of the helix, successive turns or angular components shall occupy substantially similar intervals of axial extent.

Considering now the operation of the rotor element in its converse employment, *i. e.*, as a pump, certain of the conditions remain as before, but the relation of pitch of the conduits in the delivering and receiving elements respectively, at their proximate extremities, should be modified.

In the case of a pump, the gaseous or vaporous medium is the passive element, as distinguished from the active one, and it must be raised from a relatively low veloc-

ity of movement to a relatively high one, by skin friction with the walls of the conduits in the rotor device, the intake end being at the apex extremity of the conical rotor. At the delivery end, the conditions diagrammatically illustrated in Fig. VII, are attained, that is to say, the rotor 5, which in this instance is the delivering element, is driven in the direction of the large arrow, and the moving mass of air, or gaseous medium carried thereby is traveling progressively in the direction of the smaller arrows within the conduits 144. It is to be received into the stationary conduits 164, of the stator. Hence, to minimize friction due to impact on the walls of the stator conduits and to effect the transfer from the moving delivery element to the stationary receiving one with the maximum of efficiency, the walls of the passages in one element are inclined toward those of the other in opposite relation, or what may be considered as a V-shaped direction, as shown diagrammatically in Fig. VII, there being an annular interspace 125 between the proximate faces of the two elements as in the former case. The purpose of this relative arrangement of the receiving and delivering walls is that the subdivided air streams pouring through the annular interspace 125, with a compound movement of rotation and transverse progression, flow into the oppositely inclined conduits 164, of the stator without substantial retardation due to impact on the walls theerof, the pitch of the respective passageways being determined, as in the previous instance, by the factors of intended velocity of rotative movement of the rotor and intended velocity of progressive movement of the streams delivered thereby. As in the case of the motor embodiment, the desideratum is to deliver the stream of gaseous medium in a direction tangential to the walls of the conduits in the receiving element, in this instance the stator.

In the foregoing description I have set forth the peculiar construction and advantages of the individual units of the series and the mode of operation characteristic of each unit. I will now proceed to describe that novel feature of general operation which relates to the employment of a plurality of these devices in a peculiar series relation.

Considering the action of the first rotor element, it is obvious that the gas issuing from the delivery end 103, into the axial passage 123, will have lost that portion of its energy which has been converted into mechanical energy of the rotor, plus that very small portion which has been converted into heat. The velocity of travel of the gas stream has been progressively diminished and the pressure has been adiabatically reduced. The moving mass of gas passes at this reduced velocity and reduced pressure through the passage 123, and into the axial inlet of the next stator 104. Thereafter it expands in passing through the conduits of the stator, and acquires a restored velocity substantially corresponding to its initial one, but with a corresponding adiabatic diminution of pressure. The moving mass of gas, therefore, passes into the next rotor unit of the series at a velocity which is appropriate for actuating that unit at a rate of rotation substantially corresponding to the rate of the first mentioned rotor unit. Upon the exit of the gas from the second rotor with a second reduction of velocity, and a further reduction of pressure, it is permitted to expand through the conduits of the next stator and so on throughout the series, acquiring substantially the desired velocity in each instance, but progressively diminishing in pressure until the delivery end of the series is reached, when it will be discharged into the atmosphere, at approximately atmospheric pressure, and at a velocity reduced in correspondence with the amount of energy which has either been converted into mechanical motion, or lost in friction during the passage of any given unit of the gas through the entire series. Since the permissive expansion of the gas through the stator conduits at each step results in the attainment of a substantially similar velocity of the moving mass of gas at the moment of issuance from the stator conduits, the appropriate condition is attained for successive actions of a given unit of gas upon rotors mounted upon a common shaft and substantially similar to one another in dimensions, although progressively increasing in cross-sectional area in correspondence with the progressively decreasing density of the gas.

Thus, at each stage represented by the action of a unit of the motor series the peculiar advantages of my invention in utilizing potential energy corresponding to the reduction of pressure, which takes place in the stator and rotor of that unit, are attained, and, by the succession of a plurality of stages of this character, in series, a part of the residual potential energy of the gas at the conclusion of each stage is converted into appropriate velocity of flow and utilized as kinetic energy at diminished pressure, until the predetermined total amount of energy has been abstracted from the moving stream of gas, by the series of stages.

Turning now to the pumping series, it will be appreciated that a succession of steps comparable to those just described, but inverse in their effect, are occasioned. The air, entering the rotor element at atmospheric pressure, receives, through skin frictional action, energy mechanically imparted to it by the motion of said element, such energy being of a two-fold character, *i. e.*,

potential, manifested as increased pressure, and kinetic, manifested as increased velocity.

The air is then delivered into the stator element and progresses through the passage 140, at reduced velocity, but with correspondingly increased pressure, to the intake end of the next rotor element of the pumping series, where the action just described is repeated, and the air is delivered to the next stator 6, with the velocity and pressure characteristic of that stage, this action being repeated until the air having attained the predetermined final pressure is delivered through the passage 9, into the chamber 8, and thence through the conduit 7, into the injector casing 13. At each stage of the pumping series the individual advantages due to the peculiar character of the rotor element are experienced, while in the combination of the successive stages the imparting of energy, step by step, to air taken in at what may be considered as the zero of energy, is attained in the manner characteristic of my invention.

Comprehension of the claims about to be predicated upon the foregoing disclosure will be facilitated, and the novelty of the invention will be more clearly appreciated, by an analytical statement of certain underlying principles of operation characteristic of the invention, and a comparison thereof with previously existing devices.

Considering the invention in its highly organized embodiment, as above set forth, it will be noted that the invention comprises a new method of executing a thermodynamic cycle of transformations occurring in, or impressed upon, a substantially steady and continuous stream of thermodynamic medium. The individual transformations, though successive in their relation to any given unit of the stream of thermodynamic medium, are occurring at all times, simultaneously, on different units of the stream in their respective temporary locations in the system. The method is not restricted to any particular thermodynamic cycle, but if it be assumed that but a single pumping unit and a single motor unit are employed upon a common shaft in connection with the intermediate heating group above described, it may be set forth in its relation to the cycle comprising four steps, as follows:

1. The continuous adiabatic compression of a steady stream of thermodynamic medium, taking place in the rotor and in the stator of the turbo-compressor.

(*a*) In the rotor there is a continuous adiabatic compression of the thermodynamic substance and a continuous uniform and progressive acceleration of the velocity of the stream thereof by means of the skin friction action of the surface of the rotor element, converting a part of the mechanical energy of the rotating shaft into the potential energy of the adiabatically compressed medium and a part of said mechanical energy into the kinetic energy of the mass velocity of the stream of medium, said compression and acceleration being so conducted as to minimize loss of energy through frictional slip of the moving mass with relation to the contacting surface of the rotor elements.

(*b*) In the stator there is a further continuous adiabatic compression of the gas and a continuous uniform and progressive retardation of the velocity of the moving mass, due to the pressure gradient in the conduits of the stator, such compression converting the kinetic energy of the mass velocity into the potential energy of an adiabatically compressed gas.

2. The continuous absorption of heat by the stream of medium in the heating chamber, the heat being afforded by internal combustion of the sprayed fuel at the constant pressure due to the adiabatic compression existing within the chamber, converting the heat energy derived from the fuel into the energy of a compressed gas heated at constant pressure.

3. The continuous adiabatic expansion of a steady stream of thermodynamic medium, taking place in the stator and rotor of the motor-turbine.

(*a*) In the stator there is a continuous adiabatic expansion of the gas and a progressive acceleration of the velocity of the moving mass, owing to the pressure gradient in the conduits of the stator, such expansion converting a part of the potential energy of the medium into the kinetic energy of its mass velocity.

(*b*) In the rotor there is a further continuous expansion of the medium and a continuous uniform and progressive retardation of the velocity of the moving mass by means of the skin friction action of the moving mass of medium on the conduit walls of the rotor element, converting a part of the potential energy of the expanding gas and a part of its kinetic energy of mass velocity into the mechanical energy of a rotating shaft, said expansion of medium and retardation of its velocity being so conducted as to minimize the loss of energy through frictional slip of the moving mass with relation to the contacting surface of the rotor element.

4. The ultimate dissipation of heat, which takes place in the atmosphere, where the exhausted medium is reduced to the atmospheric conditions of temperature, pressure and volume.

Comparing this cycle with a typical cycle of operations, which may be considered as the most highly developed in the prior art, viz: the Diesel cycle, it will be noted that

while the features of adiabatic compression, absorption of heat, adiabatic expansion, and final dissipation of heat on the return of the gas to the initial conditions of temperature, pressure and volume, are, in a broad sense, common to both, the individual steps and their organization are in striking contrast to those characteristic of my invention. Thus, in the individual steps of the Diesel cycle the compression is effected, and the expansion is utilized, by direct impulse, as distinguished from skin friction reaction.

Second, the Diesel cycle occurs, in its entirety, upon successive isolated units of the medium, being complete as to one unit, before it commences upon the following one, so that, considering the organization as a whole, it comprises a series of recurring cycles with intermissions and consequent periodical variations of power. In the case of my invention the steps of the cycle are proceeding simultaneously at all times in the respective regions and hence periodical variations of power are eliminated.

Considering now the action of a series of motor turbines employed in accordance with my invention and supplied either in the manner above described, or in any other manner, with a stream of highly compressed and heated medium, it should be noted that one of the difficulties of economically utilizing a gaseous medium expanding under a high pressure is the enormous velocity with which it tends to flow. Since the practical limit of peripheral velocity of a turbine motor may be stated as between thirteen hundred and fourteen hundred feet per second, any excess velocity of the gas beyond this limit is attended by a loss of mechanical efficiency due to friction and spilling over. In this aspect of the invention I point out that in the third step of the cycle above described, (*i. e.*, the continuous adiabatic expansion of a steady stream of thermodynamic medium and continuous and progressive retardation of the velocity of the moving steam thereof by means of skin friction action), I provide one or more subdivisions of the step into stages, (whose number and character are predetermined in the manner hereinafter set forth), whereby the potential energy of the expanding medium is fractionally utilized in a series of such stages, there being interposed between each fractional stage and the successive one a stage of restoration of velocity of the moving stream, due to, and corresponding with, the predetermined fractional reduction of pressure. Hence, it becomes possible to utilize upon a plurality of rotor elements, traveling at a mechanically permissible peripheral speed, a steady stream of actuating thermodynamic medium at great initial pressure, whose enormous potential velocity is so controlled by successive reductions of pressure as not to exceed the mechanically efficient rate of travel for skin friction reaction.

An analogous subdivision of the first step of the cycle into stages occurs in the turbo-compressor portion of my system when the compressors are used in series as shown and described. The stages are the converse of those just stated, *i. e.*, the thermodynamic medium is raised from zero of velocity and pressure to the maximum by subdivided applications of skin friction action, accompanied by progressive increase of pressure so that the skin friction is attained with the highest efficiency and without the slip which would be characteristic of a similar change of conditions if effected at a single stage.

Again, considering the action of each rotor element without relation to the other similar parts of the series, it will be noted that the first and third steps of the cycle are so conducted therein as to attain the highest efficiency of skin friction re-action. This is due to the fact that each moving stream of the thermodynamic medium is caused to flow through an inclosed helical conduit whose walls afford proper operative contact and that the path afforded by this helical passage-way is definitely related to the axis of rotation in correspondence with the change of velocity of the stream, due, in the case of the first step, to the progressive imparting of the energy of the moving rotor element to the mass motion of the medium, and, conversely, in the case of the third step, to the progressive imparting of the energy of the mass motion of the stream to the rotor element. Hence, the total slip between the stream and the contacting surface of the inclosed conduit may be minimized and maintained substantially constant. This feature is, so far as I am aware, new in gas, or vapor-actuated, turbine engines.

As a consequence of the control of the conditions afforded by my invention, it becomes possible to convert a definite amount of the kinetic energy of mass velocity of the moving stream of gas and a definite and approximately equal amount of its potential energy, into kinetic energy, and vice versa. Thus, considering first the compressing operation, it is evident that in a compressor of this type part of the mechanical energy of the rotating member is converted into the potential energy of an adiabatically compressed gas, in correspondence with the compression produced. It is also evident that part of the mechanical energy of the rotating member is converted into the kinetic energy of the mass velocity of the stream of adiabatically compressed gas in correspondence with the increase in velocity produced.

By correctly delimiting the cross sectional area of the path, the increase in potential energy can be substantially equal to the increase in the kinetic energy of the mass velocity.

Conversely, in the motor turbine action, if the conditions be provided that the axial component of the velocity of the gas stream is maintained constant throughout the rotor, and that the radial plane component of the velocity of the gas stream is everywhere directly proportional to the radius, the angular velocity of the gas stream will be constant, and the reduction in pressure and retardation in velocity will be such that substantially equal amounts of potential and kinetic energy will be converted.

Supplementing the foregoing statements, I would point out that the overall efficiency of any heat engine is the ratio of the power developed for external work to the power available from the fuel, and may be considered to be the product of three factors, *i. e.*, fuel efficiency, thermal-efficiency, and mechanical efficiency.

In internal combustion engines, as a class, fuel efficiency can be attained in a very high degree. Thermal-efficiency of such an engine may be expressed as a definite function of the ratio of the pressure, at which the heat of the fuel is absorbed, to the pressure at which the exhaust heat is dissipated. To attain thermal-efficiency in the highest degree, it is therefore necessary for the working to take place under a very high ratio of pressure. The conditions presented in a turbine motor, are favorable to thermal-efficiency, but, on the other hand, mechanical efficiency is difficult to attain at the velocity characteristic of the maximum of the other two factors, for if the velocity of the moving stream of gas be much greater than the velocity of the contacting surface of the rotor, there will be, as above pointed out, a loss of mechanical efficiency due to wasted friction and spilling over.

The desired combination of the three efficiencies is found in my method, however, because it permits the mass velocity of the stream of gas to be developed from a high ratio of the pressure at which the heat of the fuel is absorbed, to the pressure at which the exhaust heat is dissipated, the contact of the moving stream with the moving rotor being so controlled that the peripheral velocity of the actuated part may be within the desired limit and yet the ratio of such velocity to the velocity of the actuating stream of gas shall be everywhere substantially constant, and preferably nearly equal in unity.

Referring to the factors which determine the number of stages into which the third step of my cycle is divided, for the turbo-motor action, it may be stated that they are dependent upon the relation of the total available energy of the medium, compressed to a predetermined ratio, to the kinetic energy of a stream of medium moving with a predetermined velocity, and as a definite example, which is typical, though not restrictive, the following data may be taken:

Assuming as the desired thermal-efficiency, sixty per cent., a ratio of pressures of twenty-two is approximate; and, assuming eleven hundred feet per second as the desired maximum peripheral velocity of the rotating element, five stages would be advantageous for the subdivision of the turbine-motor system.

For the subdivision of the first step of my cycle, (*i. e.*, the compression of the thermodynamic medium), under the stated conditions, four stages would be advantageous.

It may be stated, however, that while it is convenient that the various conversions of energy at the successive stages should be substantially equal to one another and carried out by means of rotor elements mounted upon the same shaft and consequently having the same angular velocities, such relation of the parts is not essential, since the fractional conversions of the potential energy of the compressed moving stream into the kinetic energy of an actuated member on the one hand, or the fractional conversions of the kinetic energy of an actuating member into the potential energy of a compressed moving stream, on the other hand, are capable of control in the manner and for the purposes set forth, irrespective of the locations or constructions of the individual parts by which skin friction reaction is made available in the several stages.

In the foregoing specification I have employed the term "conduit" as a convenient one to indicate the delimited passage-ways of the rotor and stator elements, but it must be understood that said term is descriptive, and is not to be taken as imposing limitations upon the feature of either element.

I employ the term "helical" as a convenient term to describe the preferred conformation of the rotor conduit, but, as before stated, without limitation to the geometrical figure to which it is strictly applicable.

I employ the term "gas", as comprehensive of air, vapor, or other thermodynamic fluid adapted to produce skin friction reaction.

I employ the term "stator" as comprehensive of any fixed member having conduits adapted to deliver, or receive a stream of gas, to or from, the rotor conduits.

I use the expressions "turbine" and "turbo-member" as comprehensive of devices of the character described, whether the rotor element be employed as a pump for compres-

sion of a fluid medium, or as a motor driven by such medium.

In defining the characteristic feature of construction of the passageways in the turbo-member, I employ the term "progressively" in order to indicate that the increase of cross sectional area is not interrupted by regions of diminution of cross sectional area followed by another increase. Theoretically, it is desirable that the increase of cross section of the passageway should be practically continuous, or, in other words, that there should be no abrupt transitions of large extent at successive points in the passage, but, irrespective of this desideratum, it is important that the increase should progress without substantial reduction at any point.

Having thus described my invention, I claim:

1. The method of converting kinetic energy of the mass velocity of a moving stream of an adiabatically expanding gas, and potential energy thereof into the kinetic energy of a rotatable turbo-member; which consists in permitting the progressive adiabatic expansion of the moving gas in skin frictional contact with the surface of said member; progressively conducting the moving stream in a delimited path of said contact, from a region of rotation of said member having relatively high linear velocity, to a region having lower linear velocity; and progressively increasing the cross sectional area of the stream, in its passage from the former region to the latter one, in substantial correspondence with the said progressive adiabatic expansion and said reduction of velocity.

2. The method of converting a definite amount of the kinetic energy of mass velocity of a moving stream of an adiabatically expanding gas and an approximately equal amount of its potential energy, into kinetic energy of a rotatable turbo member having a contacting surface adapted for skin frictional action of said stream under adiabatic expansion; which consists in progressively conducting said stream in a delimited path of such contact, from a region of rotation of said member having relatively high linear velocity and containing said gas at relatively high pressure, to a region having lower linear velocity and containing said gas at lower pressure, and progressively increasing the cross-sectional area of the stream, in substantial correspondence with the reduction of the velocity and reduction of pressure of the moving stream, whereby the ratio between the velocity of the gas stream and the velocity of the contacting surface is maintained substantially constant, and high mechanical efficiency is secured.

3. In the process of utilizing, for a skin frictional turbine system having a predetermined rotor velocity, the potential energy of a moving stream of heated and compressed gas, the residue of which energy is ultimately to be dissipated at a pressure having a predetermined ratio to the pressure at which the heat has been absorbed; the hereinbefore described method, which consists in dividing the skin frictional contact between said stream and the surface of the rotor into a plurality of successive stages, whose number is determined by the relation existing between the total available energy of the medium compressed to the said predetermined ratio, and the kinetic energy of its mass velocity when moving with a predetermined slip along the rotor surface; and, in the interval between said stages, converting a portion of the potential energy of the gas into the kinetic energy of mass velocity thereof, by permitting adiabatic expansion in a stator element.

4. In the process of utilizing, for a skin frictional turbine system having a predetermined peripheral rotor velocity, the potential energy of a moving stream of heated and compressed gas, the residue of which energy is ultimately to be dissipated at a pressure having a predetermined ratio to the pressure at which the heat has been absorbed; the hereinbefore described method, which consists in dividing the skin frictional contact between said stream and the surface of the rotor into a plurality of successive stages, whose number is determined by the relation existing between the total available energy of the medium compressed to the said predetermined ratio, and the kinetic energy of its mass velocity when moving with a predetermined slip along the rotor surface; converting a portion of the potential energy of the gas into the kinetic energy of mass velocity thereof by permitting adiabatic expansion in a stator element, in the interval between said stages; and delivering the gas stream from the stator to its rotor in a direction approximately tangential to the resultant positions of the receiving walls of the moving rotor; whereby high mechanical efficiency in the conversion of said potential energy of the gas into the kinetic energy of the rotor is attained.

5. In the process of converting, by a skin frictional turbo-compressor system having a predetermined peripheral rotor velocity, the kinetic energy of a rotating shaft into the potential energy of a gas compressed to a predetermined ratio of the pressure at the point of intake to the pressure at the point of exit; the hereinbefore described method which consists in dividing the skin frictional contact between the stream and the surface of the rotor elements into a plurality of successive stages, whose number is determined by the relation existing between the total potential energy of the medium, compressed to the said predetermined ratio, and the

kinetic energy of its mass velocity when moving with a predetermined slip along the rotor surface; and, in the interval between said stages, converting a portion of the kinetic energy of the mass velocity of the gas stream into the potential energy of the further compressed gas by permitting adiabatic compression in a stator element.

6. In the process of converting, by a skin frictional turbo-compressor system having a predetermined peripheral rotor velocity, the kinetic energy of a rotating shaft into the potential energy of a gas compressed to a predetermined ratio of the pressure at the point of intake to the pressure at the point of exit; the hereinbefore described method which consists in dividing the skin frictional contact between the stream and the surface of the rotor elements into a plurality of successive stages, whose number is determined by the relation existing between the total potential energy of the medium, compressed to the said predetermined ratio, and the kinetic energy of its mass velocity when moving with a predetermined slip along the rotor surface; in the interval between said stages converting a portion of the kinetic energy of the mass velocity of the gas stream into the potential energy of the further compressed gas by permitting adiabatic compression in a stator element; and delivering the gas stream from the rotor to its stator in a direction approximately tangential to the receiving walls of the stator; whereby high mechanical efficiency in the conversion of the said kinetic energy of the gas into the potential energy of further compressed gas is attained.

7. In a turbine; the combination of a skin friction rotor provided with a delimited passage-way extending between regions of different radial distance from the axis of rotation, the cross-sectional area of said passage-way progressively increasing as it approaches the axis of rotation; with a stator, comprising a passage-way arranged in operative relation to the rotor passage-way at the extremity of smallest area of the latter.

8. In a gas turbine, the combination of a skin friction rotor provided with a delimited spiral passage-way, whose cross-sectional area progressively increases as it approaches the axis of rotation; with a stator comprising a passage-way arranged in operative relation to the rotor passage-way, at the extremity of smallest area of the latter; the respective pitches of the stator passage-way and the rotor passage-way at their adjacent extremities being adapted, under predetermined velocities of gas flow, and rotor movement, to deliver the gas stream into the passage-way of the receiving member in a resultant direction substantially tangential to the walls thereof.

9. In a gas turbine, the combination of a skin friction rotor, provided with a plurality of tapering helical delimited passage-ways, whose cross sectional area progressively increases as they approach the axis of rotation; with a stator comprising a plurality of passage-ways arranged in operative relation to the rotor passage-ways at the extremities of smallest area of the latter.

10. In a gas turbine, the combination of a skin friction rotor, provided with a plurality of tapering helical delimited passage-ways, whose cross sectional area progressively increases as they approach the axis of rotation, and whose angular components occupy substantially similar intervals of axial extent; with a stator comprising a plurality of passage-ways arranged in operative relation to the rotor passage-ways at the extremities of smallest area of the latter.

11. The combination of a turbo-rotor, comprising two casings having concentric surfaces of revolution both progressively approaching the axis, and arranged one within the other, the inner surface approaching the axis more rapidly than the outer; a plurality of delimiting members arranged in the interspace between said surfaces to form definite passage-ways whose cross-sectional areas progressively increase as they approach the axis; and a stator, comprising a plurality of conduits arranged in operative relation to the rotor passage-ways, at the extremities of smallest area of the latter.

12. The combination of a rotatably mounted shaft, a plurality of turbo-rotors mounted in series thereon, each comprising a number of tapering helical inclosed conduits whose cross-sectional areas progressively increase as they approach the axis; a plurality of stators arranged respectively in operative relation to said rotors; inclosed conduits communicating between each rotor and the stator of the next succeeding one; a pressure chamber; and a conduit communicating between said pressure chamber and the first stator of the series; whereby changes in velocity and pressure of a moving stream of gas may be effected in successive stages, while maintaining the velocity of the moving stream approximately equal to that of the moving surfaces of the rotor elements, with which each portion of said stream is, for the time being, in contact.

13. The method of converting kinetic energy of a rotated turbo-member into the potential energy of a gas compressed to a predetermined ratio of the pressure at the point of intake to the pressure at the point of exit which consists in progressively causing adiabatic compression of the gas in skin frictional contact with the surface of said member; progressively conducting the moving stream of gas in a delimited path of said contact from a region of rotation of said member having relatively low linear veloc-

ity to a region having higher linear velocity and progressively decreasing the cross sectional area of the stream in its passage from the former region to the latter one in substantial correspondence with said progressive adiabatic compression and with the increase of velocity of the moving stream.

In testimony whereof, I have hereunto signed my name at Philadelphia, Pennsylvania, this eighth day of February, 1917.

ROBERT H. HOUGH.

Witnesses:

JAMES H. BELL,

E. L. FULLERTON.