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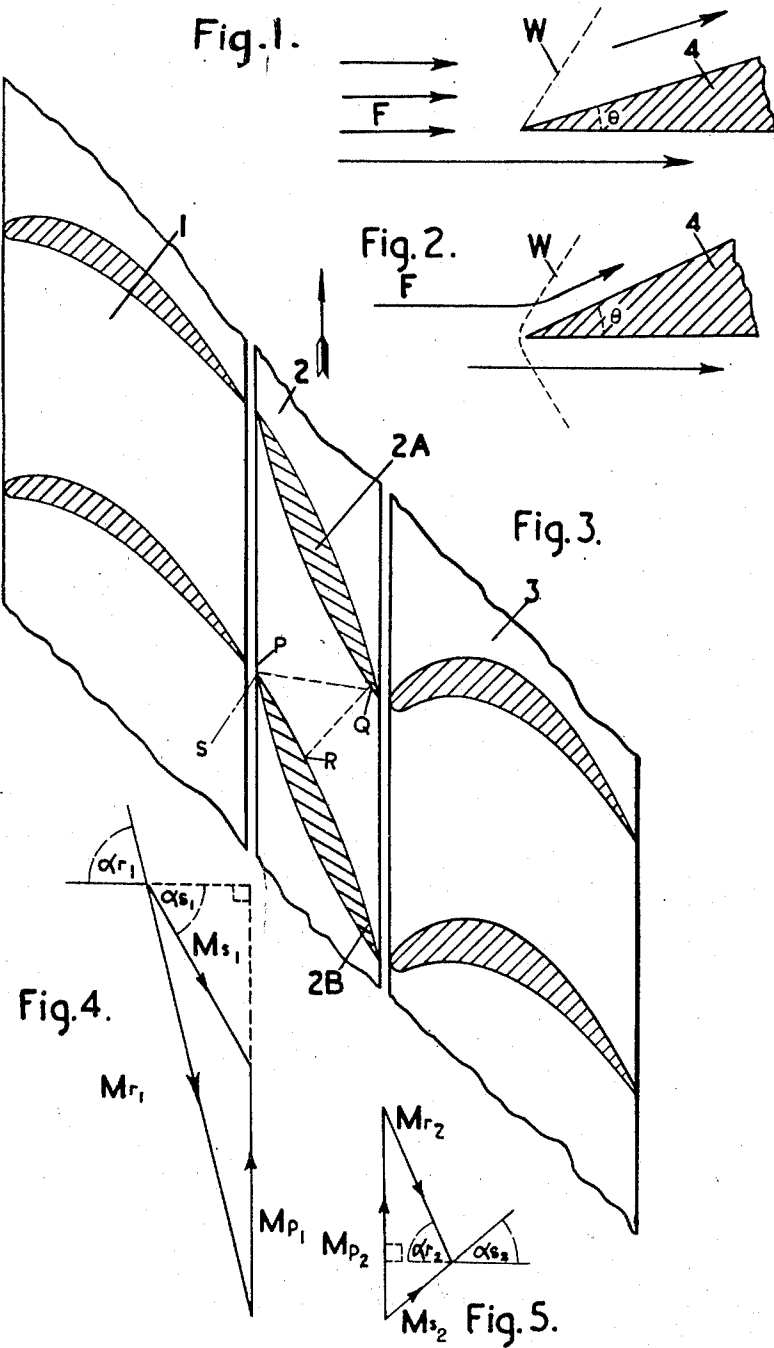
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2,623,688

ROTARY POWER CONVERSION MACHINE

Filed Dec. 9, 1946

2 SHEETS—SHEET 1



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2 SHEETS—SHEET 2

FIG. 6

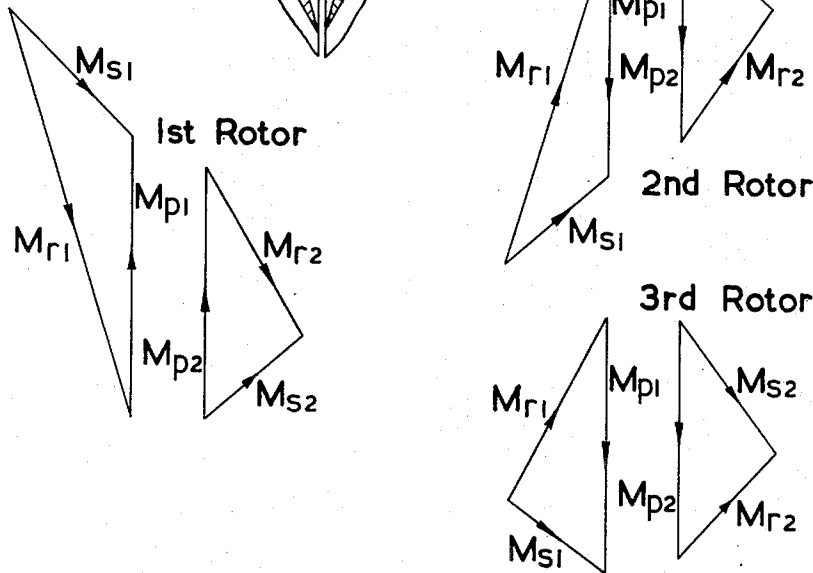
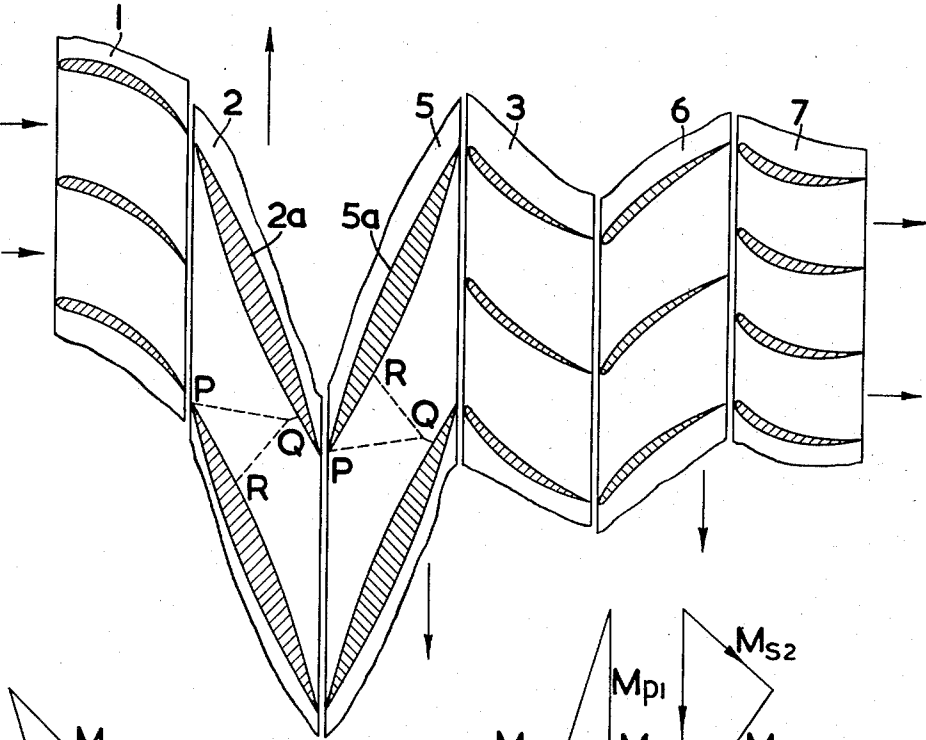


FIG. 7

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ROTARY POWER CONVERSION MACHINE

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4 Claims. (Cl. 230—122)

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This invention relates to improvements in gaseous fluid rotary compressors of the class in which the dynamic properties of the working fluid are utilised in order to effect compression thereof, and one of its objects is to provide a compressor of that class which is more compact and simple in design and construction than the hitherto known compressors for a given output.

Amongst the possible species of compressor of the class referred to, the invention is considered to have application to those of the axial flow and radial flow types, even though there may be a centrifugal component in the flow system, but not to those of the pure centrifugal type. References to a "compressor of the kind referred to" in the following specification and claims are accordingly to be read in this limited sense unless the context otherwise requires.

Existing compressors have usually been designed to operate by accelerating the working fluid and then diffusing it (i. e. compressing the fluid by deceleration) in order substantially to recover the dynamic pressure thus generated. This acceleration and diffusion can be effected either in the rotor, or in the stator, or in both.

In existing compressors the Mach number (i. e. the ratio of the velocity of the fluid at any point to the velocity of sound in that fluid at the same point) is generally less than unity and under these conditions the acceleration of the working fluid presents little difficulty, but the diffusion process is subject to serious limitations owing to the ease with which flow instability can occur. Moreover, if the maximum Mach number employed in a compressor is less than unity there is a definite upper limit to the stage pressure ratio obtainable.

When however, the Mach number in a fluid exceeds unity the conversion of dynamic energy into pressure energy is possible in two ways, either by gradual deceleration, which involves a flow which is very unstable and is therefore difficult to realise in practice, or by means of the phenomenon known as a compression shock wave. This phenomenon is represented by a more or less instantaneous change of pressure at the junction of contiguous zones of flow, at either side of which the flow velocities are more or less instantaneously changed in such a fashion that the velocity components upstream and down-

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stream of and normal to the shock, and determined under local conditions, are respectively supersonic and subsonic (or in other words, the component Mach numbers at the points in question are respectively greater and less than unity). It is thus a characteristic of a shock wave that it can effect compression in an extremely short distance and with relatively high efficiency, the amount of the pressure rise being a measure of the intensity of the shock wave.

The present invention is based on the conception of utilising this shock wave principle of energy conversion to obtain a useful pressure rise in a compressor of the kind referred to. For this purpose, according to the present invention, it is arranged that, in use in the condition of maximum efficiency, a compression shock wave system of the continuity type (as will be explained below) will be set up within the space swept by and will rotate with a compressor rotor in order to utilise the characteristic of rapid conversion of dynamic to pressure energy of such a system to obtain a pressure rise within that space. The expression "compression shock wave system" used here and in what follows is intended to mean either a systematic distribution of shock waves or a singly identifiable shock wave.

Ideally, the whole of the shock wave system should be contained within the space swept by the rotor; in practice this ideal is very difficult of attainment and the invention therefore contemplates, as a further feature, that provision will be made to ensure that at least a major part of the shock system (considered from the point of view of intensity) will be so contained.

The invention will be better understood by reference to the accompanying drawings, which include examples of construction in accordance therewith and in which:

Figures 1 and 2 are diagrams illustrating the behavior of a wedge in a gaseous fluid stream of supersonic velocity;

Figure 3 illustrates diagrammatically the blade arrangement of a possible form of axial flow compressor according to the invention;

Figures 4 and 5 are vector diagrams corresponding to Figure 3;

Figure 6 illustrates a compound axial flow compressor embodying two contra-rotating rotors.

stages in accordance with the invention and one rotor stage of normal form; and

Figure 7 sets out vector diagrams corresponding to Figure 6.

In order to generate the required shock wave system, the invention, preferably, makes use of the fact that if an obstruction is placed in a fluid stream having supersonic velocity relative thereto (i. e. with a relative Mach number greater than unity) so that the stream is deflected from its original path, a compression shock wave system will be generated, and that if, further, the obstruction is a wedge with one surface parallel to the direction of flow, then only that part of the stream incident on the other surface is deflected and by suitable choice of the included angle of the wedge, it can be arranged that a compression shock wave system is generated on one side only. A shock wave system produced by deflection, for example by a wedge in the manner just described, may conveniently be termed a "continuity" shock, since it is considered to be the result of an attempted contravention of the principle of the continuity of mass flow, as distinct from what may be described as a "momentum" shock, which is considered as one due to an attempted contravention of the principle of conservation of momentum. The latter form is exemplified in the behaviour of a supersonic flow in an overexpanding de Laval nozzle; in such a nozzle, if there were no losses and the fluid were a perfect gas, expansion would take place until the Mach number became infinite and the temperature infinitesimal, but in practice these conditions cannot be satisfied so that a shock wave must be formed in the nozzle if the law of conservation of momentum is to be obeyed.

Reliance upon a momentum shock wave system as the pressure-raising shock system called for by the invention within the space swept by the rotor would be a practicable alternative to the use of a continuity shock system, since the former system could be made to operate efficiently and could be produced by arranging for the flow through the rotor blading to be supersonic and shaping the blades to simulate an overexpanding de Laval nozzle. Although in such a case, given an inlet Mach number of not less than unity, some sort of continuity shock wave would necessarily be generated at the leading edges of the blades (since these must have a finite thickness), such a shock wave would not necessarily be propagated so as to be contained within the space swept by and to rotate with the rotor, in which case from the point of view of obtaining useful pressure rise for the purpose of the present invention, the momentum shock wave system within the blade passages could be regarded as operating alone. It is thought, however, that an arrangement using a momentum shock system alone in this way would possess inferior aerodynamic stability and width of operating range as compared with one relying upon a continuity shock to provide the pressure raising shock system called for, and that for fully effective operation such a momentum shock system would require to be stabilised by the formation of a continuity shock system upstream thereof and within the space swept by the rotor.

Accordingly (but without prejudice to the generality of the appended claims) the invention in its present preferred form contemplates in the first place, that the shock wave system should be generated at the rotor inlet by reason of deflection by the rotor blading of a flow which is super-

sonic relative thereto, and, as a further feature, that the leading edge of this blading should constitute a wedge (which requirement for the purpose of this specification is to be taken to be satisfied if the faces of a blade intersect to form a well defined edge at which planes tangential to the faces of a blade define a wedge shape). Preferably said leading edge is knife-edged, whilst in order to ensure the desired preponderance of shock intensity within the space swept by the rotor it is arranged that the major deflection of flow is by the leading face of a blade, the rear face being arranged (ideally) parallel with the incident relative fluid flow, or at least more nearly parallel therewith (before deflection) than is the leading face.

Some degree of choice is possible in the selection of the wedge thickness, but to give the best results the included angle of the wedge, for a given incident Mach number, should be less than what will be termed herein the detachment angle. The explanation of this term is as follows:

If, as illustrated in Figure 1 of the accompanying drawings, a relatively thin wedge 4 is placed in a supersonic stream F the resultant shock wave W will be seated on the wedge apex and (if the incident relative flow is parallel with one of the faces) at one side only thereof, as illustrated, but if, for a given Mach number of the incident flow, the included angle θ be increased there will be reached a value at which the shock wave moves a short distance upstream, as illustrated in Figure 2, and is thus completely detached from the wedge as well as being propagated at both sides thereof. It is this value of the included wedge angle that for a given incident Mach number is considered herein to be the detachment angle of the wedge at that Mach number.

The formation of a continuity shock wave system as described in the foregoing, of course, necessarily involves a Mach number of the fluid relative to the rotor at inlet thereto of not less than unity; preferably, however, the Mach number at this point, considering the velocity of the fluid alone (i. e. relative to a stator element), is less than unity. Similarly it is desirable that the Mach number of the fluid relative to the rotor at outlet therefrom should be less than unity, although adequate results should be obtainable even if there are local zones of supersonic velocity at the rotor outlet. In general, if the fluid velocities relative to the rotor only are permitted to become supersonic, as is the case in the ideal form of this invention, higher efficiencies will result than those otherwise obtainable with supersonic compression.

A system according to the invention as applied to one axial flow compressor stage and relying upon a continuity shock wave system for obtaining pressure is illustrated diagrammatically in Figure 3 of the accompanying drawings in which a rotor element 2, of which 2A, 2B are two adjacent blades, rotates in the direction shown by the arrow and is disposed between an inlet stator element 1 and an outlet stator element 3. It will be understood that the rotor and stator elements fragmentarily illustrated in Figure 3 are parts of complete circular bodies which are coaxial and bladed around their entire peripheries. The symbols used in the corresponding vector diagrams appearing as Figures 4 and 5 have the following meanings:

M—Mach number

α —air angle, measured from the axial direction

and the subscripts have the following meanings:

p —peripheral

r —relative to rotor

s —relative to an adjacent stage of stator or other blading in guide blade relationship with the rotor being considered

1—stator (or guide blade) outlet and rotor inlet

2—rotor outlet and stator inlet

The diagram in Figure 4 shows the Mach numbers M_{r1} and M_{s1} of the working fluid at entrance to the rotor element, relative to the rotor and stator elements respectively.

Figure 5 shows the corresponding Mach numbers at the rotor outlet, i. e. M_{r2} and M_{s2} .

The conditions envisaged are:

(i) That the Mach number relative to the rotor at inlet to the rotor (M_{r1}) must be not less than unity, whilst that at outlet from the inlet stator 1 (M_{s1}) should be less than unity. As will be evident to those skilled in the art these conditions can be satisfied by applying normal considerations of compressor design in respect of blade stagger angles, air inlet and outlet angles and relative velocities, according to design requirements, to give vector diagrams such as those illustrated. It will be evident that the desired low value of M_{s1} and high value of M_{r1} can best be attained by making the vectors M_{s1} , M_{p1} arithmetically additive, implying the arrangement of the blades of the stator 1 and rotor 2, as illustrated, with their stagger (inclination to the fore-and-aft line) in the same sense as each other and the direction of rotation of the rotor;

(ii) That the leading edge of each rotor blade should constitute a wedge as hereinbefore defined (preferably knife-edged) whose included angle is not greater than the detachment angle for the incident Mach number in the design conditions of operation;

(iii) That ideally the angle of incidence of the fluid on the rotor blades should be so related to the disposition of the blade faces on the basis of the principles already explained that the compression shock wave system is generated only at the leading face of each blade, so that compression shock waves are not propagated into the upstream stator element; or at least that the intensity of the shock wave system at the leading face of a blade should be greater than that at the rear face; further, that the shock wave generated at the leading face of a blade should be confined to the rotor space by the rear face of the preceding blade.

The ideal arrangement contemplated might, for example, be such that a compression shock wave PQ from a rotor blade 2B is reflected one or more times (as indicated by QR) at the underside of the next rotor blade 2A in the series.

In a non-ideal, but nevertheless useful system, there might, however, be a compression shock wave PS of less intensity than PQ which, due to its direction at the rear of the blade 2B, might be propagated into the upstream stator element 1.

In order to obtain a large pressure rise from the compressor stage under consideration it is desirable that the relative outlet Mach number from the rotor (M_{r2}) should be less than unity. The blading might well be designed, however, for a shock wave system within the space swept by the rotor such as would result in supersonic velocities at some zone of the outlet, without unacceptably impairing the effectiveness of the compressor. In any event the inlet Mach number at the stator 3 should be less than unity, a

condition which can best be satisfied by making the vectors M_{p2} , M_{r2} , arithmetically subtractive as illustrated, the inlet angle of the stator 3 being selected to conform to the resultant in accordance with usual practice. The remaining design of the stator 3 will follow normal practice, and depend on the duty it is to perform and the air outlet angle required.

As the fluid velocities relative to the rotor are high it is desirable, if large losses are to be avoided, that as well as the provision of a leading edge of wedge form having an appropriate included angle, unnecessarily high curvatures should be avoided in the design of the rotor blade profiles. For this purpose one form of rotor blade may conveniently be that shown in Figure 3, namely, a bi-convex profile having very little camber, but other profiles, for example, concavo-convex or double wedge i. e. rhombic, having little or no camber, could also be employed.

It will be understood that the compressor should be designed so that the shock wave system in the space swept by the rotor will be maintained throughout the intended useful operating range of the machine (i. e. throughout this range the value M_{r1} should be not less than unity).

The main advantages of a compressor of the type described are that whilst offering the possibility of achieving simplicity and lightness comparable with that of a centrifugal unit it also has the superior form of the axial flow compressor. Two or more compressor stages according to the invention may be compounded comparatively easily, thus making high pressure ratio practicable in a single compact machine, or one or more such stages may be compounded with stages (including centrifugal stages) not in accordance with the invention. Since the working fluid is deflected through a large angle, compounding might well be effected by the provision of a contra-rotating unit without the use of intermediate stator blading. For this purpose it would merely be necessary to arrange the blade inlet angles of each successive contra-rotating rotor element to suit the vector M_{s2} (see Figure 5) associated with the preceding rotor element, the first and last contra-rotating rotor elements being preceded and followed respectively by stators of appropriate angle similarly to the arrangement illustrated in Figure 3.

An example is given in Figure 6 and the corresponding vector diagrams of Figure 7 (in which the same notation as in Figures 4 and 5 is used for like or corresponding parts, the suffix s now referring to relativity between the rotor under consideration and adjacent blading whether stationary or rotating in guide blade relationship therewith) of a possible compounded arrangement embodying a stator 1 and rotor 2 having blades 2a as already described with reference to Figure 3, and a similar contra-rotating second stage rotor 5 having blades 5A with an inlet Mach number of not less than unity, followed by a stator 3. These might be followed by a rotor 6 designed for normal subsonic operation (inlet Mach number less than unity) and a corresponding outlet stator 7.

The system according to the invention is particularly suited for use in aircraft gas turbine engines, but is not of course limited to this application.

It might be thought that the end sought to be achieved could be obtained by the use of a com-

pression shock system in a stator part downstream of the rotor, but it would be found that such an arrangement would involve a large deflection of the flow by the rotor and stator blading and would result in very inefficient operation. For this reason the utilisation of a compression shock system in the space swept by the rotor is regarded as an essential feature of the invention.

I claim:

1. A gaseous fluid rotary compressor comprising a rotor and an annulus of rotor blades peripherally attached thereto, said blades defining between them passages for the flow of gaseous fluid to be compressed, each rotor blade being inclined to the axial plane of the rotor and the leading edge being in advance of the trailing edge with respect to the direction of rotation of the rotor, the leading portion of each rotor blade having forward and rear apical faces defining a wedge, an annulus of stator blades immediately upstream of said rotor blades, each stator blade being inclined in the same general direction as the rotor blades, said stator blades being so contoured, oriented, and spaced that in cooperation with the rotor at the design operating speed of the latter for the particular fluid to be compressed the resultant incident flow of gaseous fluid relative to the rotor blades is substantially aligned with the apical face at the rear of the leading portion of said rotor blades, the forward apical face of said leading portion of the rotor blades being inclined to said resultant incident flow for effecting a compression shock wave of the continuity type in the passages between the rotor blades at supersonic velocities of said resultant incident flow relative to said rotor blades.

2. A gaseous fluid rotary compressor comprising a rotor and an annulus of rotor blades peripherally attached thereto, said blades defining between them passages for the flow of gaseous fluid to be compressed, each said rotor blade being inclined to the axial plane of the rotor and the leading edge being in advance of the trailing edge with respect to the direction of rotation of the rotor, the leading portion of each rotor blade having forward and rear apical faces defining a wedge, an annulus of stator blades immediately upstream of said rotor blades, each stator blade being inclined in the same general direction as the rotor blades, said stator blades being so contoured, oriented, and spaced, that in cooperation with the rotor at the design operating speed of the latter for the particular fluid to be compressed, the resultant incident flow of gaseous fluid relative to the rotor blades is substantially aligned with the apical face at the rear of the leading portion of said rotor blades, the forward apical face of said leading portion of the rotor blades being inclined to said resultant incident flow for effecting a compression shock wave of the continuity type in the passage bounded by the forward face of said rotor blade and the rear face of the next preceding rotor blade at supersonic velocities of said incident flow and said compression shock wave being confined within said passage by the rear face of said next preceding rotor blade.

3. A gaseous fluid rotary compressor comprising a first rotor and a first annulus of rotor blades peripherally attached thereto, a second rotor coaxial with and adapted to rotate in the opposite direction to said first rotor and a second annulus of rotor blades peripherally attached thereto and lying immediately downstream of

said first annulus; the blades of each said annulus defining between them passages for the flow of gaseous fluid to be compressed; each said blade of said second annulus being inclined to the axial plane of the rotors and the leading edge being in advance of the trailing edge with respect to the direction of rotation of said second rotor; the leading portion of each blade of said second annulus having forward and rear apical faces defining a wedge, each said blade of said first annulus being inclined to the axial plane of the rotors and the leading edge being in advance of the trailing edge with respect to the direction of rotation of said first rotor, said first annulus of rotor blades being so contoured, oriented and spaced that in cooperation with the second rotor at the design operating speed of said rotors for the particular fluid to be compressed, the resultant incident flow of gaseous fluid relative to said second annulus of rotor blades is substantially aligned with the apical face at the rear of the leading portion of said rotor blades of the second annulus, the forward apical face of the leading portion of the rotor blades of said second annulus being inclined to said resultant incident flow for effecting a compression shock wave of the continuity type in the passages between the rotor blades of the second annulus at supersonic velocities of said incident flow.

4. A gaseous fluid rotary compressor comprising a first rotor and a first annulus of rotor blades peripherally attached thereto; a second rotor coaxial with and adapted to rotate in the opposite direction to said first rotor and a second annulus of rotor blades peripherally attached thereto and lying immediately downstream of said first annulus; the blades of each said annulus defining between them passages for the flow of gaseous fluid to be compressed; each said blade of said second annulus being inclined to the axial plane of the rotors and the leading edge being in advance of the trailing edge with respect to the direction of rotation of said second rotor, the leading portion of each blade of said second annulus having forward and rear apical faces defining a wedge, each said blade of said first annulus being inclined to the axial plane of the rotors and the leading edge being in advance of the trailing edge with respect to the direction of rotation of said first rotor; said first annulus of rotor blades being so contoured, oriented and spaced that in cooperation with the second rotor at the design operating speed of said rotors for the particular fluid to be compressed, the resultant incident flow of gaseous fluid relative to said second annulus of rotor blades is substantially aligned with the apical face at the rear of the leading portion of said rotor blades of the second annulus, the forward apical face of the leading portion of the rotor blades of said second annulus being inclined to said resultant incident flow for effecting a compression shock wave of the continuity type in the passage bounded by the forward face of said rotor blade of the second annulus and the rear face of the next preceding rotor blade of the second annulus at supersonic velocities of said incident flow and said compression shock wave being confined within said passage by the rear face of said next preceding rotor blade of the second annulus.

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