May 18, 1965 F. BOURQUARD 3,184,152

SUPERSONIC COMPRESSORS

Original Filed July 6, 1959 3 Sheets-Sheet 1

Fig.1.

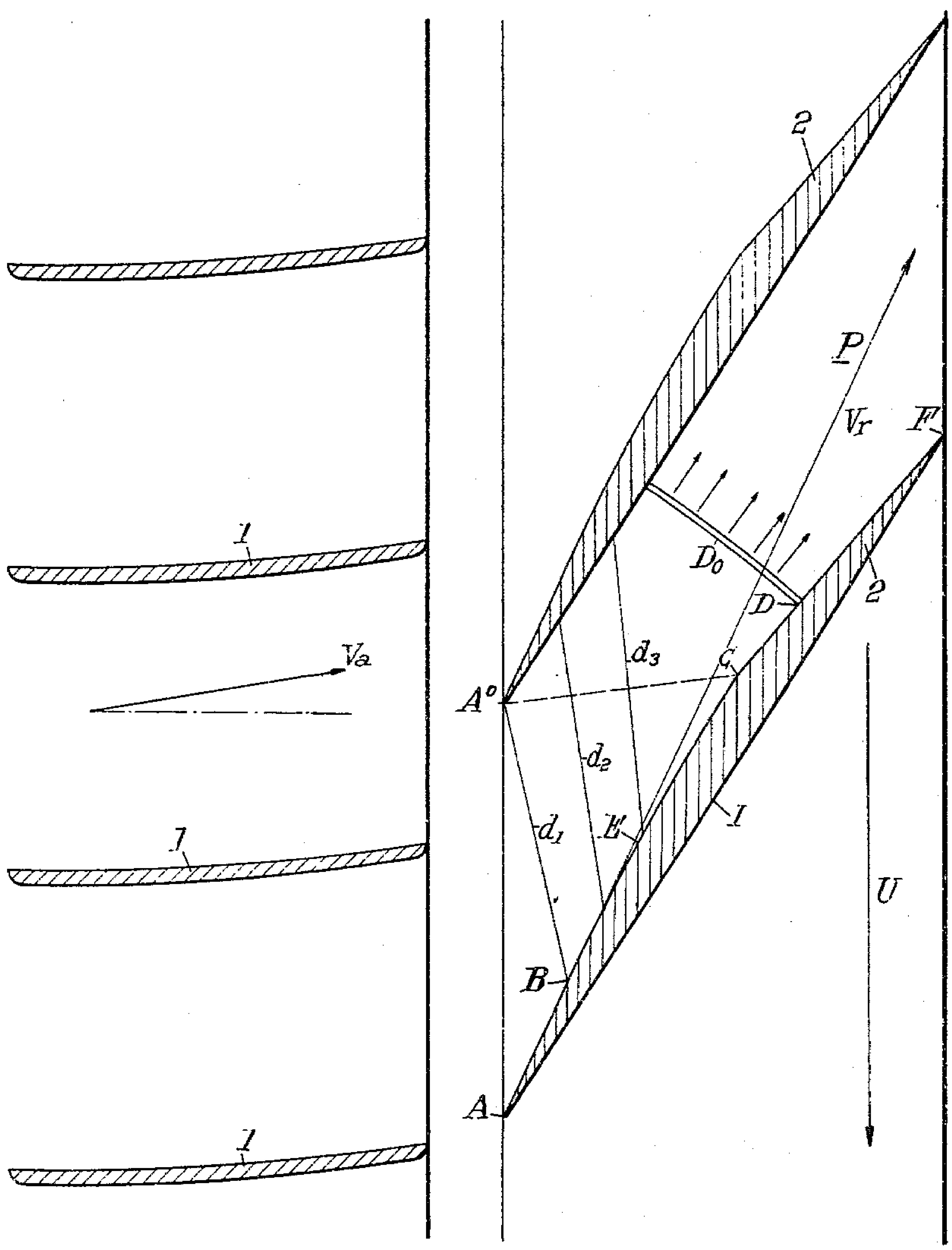

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Fig. 2.

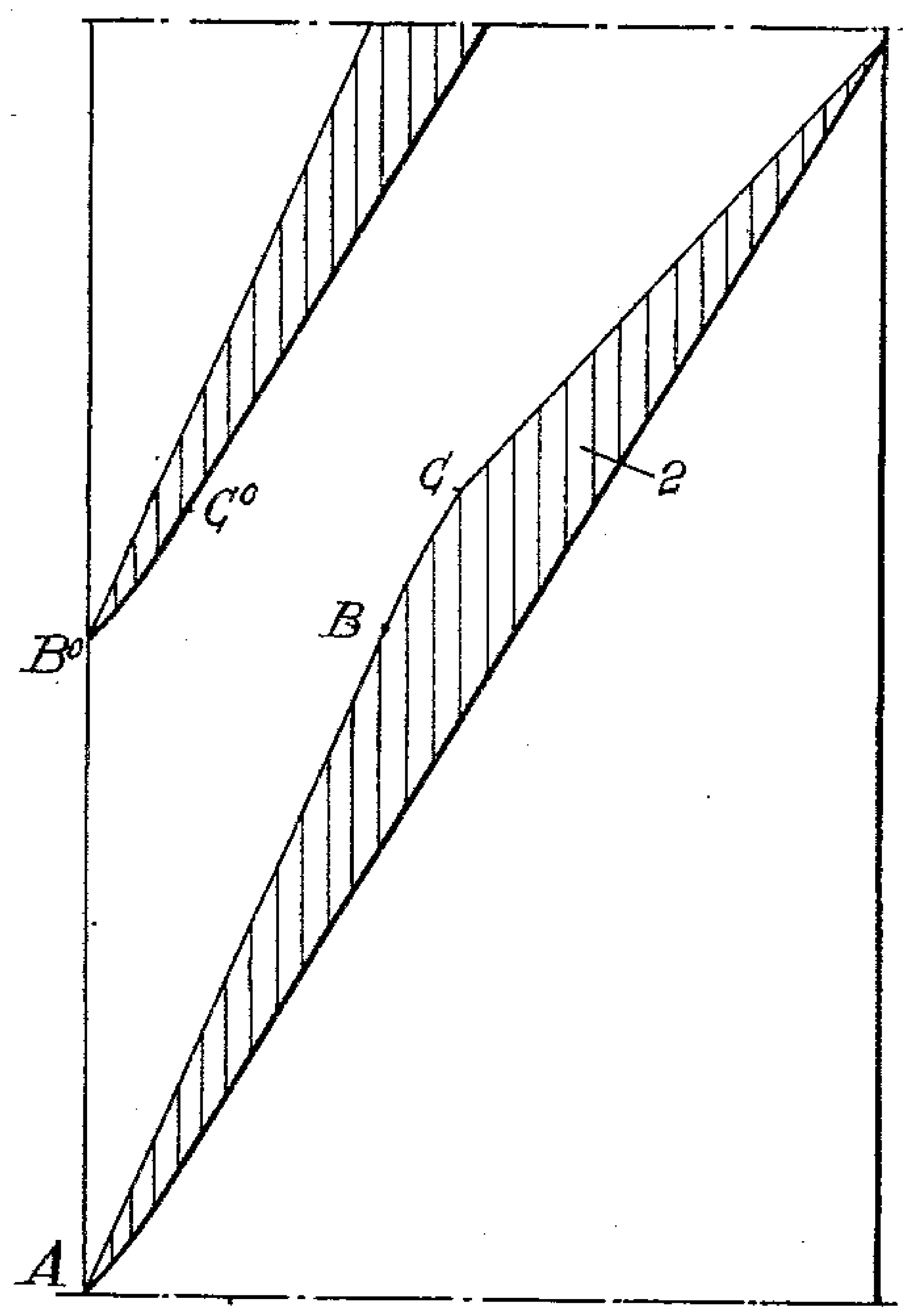
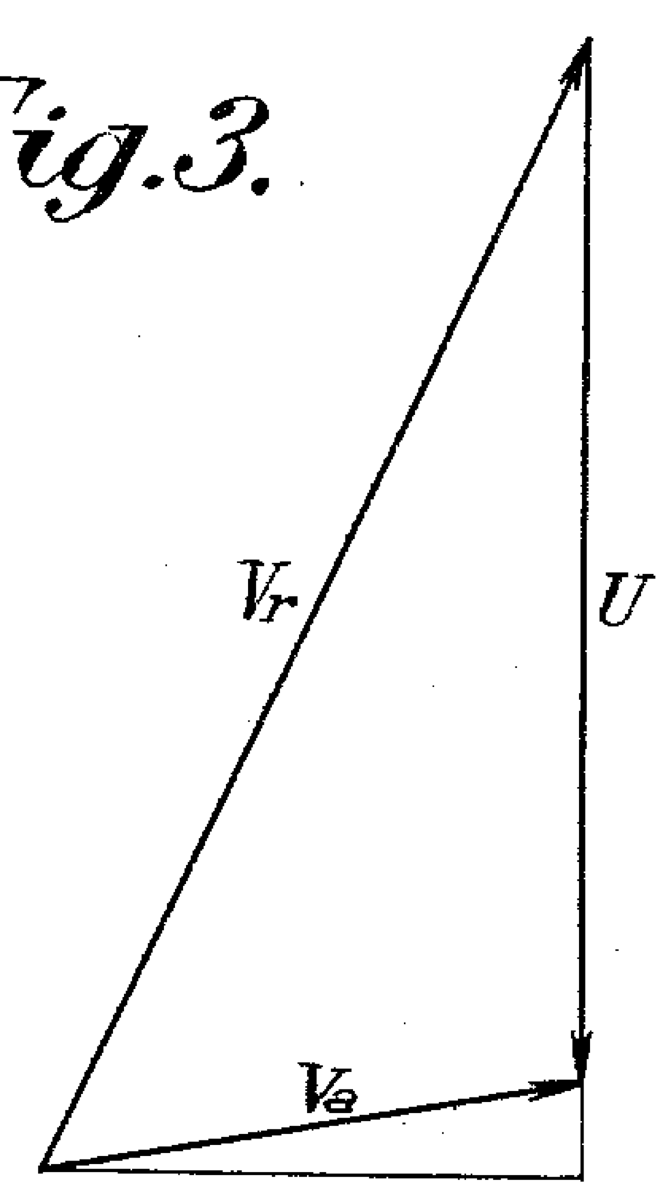


Fig. 3.



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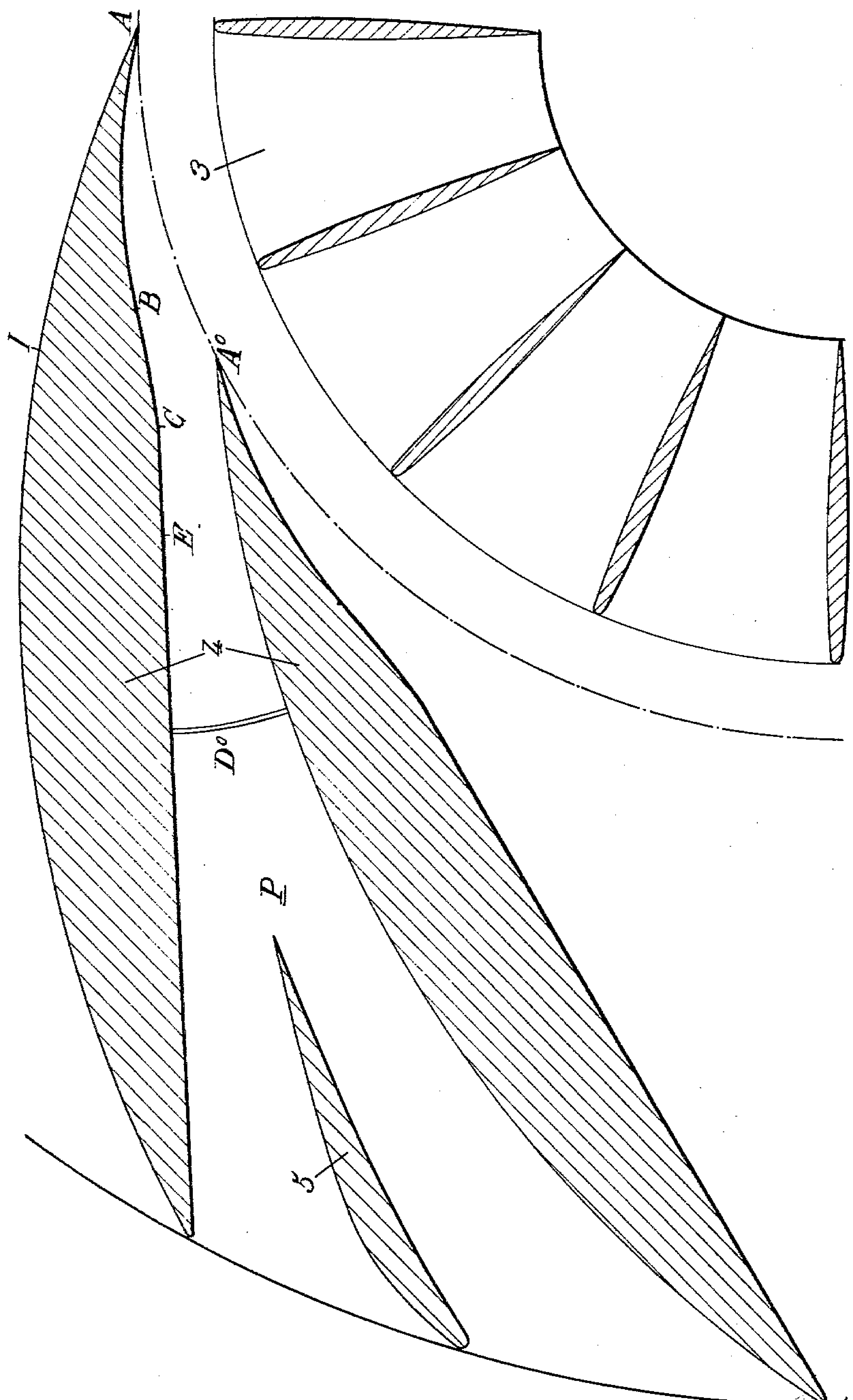

Fig. 4.

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3,184,152

SUPERSONIC COMPRESSORS

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Original application July 6, 1959, Ser. No. 825,166, now Patent No. 3,156,407, dated Nov. 10, 1964. Divided and this application Aug. 7, 1964, Ser. No. 388,122
Claims priority, application France, July 7, 1958, 769,692, Patent 1,232,326
3 Claims. (Cl. 230—127)

The present application is a division of my prior patent application Ser. No. 825,166, filed July 6, 1959, for "Improvements in Supersonic Compressors," now Patent No. 3,156,407.

The present invention relates to supersonic centrifugal flow compressors for gaseous fluids, that is to say to compressors including at least one blading ("supersonic blading"), either fixed or movable, through which the relative velocity of the fluid with respect to the blades is higher than the local velocity of sound at least in some portions of the passages formed between said blades.

The invention is more especially but not exclusively concerned with compressors of this type including a blading, either fixed or movable, arranged in such manner that the velocity of the fluid at the inlet thereof is supersonic.

The chief object of the present invention is to provide a compressor of this type which is better adapted to meet the requirements of practice than those used up to now, especially concerning the stability of operation.

According to this invention, each of the passages provided between the blades of the supersonic blading, including an intermediate zone in which a normal shock wave is produced (so that the flow in the passage is supersonic upstream of said zone and subsonic downstream thereof), has its portion located upstream of said intermediate zone shaped in such manner as to produce in said last mentioned portion a succession of expansion waves, that is to say of waves creating an acceleration of the fluid on its way toward said shock wave, such a compressor comprising a rotor delivering at a supersonic relative speed a gaseous fluid to a set of fixed diffuser blades, and being arranged in such manner that in the inlet zone of every passage between two successive blades of said fixed diffuser set, the suction face of the blades has, from its leading edge to a given intermediate point of the passage, the shape of a concave spiral arc producing recompression waves directed toward said rotor, the end of said spiral arc corresponding to the last recompression wave capable of reaching said rotor without being stopped by the leading edge of the next diffuser blade, said suction face extending from said end in the form of a convex portion intended to create in the transition zone located upstream of the normal shock wave, the expansion waves intended to accelerate the flow.

Preferred embodiments of the present invention will be hereinafter described with reference to the accompanying drawings, given merely by way of example and in which:

FIG. 1 is a part view showing the development of the annular members of a supersonic axial flow compressor made according to the invention, this view being a section by a cylinder coaxial to the compressor and cutting the blades at mid-height thereof.

FIG. 2 is a similar section of a portion of a rotor blading corresponding to a modification.

FIG. 3 shows the velocity triangle characterizing the operation of this compressor.

FIG. 4 is a section of a portion of a centrifugal compressor according to the invention by a plane perpendicular to the axis of said compressor.

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The axial flow compressor diagrammatically illustrated by FIG. 1 includes the following elements:

On the one hand, a set of fixed guide blades **1** which are preferably slightly inclined in such manner that the fluid as it leaves said blades has an absolute velocity V*a* inclined in a given direction, for instance at an angle of approximately 10°, and

On the other hand, a rotor including a set of blades **2** located opposite the set of guide blades **1**, said blades **2** having a velocity U (at mid-height of said blades **2**) in a direction opposed to that toward which the guide blades **1** are inclined, the value of this velocity U being such that the mean relative velocity V*r* of the fluid entering the passages between the rotor blades **2** is supersonic.

By way of example, illustrated by the velocity triangle of FIG. 3, if *a* is the local velocity of sound at the inlet of rotor **2**, the velocity V*a* may be given a value of approximately 0.7*a* and the velocity U is given a value of about 1.2*a*.

Thus the velocity V*r* of the fluid at the inlet of the passages between blades **2** has a value of about 1.6*a*, that is to say is supersonic.

It is known that it has already been endeavoured, by a suitable shaping of the blades **2** of such a rotor, in particular by giving a divergent shape to the end portion of every passage P provided between two successive blades, to create during the operation, in each of the respective passages P, a normal shock wave D^0 (recompression wave) downstream of which the velocity of flow becomes subsonic whereas the velocity upstream of said shock wave is supersonic.

In a supersonic blading of this kind, where normal shock waves are formed, it is advantageous to produce, upstream of the normal shock wave D^0 of every passage, an intermediate transient zone where take place phenomenons which modify the pressure and velocity of the gaseous stream flowing through said transient zone.

For this purpose, it has been suggested to shape the supersonic blades, in their portions located upstream of the normal shock wave, in such manner as to create, in every passage, upstream of said normal shock wave, one or several oblique shock waves (recompression waves) intended to slow down the gaseous flow and to increase its pressure before it reaches said normal shock wave.

Such an arrangement, which has the advantage of increasing the pressure of the gaseous flow gradually from the first recompression oblique wave to the normal shock wave, involves a lack of stability of said normal shock wave for some conditions of operation, in particular in the case of a sudden increase of the flow in the downstream direction, this lack of stability preventing the normal shock waves from being maintained in the velocity of the supersonic throat.

The object of the present invention is to overcome this drawback at the cost of a small supplementary loss of pressure in the gaseous flow.

According to this feature, blades **2**, in the portion of each of them limiting the transient zone of every passage P and located upstream of the normal shock wave D^0, are arranged in such manner as to produce in said transient zone, instead of recompression waves, expansion waves d_1, d_2, d_3 (only some of which are shown on FIG. 1). The effect of these expansion waves is to accelerate the flow of fluid upstream of the normal shock wave D^0 (whereas the recompression waves according to prior devices slowed down the flow in the transient zone) thus further permitting at the place of said normal shock wave, a distribution of velocities of regular divergence.

It results therefrom that the normal shock wave D^0 has a convexity turned toward the downstream direction, such a convexity being favorable to the stabilization of said shock wave. When shock wave D^0 is urged in the downward direction by an increase of the flow rate of the gaseous stream, it moves slightly in this downstream direction, thus increasing the suction produced immediately upstream of said normal shock wave by the successive actions of expansion waves d_1, d_2, d_3 . . . etc.

Shock wave D^0 having been moved toward higher velocities, a more violent shock is produced at the passage through said shock wave D^0, so that there is an increased pressure drop which compensates for the increase of suction in the downward direction.

The normal shock wave D^0 is thus stabilized in its new position.

It will be understood that such an operation is inherent in the presence of expansion waves upstream of the normal shock wave because, when according to the old system, the transient zone is occupied by recompression waves, the pressure drop at the passage through the normal shock wave is the lower as the shock wave is moved a greater distance in the downward direction by suction. Therefore in this case, the normal shock wave is unstable in case of sudden suction thereof in the downward direction.

Concerning now the means to be provided for creating, in said transient zone, the expansion waves that are to accelerate the gaseous fluid flow through said zone, they may be obtained by giving at least the suction face E of every blade, in the portion thereof located in the transient zone, a suitable convexity, the portion of the suction face located upstream of this convex portion being preferably rectilinear and extending substantially in the direction of the inlet velocity Vr of the gaseous fluid stream.

Thus the suction face E of every blade 2 includes a substantially rectilinear flat area starting from the blade leading edge, parallel to the velocity Vr of the gaseous stream entering the passages between the blades, this flat area extending from the leading edge A of the blade to the point B from which an expansion wave d_1 starting from the suction face of the blade that is considered reaches the next blade at the leading edge A^0 thereof. After this flat area, the suction face E of blade 2 includes a slightly convex portion BC (the respective tangents at B and C making an angle of approximately 7° with each other). This convex portion BC preferably has a constant curvature and its end C is advantageously at the point where an oblique shock wave A^0C starting from the leading edge A^0 of the next blade reaches the blade suction face that is being considered. Finally the blade suction face E includes, after this convex portion BC, a rectilinear portion CD extending at least as far as the place where the normal shock wave D^0 is located. This rectilinear portion increases the deflection produced by convex portion BC (the angle between the tangent at C to BC and the rectilinear portion having advantageously the same order of magnitude as the dihedral angle of the leading edge of the blade). This rectilinear portion CD extends beyond point D possibly as far as the trailing edge F of the blade. It may also be followed by a curvilinear portion arranged in accordance with the laws of subsonic aerodynamics so as to obtain the desired result at the outlet of the blading.

As for the pressure face I of the blade, it may be given a substantially rectilinear shape from the leading edge A to the trailing edge F.

According to the modification illustrated by FIG. 2, the convexity of 7° above referred to with reference to FIG. 1 may be distributed between the two opposite walls that limit the transient zone, these two walls including for instance convex portions BC and B^0C^0, each of which correspond to a change of direction of 3.5°. Each of said convex portions may be followed by rectilinear portions forming the divergent diffuser passage.

Anyway, there is obtained in every passage P, upstream of the normal shock wave D^0 thereof, an increasing velocity gradient for the air stream, accompanied by an expansion, then, after the shock wave, a recompression and fan-like distribution of the velocities, which are suddenly reduced by the passage of the fluid through the shock wave, such an arrangement making it possible to stabilize the normal shock wave.

FIG. 4 shows a centrifugal compressor made according to the present invention. This compressor includes a bladed rotor 3 delivering a gaseous fluid at supersonic relative velocity to a fixed diffuser blading.

Preferably, at the inlet of every passage P formed between two successive blades, there is obtained for the flow of the fluid a movement of permanent velocity such that the surfaces of equal velocities and equal pressures are of revolution about an axis of rotor 3. For this purpose, the inlet portion AB of the suction face of every blade is given the shape of a concave spiral arc producing recompression waves directed toward rotor 3, the end point B of this arc corresponding to the last compression wave BA^0 capable of reaching said rotor without being stopped by the leading edge A^0 of the next blade.

After point B, the suction face E of the blade includes a convex area intended to create, in the transient zone located upstream of the normal shock wave D^0, expansion waves capable of accelerating the flow of the fluid, the end point C of this convex portion (the curvature of which may, as above, correspond to a deflection of 7°) being preferably the point where the oblique shock wave starting from the leading edge A^0 of the next blade reaches the pressure face E of the blade that is being considered. After this convex area, there is provided a rectilinear flat area which increases the deflection by an angle approximately equal to the angle of the leading edge, this last mentioned flat area extending as far as the trailing edge of the blade.

Thus point B constitutes an inflexion point whereas point C constitutes an angular point in the profile of the blade.

As for the pressure face I of every blade, it may include a rectilinear flat area starting from the leading edge and continued by a convex portion limiting, together with the oppositely disposed suction face of the next blade, a subsonic diffuser in which may possibly be disposed a guide blade 5.

Whatever be the type of compressor made according to the invention, the passages P between the blades may be either of rectangular transverse section or of ovoid or circular transverse section.

In a general manner, while I have, in the above description, disclosed what I deem to be practical and efficient embodiments of my invention, it should be well understood that I do not wish to be limited thereto as there might be changes made in the arrangement, disposition and form of the parts without departing from the principle of the present invention as comprehended within the scope of the accompanying claims.

What I claim is:

1. A supersonic centrifugal flow compressor for a gaseous fluid which comprises a rotor turning in one direction, a fixed diffuser member coaxially surrounding said rotor, centrifugal blades carried by said rotor so as to deliver at their trailing edges fluid streams flowing at supersonic velocity and inclined at acute angles to the circular periphery of said rotor turning in said direction, and diffuser blades carried by said fixed member to form between them a plurality of passages for said gaseous fluid inclined at obtuse angles to the circular periphery of said rotor turning in said direction, the face of each of said diffuser blades that is turned toward the axis of said rotor having, from the leading edge thereof to an intermediate point of the corresponding passage, an area

in the form of a concave spiral arc to produce recompression waves directed toward said rotor, the end of said spiral arc corresponding to the last recompression wave capable of reaching said rotor without being stopped by the leading edge of the next diffuser blade, the fore portion of each of said passages being convergent and the rear portion divergent in the direction of the gaseous fluid flow, with a throat between said portions, so as to produce a normal shock wave rearwardly of said convergent portion, downstream of which shock wave the fluid flow is subsonic, the above mentioned face of each of said diffuser blades comprising, after said spiral arc area, a convex area extending from said concave area toward said throat, said concave and convex areas being arranged to produce, in said convergent portion of said passage, a succession of expansion waves creating an acceleration of the gaseous fluid flowing past them to reach said throat, said convex area beginning at the point from which an expansion wave starting from said last mentioned face turned toward the axis of said rotor reaches the leading edge of the next blade facing said last mentioned face.

2. A supersonic centrifugal compressor according to

claim 1 in which the end of said convex area corresponds with the point where an oblique shock wave starting from the leading edge of said next blade reaches said face of the first mentioned blade that is turned toward the axis of said rotor, said convex portion being followed by a rectilinear flat portion.

3. A supersonic centrifugal compressor according to claim 1 in which the leading edge portion of the pressure face of every blade of the diffuser blading that is turned away from said rotor axis is a flat rectilinear area followed by a convex portion which, downstream of said throat limits with the opposite face of the next blade, a subsonic diffuser conduit.

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