Feb. 17, 1953 A. KANTROWITZ **2,628,768**

AXIAL-FLOW COMPRESSOR

Filed March 27, 1946 2 SHEETS—SHEET 1

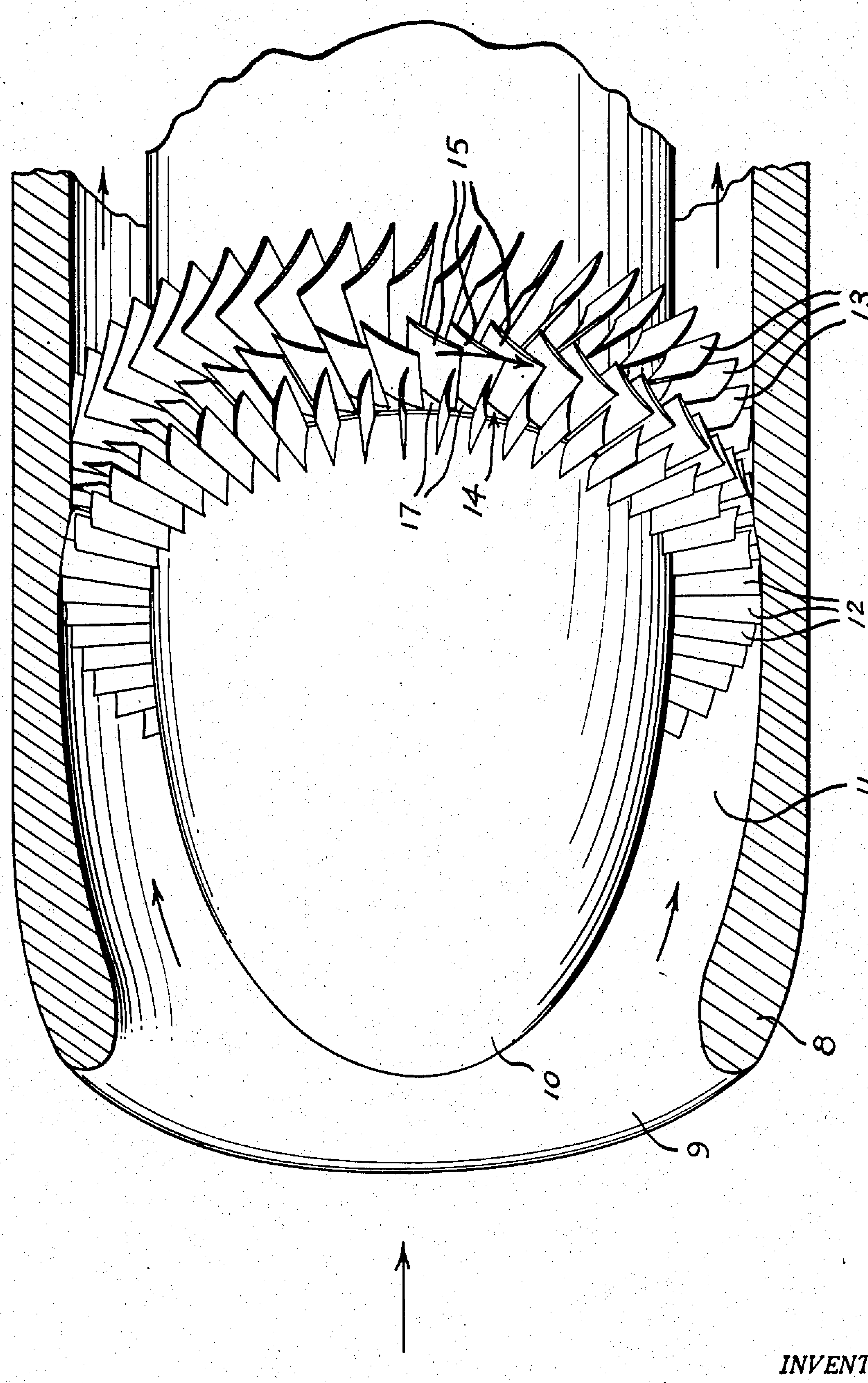

FIG. I

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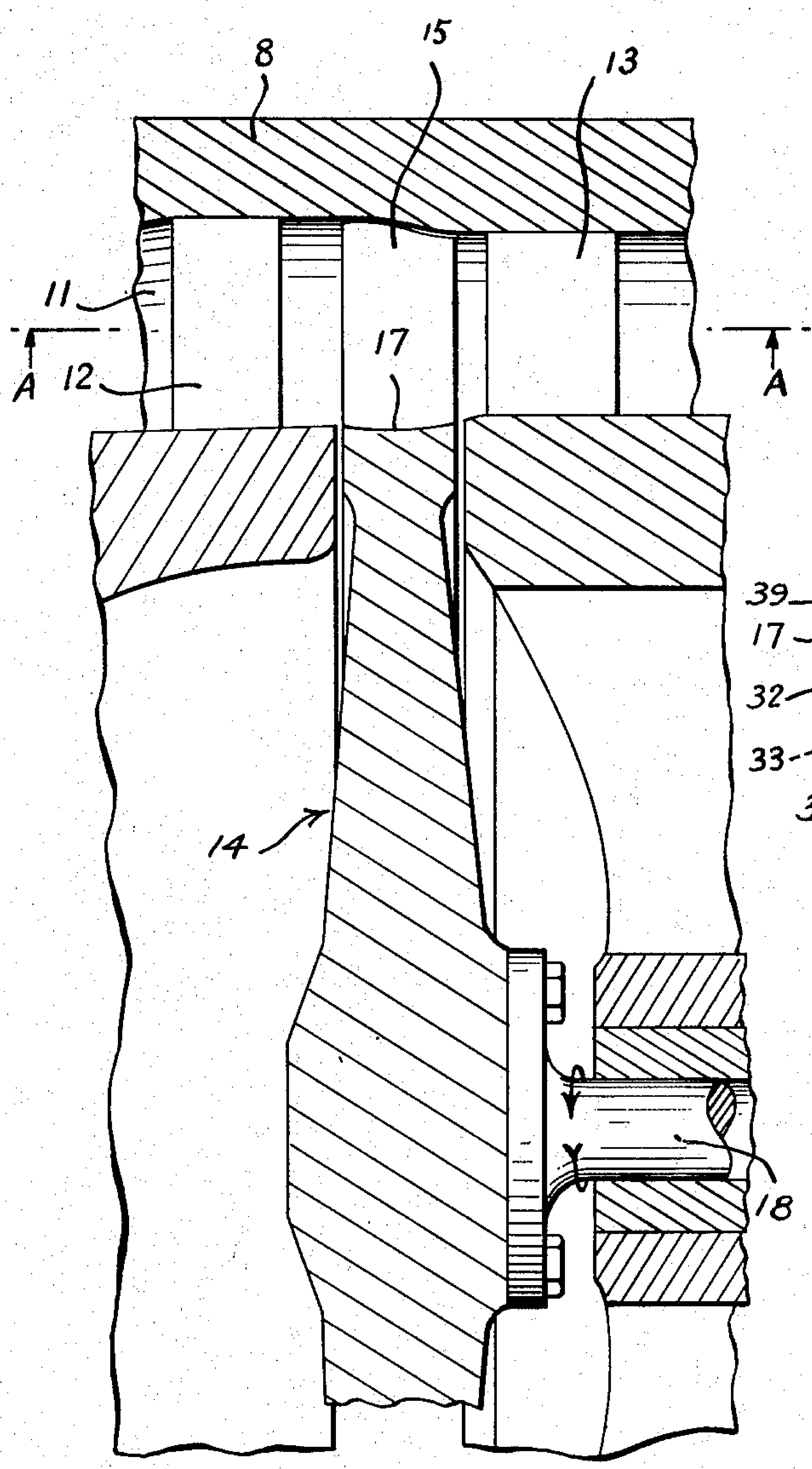

FIG. 2

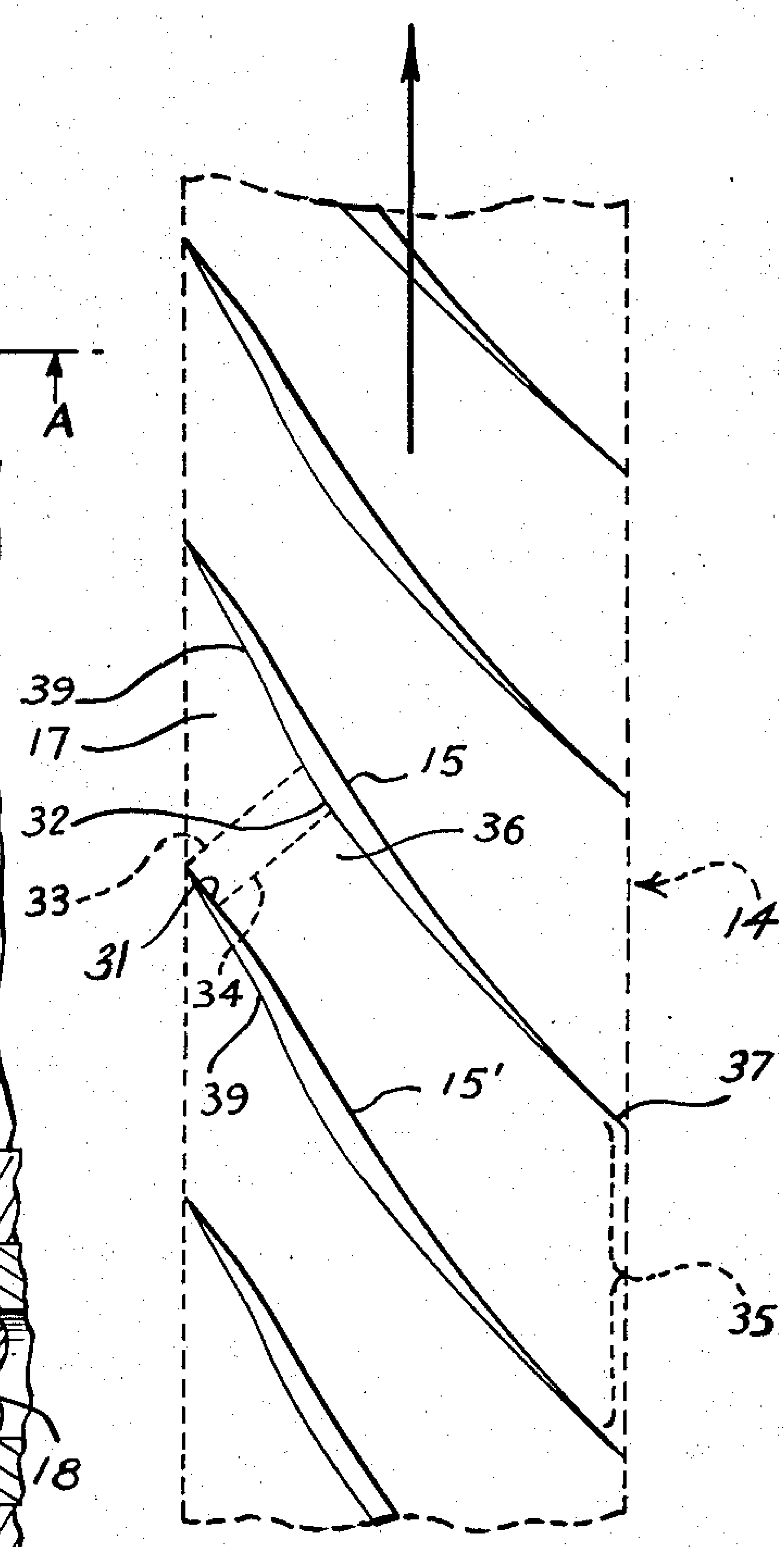

FIG. 3

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AXIAL-FLOW COMPRESSOR

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8 Claims. (Cl. 230—122)

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This invention relates to the shapes of blades for use in an axial-flow compressor, and is intended to produce a higher pressure ratio per stage than has hitherto been effected in this type of machine. Heretofore, in order to achieve high efficiency in machines of this type, the local gas velocities entering the rotors and stators have been restricted to less than the velocity of sound in the gas. This has meant that the compression ratio produced by an axial-flow compressor stage has been restricted to about 1:3.

It is an object of this invention to provide an improved method for compressing gas so that a large compression ratio can be obtained in a single stage and with high efficiency.

Another object is to provide an improved blade shape and correlation of blading for effecting larger compression ratios in single stage axial-flow compressors.

With this invention supersonic gas velocity is used and the resulting shock waves are controlled so that high compressor efficiency is obtained in spite of the shock. It is this control of the shock waves that makes it possible to obtain such higher pressure rises in a single stage.

Features of the invention relate to the blading of the compressor, and the preferred embodiment of the invention has blades of novel shape and in a particular relation with one another for effecting deceleration of gas flow against the back pressure with control of the shock waves producing the velocity change.

Other objects, features and advantages of the invention will appear or be pointed out as the description proceeds.

In the drawing, forming a part hereof in which like reference characters indicate corresponding parts in all the views,

Fig. 1 is a perspective view of a compressor embodying this invention, the casing being shown in section in order to illustrate the blading.

Fig. 2 is a fragmentary enlarged sectional view through a portion of the rotor and stator of the compressor shown in Fig. 1.

Fig. 3 is a development of the blading along the cylinder A—A of Fig. 2.

The axial compressor shown in Fig. 1 includes a casing 8 having an inlet opening 9 at one end. Within the casing there is a fixed stator hub 10. The gas or air enters the compressor through the annular space 11 between the inside wall of the casing 8 and the peripheral surface of the stator hub. The stator has fixed blades 12 at equiangular positions around its entire circumference and the outer ends of these blades are rigidly connected to the casing 8.

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Other stator blades 13 are similarly connected to the casing 8, and the blades 13 are spaced from the blades 12 to leave room for a rotor 14 having blades 15 constructed and arranged to draw air through the passages between the stator blades 12, and to discharge the air through the passages between the stator blades 13.

Fig. 2 shows the relation of one of the rotor blades 15 to the stator blades 12 and 13. The outer edge of the blade 15 extends close to the wall of the compressor casing 8, and in the construction illustrated the radial length of the blade 15 is slightly greater toward its intake side. The internal diameter of the casing 8 decreases proportionately to leave ample running clearance for the blade 15. This construction avoids too rapid an increase in the cross section of the passage between successive blades 15. Too rapid an increase in the passage area would result in dead air regions in the passages which would lead to reduced efficiency.

The "gas passages" of the rotor are the passages bounded on the sides by successive rotor blades, on the bottom by the surface 17 of the rotor between blades, and on the top by the inside surface area of the casing across which the outer ends of the blades sweep as the rotor revolves. The rotor can be constructed with a cylindrical shell connected with the tips of the rotor blades. Such shrouds are used on turbines and axial-flow compressors for the purpose of preventing tip clearance losses and for reducing vibration, and are well understood in the art.

The rotor 14 is connected with a driving shaft 18 that turns in bearings within the compressor, and power is applied to the drive shaft 18 from a motor or any external source of power.

The principle of the invention, the shape of the blades, and the correlation of the blades can best be understood by considering the operation in connection with two successive blades 15 and 15' of Fig. 3.

As the rotational speed of an axial flow compressor is increased, a speed is reached at which the relative gas velocity exceeds the local speed of sound at some point on the blading. If the speed is still further increased a shock wave forms at some point on the blading usually between points 31 and 32. As the speed increases still further the shock grows, extending further away from the blade surfaces and eventually ahead of the leading edge of the adjacent blade 15'. A shock wave of this type which exists upstream from the leading edge of a blade will be referred to herein as a "detached bow wave." These detached bow waves existing ahead of each of the blades eventually extend far out from the cascade and form an extended wave system. The losses due to this extended wave system are so large that designers have avoided the occurrence of supersonic velocities in order to avoid these losses.

In order to maintain the compressor efficiency it is necessary to have the bow wave move back far enough to attach to the next successive blade 15'. Such attachment prevents the setting up of an extended wave system.

The amount that the bow wave moves back along the blade 15 depends upon several different factors. One is the blade speed. The bow wave tends to move back as the velocity of the blade through the air increases. Another factor is the wedge angle, that is, the sharpness of the leading edge of the succeeding blade 15'. The bow wave moves back further, at a given speed, if the leading edge of the succeeding blade is sharp. If the angle of the blade surfaces that meet to form the leading edge is greater than 90°, it is not possible in air to get attachment no matter how high the blade speed may become.

Another factor affecting the ultimate position of the bow wave is the width of the narrowest section between the blades, that is, the area of cross section of the space between the blades 15 and 15' in a plane normal to the direction of the gas flow between the blades. If there is any considerable reduction in section along the passage between the blades the bow waves cannot become attached to the blades. For reasons that will become apparent, it is desirable to have a slightly restricted throat between the blades, and to have the shock wave between the blades downstream of the minimum section of the passage between the blades.

The position of the bow wave is affected also by the back pressure ratio, that is, the ratio of back pressure to inlet pressure. A higher back pressure ratio opposes downstream movement of the bow wave, but with sonic or supersonic velocity of the air at the minimum throat section 34, the back pressure ratio is not directly effective on the position of the detached bow wave.

If, however, the throat section is large enough, the back pressure low enough, the wedge angle small enough and the rotational speed high enough the bow waves become attached. The portion of the waves upstream from the cascade then nearly disappears and the portion between the blades moves downstream and is confined entirely within the blading. This confined shock decelerates the air thru the speed of sound and in this process compresses the air efficiently.

Although it is possible to accelerate gas to supersonic velocity without shock, it is not possible to decelerate through the sonic velocity without having a shock wave in the gas stream.

In the operation of the compressor, the rotor is driven at sufficiently high speed to make the relative velocity of the air entering the rotor blading higher than the sonic velocity. The air velocities relative to the stator blades, both inlet and discharge, is subsonic and the design of the stator blading is conventional.

The blade surfaces at the leading edge meet in an angle less than 30 degrees and preferably less than 20 degrees. In the illustrated embodiment of the invention the blade faces form an angle of approximately 10 degrees at the leading edge. The leading edge thus forms a sharp wedge so that bow waves can become attached to the blades. In this specification and in the claims, the term "sharp" as applied to the leading edge designates an edge in which the effective angle between the forward and rearward blade surfaces is less than 30 degrees, and the leading edge radius is less than 2 percent of the circumferential distance between the leading edges of successive blades; or the blades are made of such thin material that the thickness of the leading edge is less than 2 percent of the circumferential distance between blades.

The cross-sectional area of the inlet of the gas passage between the blades 15 and 15' is indicated by the plane 33. All gas passage cross-sections referred to in this specification and in the claims are areas of planes normal to the direction of gas flow through the passage at the location where the cross-section is taken.

As the result of the increase in thickness of the blades 15 and 15' downstream from the passage inlet 33, the cross-section of the rotor gas passage between these blades decreases progressively to a throat section 34 where the cross-sectional area is a minimum, but not substantially less than the passage entrance or inlet 33. The area of the throat section 34 is approximately 93 percent of the cross-section of the inlet 33 in the compressor shown in the drawing. This value is given merely as an illustration.

The back pressure at the discharge region 35 is so correlated with the inlet pressure and the rotor speed that the air flow decreases through the sonic velocity and undergoes normal shock at the region 36 just downstream from the throat 34. The gas passage between the blades 15 and 15' increases in cross-section beyond the throat 34, and this insures stability of the shock wave.

Although the shock wave tends to be substantially normal to the direction of gas flow, it is, in practice distorted by interaction with the boundary layers on the blades, the rotor and the casing. Angular waves given off from the boundary layers interact with the normal shock and sometimes result in multiple reflections. In the compressor of this invention, this entire normal shock complex is confined within the blade passage in the region 36; and the term "region of shock," as used herein, refers to the space occupied by this normal shock complex.

It is essential, in order to maintain high compressor efficiency, that this shock region 36 is within the gas passage, and that the normal shock complex is thereby confined on all sides by the walls of the rotor gas passage. The blading, therefore, must have sufficient chord length from the leading edges 31 to the trailing edges 37, as compared with the spacing between the blades, so that planes normal to the gas flow throughout the region of shock is bounded on both ends by the blade surfaces; and it is important that this be true at the top as well as at the lower ends of the blades where they connect to the body of the rotor, and are closer together than at their tips.

In order to reduce the intensity, and hence the energy losses, in the normal shock complex at the region just beyond the throat 34, the rearward surface of each of the blades 15 is made with a concave portion 39 for a short distance back from the edge 31. This concave region originates compression waves which reduce the velocity of the air smoothly before the air reaches the region of normal shock. These compression waves will thus reduce the intensity of the shock and the losses that go with it.

In order that supersonic flow into the cascade may be started, it is necessary that the narrowest section of the passages formed by the blades downstream from the inlet section 33 be nearly as large as the area available for gas flow at the inlet section 33. In starting the machine, an extended wave system is set up in the air and this entails large losses. In order to have the desired flow conditions set up, it is necessary that the air, after undergoing these large losses, be still capable of passing through the blading. If a throat with considerably less air flow area than the inlet section 33 were included in the blade design, then it would not be possible for the air to get through this throat in the starting condition, and the desired flow conditions could not be set up.

It will be understood that the blades 15 of the rotor may be used in the stator on the discharge side of a rotor that delivers the gas to the downstream stator blades at supersonic velocity. The relative velocity of the blades and gas is the important consideration whether or not the blades are moving in space. The term "cascade" is used herein to designate a circle of blades whether secured to a rotating or stationary part of the apparatus. In any event, the blading offers the advantage that the gas having supersonic velocity with respect to the gas passages can decelerate to a subsonic value with the shock waves contained entirely within the blade passages.

In the case of stationary blading the forward and rearward surfaces of the blades are the surfaces corresponding to the forward and rearward surfaces of the blades when used on a rotor. The direction of the air entering the passages between the blades has both an axial and a tangential component, and the direction of the tangential component is toward the forward surfaces of the blades and away from their rearward surface.

The preferred embodiment and method of this invention has been illustrated and described, but changes and modifications can be made and some features of the invention can be used in different combinations without departing from the invention as defined in the claims.

I claim as my invention:

1. A supersonic compressor including a cascade of blades, angularly spaced from one another around a surface of revolution, said blades having sharp leading edges which are disposed at acute angles to a plane normal to the axis of the body of revolution and being of sufficient chord length so that successive blades intersect common parallel planes that are spaced from one another by a substantial distance and that are normal to the direction of gas flow between the blades, the confronting faces of said blades diverging from one another in the direction of gas flow for at least a portion of their length between the parallel planes.

2. A supersonic axial-flow compressor comprising a casing, a bladed rotor supported within the casing for rotation with running clearance between the blade tips and the inside surface of the casing, angularly spaced blades on the rotor with sharp leading edges disposed at acute angles to both the axis of rotation and the plane of rotation of the rotor, said blades being of sufficient chord length so that successive blades intersect common parallel planes that are spaced from one another by a substantial distance and that are normal to the direction of gas flow between the blades, the confronting faces of said blades diverging from one another in the direction of gas flow for at least a portion of their length between the parallel planes.

3. A supersonic axial-flow compressor comprising a cascade having angularly spaced rotor blades with sharp leading edges at acute angles to the plane of rotation of the rotor and with a concave surface on the rearward faces of the blades just beyond their leading edges, each of said blades increasing in thickness along the portion of its length that has said concave surface.

4. A supersonic axial-flow compressor comprising a casing, a rotor within the casing, and angularly spaced blades on the rotor, and each disposed at an acute angle to the plane of rotation of the rotor throughout the entire length of the blade and having a concave surface on its rearward face just beyond the leading edge of the blade, each of said blades increasing in thickness along the portion of its length that has said concave surface.

5. An axial-flow compressor for gas having supersonic velocity, said compressor comprising a casing and a bladed rotor that rotates within the casing with running clearance between the blade tips of the rotor and the inside surface of the casing, said rotor having blades of sufficient chord length to enclose a gas passage in which a plane perpendicular to the gas flow through the passage intersects the confronting faces of the blades that form the gas passage along a region of the passage where the blades are shaped to provide first a throat and then a region of expanding cross-section in the direction of gas flow, the blades having concave surfaces on their rearward faces at regions spaced a short distance beyond the leading edges of the blades for controlling the gas velocity, each of said blades increasing in thickness along the portion of its length that has said concave surface.

6. A supersonic axial-flow compressor comprising a stator, a rotor, and blades on the rotor having leading edges formed by forward and rearward blade faces that meet in an effective angle of less than 30 degrees, and with the bisector of such angle at an acute angle to the plane of rotation of the rotor, the rearward faces of the blades just behind the leading edges being concave for controlling the velocity of flow, each of said blades increasing in thickness along the portion of its length that has said concave surface and successive blades of the rotor being of sufficient chord length to intersect common parallel planes that are spaced from one another by a substantial distance and that are normal to the direction of gas flow between said blades, the confronting faces of said blades diverging from one another in the direction of gas flow for at least a portion of their length between the parallel planes.

7. An axial-flow compressor including a stator, a rotor having blades for moving gas from the stator at supersonic velocities with respect to the leading edges of the rotor blades, successive blades being shaped to provide gas passages with entrances that have a cross section slightly larger than the cross-section of the passages at an intermediate throat region, and said blades being of sufficient length so that successive blades intersect common parallel planes that are spaced from one another by a substantial distance and that are normal to the direction of gas flow in the passage just beyond the throat in

the downstream direction, the confronting faces of said blades diverging from one another in the direction of gas flow for at least a portion of their length that lies beyond the throat but between the parallel planes.

8. A supersonic velocity compressor including a cascade of blades angularly spaced around a surface of revolution and having leading edges at their upstream ends and portions of greater thickness intermediate their ends providing surfaces that cooperate with confronting surfaces of preceding and succeeding blades to form gas passages that decrease slightly in cross section to a throat area some distance back from the leading edges of the blades, and then increase in cross section toward the outlet ends of said passages, and concave surfaces on the rearward faces of the blades upstream from said throat areas.

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