April 15, 1958 E. A. STALKER 2,830,753

AXIAL FLOW COMPRESSORS WITH CIRCULAR ARC BLADES

Original Filed Nov. 10, 1951

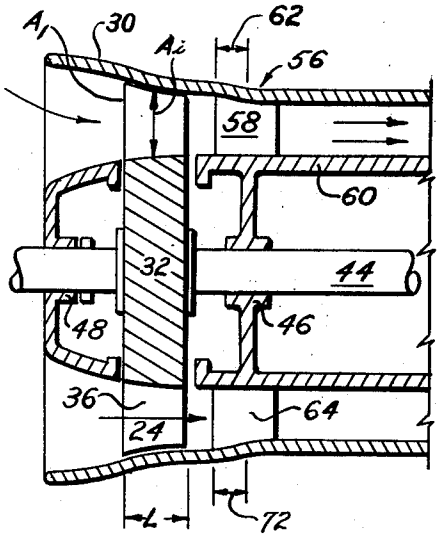


FIG. 4

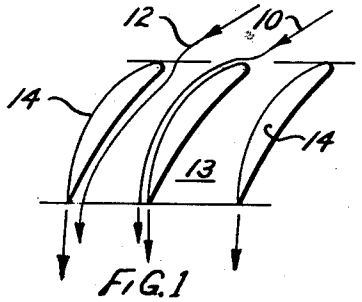


FIG. 1

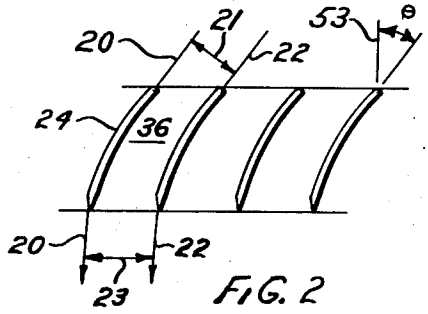


FIG. 2

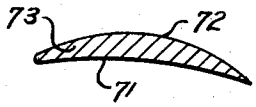


FIG. 7

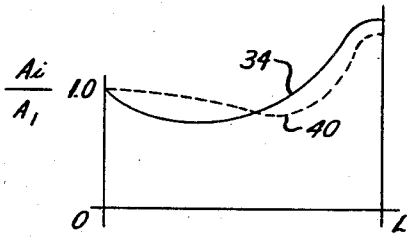


FIG. 3

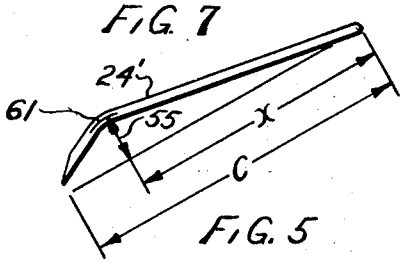


FIG. 5

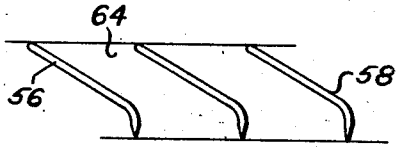


FIG. 6

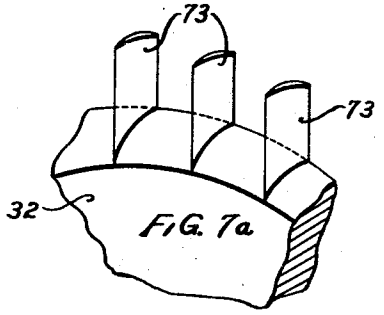


FIG. 7a

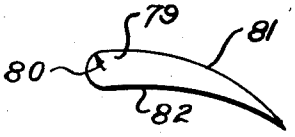


FIG. 8

INVENTOR

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AXIAL FLOW COMPRESSORS WITH CIRCULAR ARC BLADES

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Original application November 10, 1951, Serial No. 255,799. Divided and this application September 2, 1953, Serial No. 378,153

7 Claims. (Cl. 230—120)

This invention relates to axial flow compressors and particularly to structures therefor which are economical to produce.

An object of this invention is to provide novel aerodynamic structures for compressors which can be produced by simple machine tool operations.

Another object is to provide cases and blades of simple shape which cooperate to provide efficient flows of fluid therebetween.

Other objects will appear from the description drawings and claims.

This application is a division of my U. S. application Serial No. 255,799, filed November 10, 1951, entitled "Axial Flow Compressors," now abandoned.

The above objects are accomplished by the means illustrated in the accompanying drawings in which—

Figure 1 is a fragmentary development of the blades of a prior art compressor rotor which have airfoil cross sections;

Figure 2 is a fragmentary development of the rotor blades of a compressor according to the subject invention;

Figure 3 shows graphs of the variation in the cross sectional areas of rotor passages expressed as a ratio to the cross sectional area of the passage at the inlet thereto;

Figure 4 is a fragmentary axial section through a compressor according to the subject invention;

Figure 5 is an alternate blade section defining the location of the maximum mean camber height above the subtending chord C;

Figure 6 is a fragmentary development of the stator blades of the compressor of Fig. 4;

Figure 7 shows an alternate-blade section;

Figure 7*a* shows a fragmentary perspective view of a rotor incorporating blades similar to that of Fig. 7; and

Figure 8 shows still another blade section.

This division of the parent application is directed to rotors whose blade sections are defined by upper and lower circular arcs extending substantially to the leading and trailing edges, and to such blades whose spanwise elements lie along radial lines extending outward from the rotor hub.

Figure 1 shows a fragmentary development of the blades of a rotor stage of a prior art axial flow compressor. The blades are of airfoil section and it will be observed that the streamlines **10** and **12** of the fluid flow of a relative fluid flow first converge in passing through the passages **13** between the blades **14** and then later diverge.

The convergence indicates an increasing velocity along substantial lengths of the forward parts of the blades which keep their boundary layers in a laminar state. Then for the forward portion of each blade, the resistance or drag loss is low since as is well known, a laminar flow of the boundary layer has less loss than a turbulent flow.

The main aerodynamic advantage of an airfoil section for a compressor blade resides in the production of

the accelerated flow along the forward portion of the blade and not in some overall characterization of airfoils.

The fabrication of blades of airfoil shape is very costly because of the constantly varying radii of curvature chordwise along the blade including varying nose radii along the blade span.

Sheet metal blades are readily stamped or pressed to shape and because the thickness is constant a simple tool operation, such as performed by a shaper tool for instance, can provide the nose radius desired.

Sheet metal blades of constant thickness (with rounded leading edges and sharpened trailing edges) are cheap to produce but they do not provide significant acceleration of the flow for a significant distance in passing along the forward portions of the blades. In Fig. 2 the streamlines, contiguous with the boundaries or contours of the blade sections of the blades **24**, are **20** and **22** and it will be observed that there is no significant acceleration of the flow along a significant length of blade chord.

The cross sectional width and areas are measured along such lines as **21** and **23** normal to the flow lines on the contours of the blades. The blades are said to be peripherally curved when their sections are curved in peripheral surfaces about the rotor axis.

The aerodynamic advantages of the blades with airfoil section and the economic advantages of the sheet metal blades are combined by the present invention. This is accomplished as shown in Figs. 2–4 for one embodiment of the invention by varying the shape of the bounding walls, namely case **30** and hub **32** so that the flow passages **36** between blades each decreases in cross sectional area for a substantial chordwise distance. The portion of each passage rearward of the portion of decreasing cross sectional areas has increasing cross sectional areas rearward therealong because of the peripheral or chordwise curvature in the blades.

In Fig. 3, curve **34** shows the variation in cross sectional area of each rotor passage **36** along the axial length L for blades of constant thickness as made from a sheet. A_1 is the cross sectional area at any point along the passage and A_1 is the cross sectional area at the inlet to a rotor passage between adjacent blades. Curve **40** is for an alternate passage wherein the throat occurs aft of the mid length of the passage and is particularly suited to high velocity of the flow relative to the blade. Both curves, **34** and **40**, disclose a greater cross sectional exit than inlet area indicated by the ratio of A_1 and A_1 greater than 1.

In Fig. 4 the rotor **32** is rotatably supported by the shaft **44** and bearings **46** and **48**. The blades **24** are peripherally spaced about the hub **32** at the pitch angle θ measured with respect to the direction of the axis of rotation **53**. The rotor is contained in the case **30** and is succeeded by the stator **56** comprising the blades **58** and inner case or wall **60**.

The case **30** and rotor hub **32** converge toward each other at the rotor position to provide acceleration of the flow along the forward portions of the sheet blades **24** according to curve **34** of Fig. 3. Thus each passage has a converging portion providing a throat of smaller cross sectional area than the inlet cross sectional area.

The throat is succeeded downstream by cross sectional areas of progressively increasing magnitude with the exit cross sectional area greater than the inlet cross sectional area. The increase in cross sectional area along the aft portion of a rotor passage is provided by the curving of the blades along their chords to place said aft portions more nearly parallel to the axis of rotation. Thus cross section **23** is greater than cross section **21**. Consequently the case and hub surfaces may be approxi-

mately parallel along the aft portions of the rotor passages.

The shapes required of the case and the hub are produced by turning as on a lathe and are therefore cheap to make. Thus the combination of low cost sheet blades and turned case and hub provides a very economical structure which is aerodynamically efficient.

The sheet blades may also take the form **24'** shown in Fig. 5 where the distance X to the maximum ordinate **55** of the mean camber line **61** may be aft of the mid point of the chord C. Fig. 5 shows it in the neighborhood of the 80% point of the chord. Such blades are preferably used with the cross sectional areas varying in the manner shown by curve **40** in Fig. 3.

The stator **56** as shown in Fig. 4 and Fig. 6 has sheet blades **58** similar to the rotor blades. The cases **30** and **60** constitute respectively radially inner and outer walls bounding the stator passages. These walls converge in the downstream axial direction along the forward portion **62** of each stator passage **64** between blades so that the cross sectional areas decrease along this portion. Along the aft portion of each stator passage the blades are curved in the peripheral direction so that the cross sectional areas increase with the exit cross sectional area greater than the inlet cross sectional area.

Another form of the invention is shown in Figs. 4, 7 and 7*a* wherein the upper contour of each blade section is a circular arc extending from substantially the trailing edge to substantially the leading edge and the lower contour is also a circular arc extending in like manner.

Sheet blades are the most economical to produce but other economical blade forms may also be combined with the passage shape to give passage flows of low drag loss. For instance, the blade may have circular arcs **71** and **72**, Fig. 7, forming its crescent shaped blade section **73**. The leading edge has a constant nose radius along the blade span so that it is readily cut as by a shaper or miller tool. Such blades can be produced economically. The case and hub can be given such contours that the desired acceleration of the flow will take place along the forward portions of the blades. Fig. 7*a* shows a fragmentary perspective view of the rotor in Fig. 4 wherein blades **73** of Fig. 7 have been substituted.

The circular arc blade presents a thicker blade which in some applications will resist vibrations in a superior manner.

The blading is preferably arranged so that there is no significant diffusion of the flow along a portion of each passage close to its exit. This is done by making the aft portions of the mean camber lines of blades substantially parallel or by tapering the case or hub so that the cross sectional area of each passage is substantially constant for a short distance just ahead of the trailing edges. Curves **34** and **40** of Fig. 3 show a short length of no diffusion. This should be from 5% to 25% of the axial length of the blades with a preferred value of 10%.

If there is no diffusion of the flow just before reaching the trailing edges of the blades, the rotor is not applying a force to the air and so there will be no difference in pressure between opposite sides of the blade. If a difference of pressure existed there would be a vortex form at each blade trailing edge with a consequent loss. By eliminating the diffusion just forward of the trailing edge a substantial improvement in efficiency is obtained.

The greater the maximum mean camber ordinate and the further rearward it is located, the more important it is that the diffusion be terminated ahead of the trailing edges. In particular the diffusion should be terminated well ahead of the trailing edge when the maximum mean camber ordinate is not less than 5% of the blade chord and/or the position of the mean camber maximum ordinate is aft of the mid point of the blade chord.

The blades of this invention are particularly suited to compressor rotors which give the fluid a rotation wherein

the peripheral velocity is proportional to the radius. Such a rotation may be called a rigid body type of rotation.

Bladed compressor rotors which are designed to give the fluid a wheel or rigid body type of rotation can be designed to have the same Mach number at all points along the blade span. Since the Mach number is the same as the nose radius of the blade sections can be the same at all sections along the blade span.

The blade whose blade sections are composed of circular arcs can have greater thickness at the root portion adjacent the hub than at the tip portion adjacent the case while retaining the constant nose radius along the span—by making the tip chord less than the root chord and the tip section thickness ratio greater than the root section thickness ratio referred to the respective chord lengths.

Circular arc blade sections, Figs. 7 and 8, provide some acceleration along the forward halves and the amount of acceleration can be increased between the leading edges and rearward points of the chords by tapering the case or hub or both as described earlier herein.

Where a large range of mass flow is desired for a given rate of rotation, the nose radius **80** should be a large percentage of the chord of the blade section **79** as shown in Fig. 8. The upper and lower contours **81** and **82** are circular arcs and the maximum thickness is well forward along the chord. This section in a cylindrical duct has a very short nose portion about equal to the radius bathed by an accelerated flow but by tapering the hub and case the flow can be made accelerating along even a major portion of the chord length if desired such as indicated by curve **40** of Fig. 3.

Preferably the blades are arranged so that all elements of each blade lie along radial lines so that the centrifugal force on the elements do not move them significantly laterally. Thus the centrifugal force is chiefly resisted by tension stresses and the blade does not tend to untwist due to the centrifugal forces. This is substantially accomplished by having the major portions of the blade over its chordwise and spanwise extents in coincidence with chordwise spaced radial lines from the axis of rotation passing through the root section inside its contours.

An axial flow compressor is characterized by having rotor flow passages which are directed in the general direction of the axis from an inlet at the front of the rotor to an exit at the rear of the rotor, facing rearward to discharge fluid rearward relative to the rotor in the general direction of the axis.

While I have illustrated specific forms of the invention, it is to be understood that variations may be made therein and that I intend to claim my invention broadly as indicated by the appended claims.

I claim:

1. In combination in an axial flow compressor, a case, a hub rotatably mounted in said case defining an annular channel therewith, and a plurality of blades on said hub having leading and trailing edges extending radially and being spaced peripherally thereabout and dividing said annular channel into a plurality of rotor flow passages defined between said leading and trailing edges of said blades and bounded by said case and hub and having inlets and exits for flow of fluid therethrough respectively adjacent said leading and trailing edges, said case and hub converging relative to each other in the downstream direction along forward portions of said rotor passages to progressively reduce the cross sectional areas thereof along said forward portions, said forward portions being succeeded downstream by rearward portions of said rotor passages of progressively increasing cross sectional areas with the exit cross sectional areas of said rotor passages larger than the inlet cross sectional areas thereof, each said blade having spanwise spaced blade sections along a major portion of said leading

edge transverse thereto, each said section being defined by a contour comprising an upper circular arc and a lower circular arc spaced apart at mid chord and extending with the same respective radii of curvature over substantially the entire distance between the leading and trailing edges, each said arc extending continuously from substantially said leading edge to substantially said trailing edge and converging one relative to the other toward said edges.

2. In combination in an axial flow compressor, a blade structure mounted for rotation about an axis comprising a plurality of peripherally spaced blades having their spans extending radially and defining a plurality of flow passages therebetween, each said blade having blade sections transverse to said span along a major portion thereof, each said section having a contour comprised of an upper circular arc and a lower circular arc spaced apart extending with the same respective radii of curvature over substantially the entire distance between the leading and trailing edges and defining a maximum thickness at about the midpoint of the chord of said blade, and an outer wall and an inner wall bounding said flow passages, said walls converging one relative to the other so that the forward portion of each said passage has decreasing cross sectional areas rearward therealong, said blades being curved along the chords thereof providing in cooperation with said walls increasing cross sectional areas for the rearward portions of said passages with the exit cross sectional area of each said passage greater than the inlet cross sectional area thereof.

3. In combination in an axial flow compressor, a blade structure comprising a plurality of peripherally spaced blades having spans and leading and trailing edges extending radially and defining a plurality of flow passages between said blades for conducting a flow of fluid rearward therethrough, each said passage having an inlet at the forward end thereof and an exit at the rearward end thereof respectively adjacent said leading and trailing edges, each said blade having spanwise spaced blade sections along a major portion of said span transverse thereto, each said section being defined by a contour comprised of an upper circular arc and a lower circular arc providing a locality of maximum blade thickness along the blade chord, each said arc extending chordwise with the same radius of curvature substantially to the leading edges of said sections and to the trailing edges thereof, and an outer wall and an inner wall at radially opposite ends of said blades bounding said flow passages, said walls converging one relative to the other downstream along the forward portion of each passage decreasing the cross sectional areas rearward therealong to a point aft of said localities of said maximum thickness, said blades being curved in the peripheral direction providing in cooperation with said walls increasing cross sectional areas downstream along the rear portions of said passages, the cross sectional area of said exit of each said passage being larger than the cross sectional area of said inlet thereof.

4. In combination in an axial flow compressor, a blade structure mounted for rotation about an axis comprising a plurality of peripherally spaced blades having spans extending radially and defining a plurality of flow passages between said blades for conducting a flow of fluid rearward therethrough, each said blade having its blade sections comprised of an upper circular arc and a lower circular arc spaced apart at mid chord and converging one relative to the other toward the ends thereof placing the maximum thickness of said sections at about the midpoint of the chord, each said arc extending chordwise with the same radius of curvature substantially to the leading edge of said sections and to the trailing edge of said blade, and an outer wall and an inner wall at radially opposite ends of said blades bounding said flow passages, said walls converging one relative to the other so that the forward portion of each passage has decreasing cross sectional areas rearward therealong, said blades being curved along the chords thereof providing in cooperation with said walls increasing cross sectional areas for the rear portions of said passages, the nose radii of said blade sections being substantially constant along each blade span, the exit cross sectional area of each said passage being larger than the inlet cross sectional area thereof.

5. In combination in an axial flow compressor, a case, a hub mounted in said case for rotation about an axis defining an annular channel therewith, and a plurality of axial flow blades carried on said hub and spaced peripherally thereabout with the leading and trailing edges extending in the general radial direction and dividing said annular channel into a plurality of rotor axial flow passages defined between inlets and exits thereof respectively adjacent said leading and trailing edges of said blades, each said blade having spanwise spaced blade sections including a root section adjacent said hub, each said section having a contour comprising an upper circular arc and a lower circular arc spaced apart at mid chord and closely adjacent one to the other at said leading and trailing edges positioning the maximum thickness at about mid chord of said section, each said arc extending with the same radius of curvature continuously from substantially said leading edge to substantially said trailing edge, said blades being curved along the chords thereof providing in cooperation with said hub and said case increasing cross sectional areas for the rearward portions of said passages with the exit cross sectional area of each said passage greater than the inlet cross sectional area thereof to provide a pressure rise in said rotor passages.

6. In combination in an axial flow compressor, a case, a hub mounted in said case for rotation about an axis defining an annular channel therewith for flow of fluid rearward therein, and a plurality of axial flow blades carried on said hub and spaced peripherally thereabout with the leading and trailing edges extending in the general radial direction and with said blades dividing said annular channel into a plurality of rotor axial flow passages defined between inlets and exits thereof respectively adjacent said leading and trailing edges of said blades, each said blade having spanwise spaced blade sections including a root section, said sections extending transversely of said span at different angles relative one to another and to said axis defining a twist in said blade, each said section having a contour comprising an upper circular arc and a lower circular arc spaced apart at mid chord and closely adjacent one to the other at said leading and trailing edges, each said arc extending with the same radius of curvature from substantially said leading edge to substantially said trailing edge, said blades being curved along the chords thereof providing in cooperation with said hub and case rearwardly increasing cross sectional areas for the rearward portions of said passages with the cross sectional area of said exit of each said passage greater than the cross sectional area of said inlet thereof to provide a pressure rise in said rotor passages, each said blade over major portions of its chordwise and spanwise extents being in coincidence with chordwise spaced radial lines from said axis through said root section inside the contour thereof to preclude centrifugal forces from altering said twist.

7. In combination in an axial flow compressor, a case, a hub mounted in said case for rotation about an axis defining an annular channel therewith, and a plurality of axial flow blades carried on said hub and spaced peripherally thereabout with the leading and trailing edges extending in the general radial direction and dividing said annular channel into a plurality of rotor axial flow passages defined between inlets and exits thereof respectively adjacent said leading and trailing edges of said blades, each said blade having spanwise spaced blade sections including a root section adjacent said hub, each said sec-

tion having a contour comprising an upper circular arc and a lower circular arc, each said arc extending from substantially said leading edge to substantially said trailing edge, said case and said hub converging relative to each other along forward portions of said rotor passages to reduce the cross sectional areas thereof along said forward portions rearward from said inlets, said blades being curved along the chords thereof providing in cooperation with said hub and said case increasing cross sectional areas for rearward portions of said passages succeeding rearwardly said forward portions thereof with the exit

cross sectional area of each said passage greater than the inlet cross sectional area thereof to provide a pressure rise in each said rotor passage.

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