Aug. 4, 1964 M. R. SIMONSON 3,143,334

FLOW PATH DESIGN

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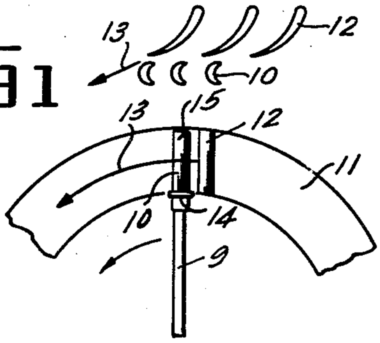
FIG 1



PRIOR ART

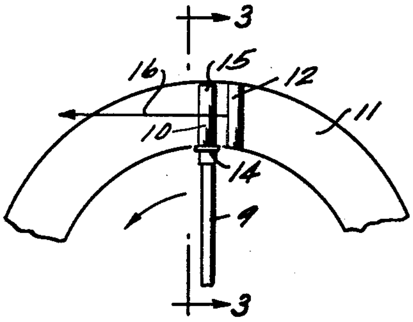
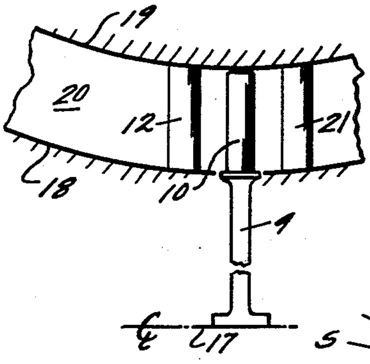


FIG 2

FIG 3



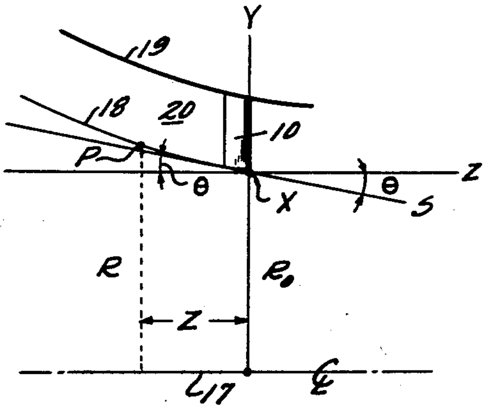


FIG 5

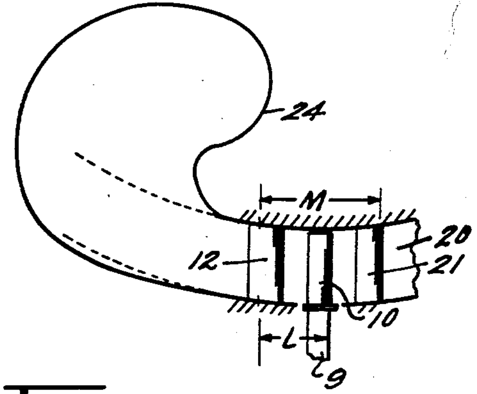


FIG 4

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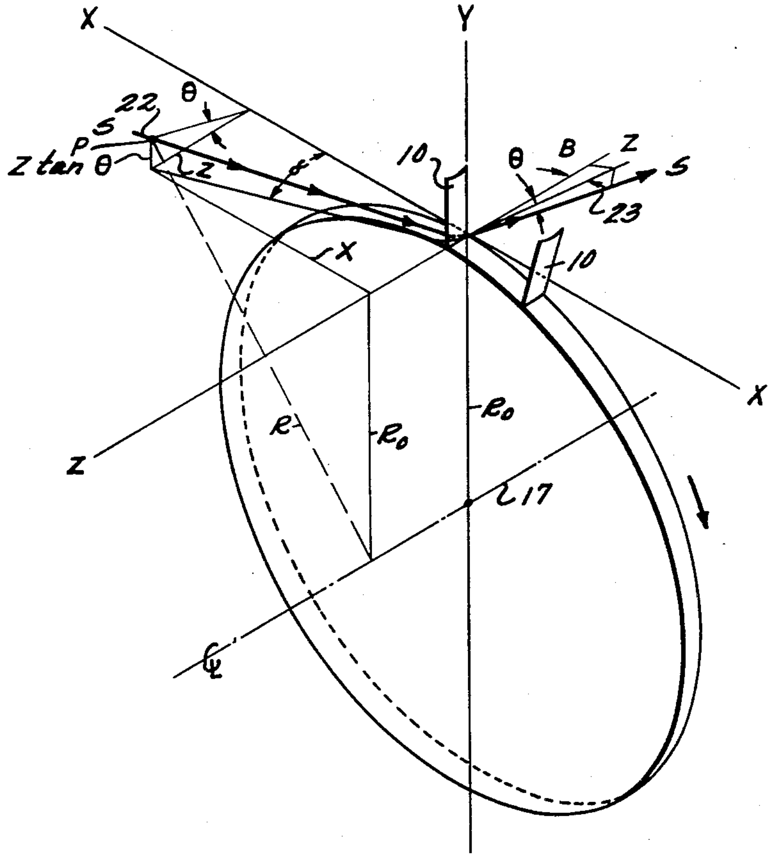
Fig 6



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FLOW PATH DESIGN

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The present invention relates to a flow path design and, more particularly, to the design of a flow path for a tip turbine type fan that results in a substantially zero static pressure gradient radially of the flow path.

The use of tip turbine fans has come into prominence in the VTOL-vertical take-off and landing-field although not being limited to this application. The invention herein described is especially applicable to such an application although, if the environment permits, the invention may be applied to conventional axial flow turbines. In the conventional free vortex twisted bucket turbine design, the static pressure in the annular space between the nozzle and bucket blade rows increases from root to tip because of the curvature of the flow in the plane of rotation. In other words, the flow tends, by centrifugal force, to pack out towards the tip of the buckets. In such conventional design the gas velocity leaves the nozzle tangentially and the centrifugal force acting on the tangential velocity as it moves around the annular space, creates a static pressure gradient rising across the annulus. In applications, such as tip turbine fans, the pressure gradient across the annular flow path results in a higher pressure at the tip of the bucket thus imposing sealing problems. In addition, twisted blading is required thus requiring more complicated hardware.

The present invention is directed to the elimination of all radial static pressure gradients across the gas annular flow path. The flow path herein imposes a curvature upon the gas flow in the radial-axial plane to counteract the effect of the curvature in the plane of rotation. In other words, because of centrifugal force, the gas tends to pack outwardly against the annulus and the present invention imposes the correct curvature to counteract this outward force and, in effect, allow a gas particle to go its normal direction as it leaves the nozzle. The flow path of the instant invention is designed to avoid the nozzle discharge velocities and flow angles varying with radius and thus results in constant cross section and blade angle.

The main object of the present invention is to provide a flow path design which results in a substantially zero static pressure gradient across the flow path.

A further object is to provide a flow path design which permits the use of constant cross section and blade angle.

Another object is to provide such a flow path which enables its use with a turbine scroll of low axial length.

Briefly stated, there is provided a fan with tip turbine buckets peripherally disposed about radially-extending fan blades, the whole being rotatable about a central axis. A flow path is provided to direct motive fluid through the buckets and includes spaced walls defining a motive fluid conduit. Fixed nozzles are placed in the conduit upstream of the buckets, and both the nozzles and buckets have a constant untwisted cross section from root to tip. In addition, the flow path is curved to offset the centrifugal force due to the fluid tangential velocity from the nozzles resulting in a substantially zero static pressure gradient across the flow path.

While the specification concludes with the claims particularly pointing out and distinctly claiming the subject matter which is regarded as the invention, it is believed the invention will be better understood from the following description taken in connection with the accompanying drawing in which:

FIGURE 1 is a partial diagrammatic view of a conventional tip turbine arrangement showing the path of a particle of fluid as it leaves the nozzle in plan and elevation;

FIGURE 2 is a view similar to FIGURE 1 illustrating the principle of the invention in the same setting;

FIGURE 3 is a partial showing of the curved flow path of the instant invention with the nozzles and guide vanes shown and taken on line 3—3 of FIG. 2;

FIGURE 4 is a partial showing of the flow path as used with a short axial length scroll;

FIGURE 5 is a diagrammatic two-dimensional view showing dimensions for the calculation of the flow path seen looking in on axis X of FIGURE 6 and wherein R is rotated up into the YZ plane; and

FIGURE 6 is a perspective three-dimensional view of the calculation of the flow path and illustrating the trajectory of a gas particle through the turbine buckets.

In the design of turbines with airfoil blades, buckets, and nozzles it is common to use the so-called free vortex design which is a design which has a constant axial component of velocity leaving the nozzle and a tangential component of velocity leaving the nozzle which varies inversely with radius. As is well known, the wheel speed varies directly in proportion to the radius. Since the tangential velocity relative to the bucket is the difference between the nozzle tangential velocity and the wheel speed, it is apparent that vectorially the tangential velocity relative to the bucket varies—decreasing from root to tip. Sincethe bucket relative velocity (which is the angle of the fluid the turbine bucket sees) in the resultant of the tangential velocity relative to the bucket plus, by definition, the constant axial component of velocity leaving the nozzle, then it will be obvious that the bucket relative velocity magnitude and angle will change. Since the bucket leading edge must be approximately in line with the flow (bucket relative velocity) the blades must be twisted. This then results in twisted blading. It is desired to avoid the twisting blading because of cost of manufacture, maintain a zero pressure gradient across the gas annulus in order to avoid high pressures at the tip of the blading and consequent leakage, and permit the use of a scroll of minimum axial depth for wing mounted fans.

Referring first to FIGURE 1, which represents conventional design, there is shown partially a fan blade **9** having a turbine bucket **10** peripherally mounted on the fan blade which rotates as shown by the arrow in an annular conduit **11** all in a conventional manner. Fixed nozzles **12** are disposed in the conduit upstream of the turbine or behind the plane of the paper as shown in the upper part of FIG. 1. Arrow **13** represents the path of a particle leaving nozzle **12** and, because of cylindrical conduit **11**, it can be seen that the particle is confined to a circle in the plane of rotation. In addition, due to the rotation, the particle path **13** is subjected to centrifugal force tending to pack it out against the outer wall of conduit **11**. This results in a pressure gradient increasing from the root **14** to the tip **15** of the bucket.

The essence of the present invention, shown in FIGURE 2, is to allow each gas particle to flow naturally in a straight path **16** as it leaves the nozzle **12**. This effect is obtained by imposing a curvature (as in FIGURE 3) on the gas flow to counteract the effect of the curvature of conduit **11** and the resulting packing due to the centrifugal force acting on the gas flow. In other words, the conduit **11** bells out in the downstream direction or coming out of the plane of the paper in FIGURE 2. This is illustrated in FIGURE 2 wherein the particle essentially follows a path shown by the arrow **16** as opposed to that shown by the arrow **13** in FIGURE 1.

This desired path is obtained by curving the flow path of the motive fluid, as it passes through the components, a predetermined amount as shown in FIGURE 3 where a typical flow path of the instant invention is shown. The same numerals refer to the same parts and it can be seen that the fan and turbine turn about a central axis of rotation **17**. In order to properly direct the motive fluid, a pair of spaced inner and outer walls **18** and **19**, respectively, define conduit **20** which, as seen in FIGURE 3, feeds somewhat radially into bucket **10**. It should be understood that, while a pair of walls is described as they occur in a flat plane as seen in the drawing, the walls actually determine the shape and direction of conduit **20**. Further, it is not necessary that the conduit direct the flow radially into the bucket and the curvature of the flow path may also be on the leaving portion or both as partially shown in FIGURE 4. Conduit **20**, equivalent to conduit **11**, is provided with the fixed nozzles **12** upstream of the bucket and with fixed guide vanes **21** downstream of the buckets. The nozzles, buckets, and guide vanes are constant cross section and untwisted or constant blade angle from root to tip. This is permitted by the particular flow path as will be defined.

It will be apparent that as the gas rotates about the conduit **11** (FIGURE 1) a centrifugal force is imparted to it tending to force it radially outward to pack it and create a pressure gradient increase across the conduit from root to tip. The instant invention effectively allows the gas to go out or to follow its natural path by belling out the conduit in the downstream direction by a predetermined curvature or amount to avoid the packing of the gas and consequently there is no pressure gradient created across the conduit.

Referring to FIGURE 6, the journey of a particle of gas following this natural path will now be analyzed. It should be appreciated that the particle is started at the place where the wall will start. Its path is then determined and this path, when rotated, is one of the conduit walls. This is done on both the inner and outer walls to determine the shape of the conduit. It can be seen that a particle of gas P from the nozzle approaches the plane of bucket rotation XY at an angle to the XY plane and an angle to the XZ plane along line **22**. The particle, after being turned by the bucket, leaves the bucket trailing edge at some angle to the same along line **23** as shown. If no static pressures act on the particle along line **22** between the nozzle and bucket and along line **23** after leaving the bucket, then these path lines **22** and **23** are straight lines. For ease of application and description and for the most general case, there is substantially no change in the Y or Z component of velocity across the bucket. Thus, the particle must follow a path lying in a slanted plane S (i.e., line **22** and **23** are in the same plane) that contains the X axis and makes an angle θ with the XZ plane.

If this path of the particle, defined by lines **22** and **23**, is now rotated about the central axis of rotation **17**, it will be seen that a curved surface of revolution is generated which will be one hyperboloid forward of the bucket leading edge and another after the bucket trailing edge to form a surface on which the path of the gas particle lies. The radius of this surface which is a surface of revolution may be calculated as R from the following formula:

$$R=\sqrt{(R_0+Z\tan\theta)^2+X^2}$$

Where

R=radial distance of the wall or particle from the central axis of rotation,
R_0=radial distance to the wall or particle at the trailing edge of the bucket from the central axis of rotation,
x and z=the tangential and axial coordinates respectively of a fluid particle on a path from the nozzle through the bucket measured in a rectangular coordinate system having its origin at the point where a fluid particle arrives at the trailing edge of a bucket,
θ=the slope angle of the particle flow path or wall at the bucket trailing edge.

It will be apparent that R_0 and θ are dimentional design choices dependent on the particular application.

Referring to FIGURE 6, which geometrically shows the application of the formula, it can be seen that R is made up of two components. One is R_0 plus Z tan θ parallel to the Y axis and the other is x parallel to the X axis. These are the two sides of the right triangle whose hypotenuse is R. Thus R can be calculated.

As seen in FIGURE 6, the angle α is the angle between the X axis and the projection in the XZ plane of entering line **22**. Similarly, the angle β is the angle between the Z axis and the projection in the XZ plane of leaving line **23**. These two straight lines **22** and **23** are connected by the small curved line through the bucket. These angles are determined by the basic turbine vector diagram and are maintained constant along the bucket and nozzle length (Y axis) in order to result in the untwisted or constant angle balding as pointed out above. The curved line through the bucket is determined by the load distribution through the bucket. These projections of the particle flow path in the XZ plane then determine x as a function of z, that is, any point on the flow path has the coordinates of x and z which are then used in the above formula.

These qunatities are also illustrated in FIGURE 5 which is a two-dimensional showing looking in on the X axis of FIGURE 6 with the R of FIGURE 6 rotated into the YZ plane. The location R is caluculated for each of the inner and outer walls **18** and **19**, respectively, FIGURE 5 showing the inner wall **18**. Thus, it is possible to calculate a number of points along the spaced walls **18** and **19**, these points being represented by different values of R. Plotting these points then defines the spaced walls of the conduit which will exactly balance the centrifugal force and result in a substantial zero static pressure gradient across the annulus or conduit **20**.

Depending on the space available for the application of the invention and the particular environment in which the predetermined conduit is to be used, it is preferable for the curved flow path to follow at least from one-third the chord distance of the fixed nozzle **12** through the trailing edge of the bucket **10** as shown at L in FIGURE 4. Where downstream fixed guide vanes are used it is then desirable to continue the predetermined curvature from at least one-third of the chord distance of fixed nozzles **12** through the trailing edge of the fixed guide vanes **21** as shown at M in FIGURE 4. These are minimum compromises over making the complete flow path with the preferred curvature and are satisfactory from the standpoint of performance.

In order to obtain a substantially and performancewise satisfactory zero static pressure gradient it is not necessary that the curved flow path continue a long distance and thus it lends itself readily to use with a scroll **24**, as shown in FIGURE 4, that fairs into the curved portion of the flow path upstream of fixed nozzles **12**. This permits a highly sloped flow path at the nozzle entrance and permits the design of a turbine scroll of much less axial depth than possible for a conventional cylindrical flow path. Obviously, a thin axial depth, which is the diminsion from left to right in FIGURE 4, is of great advantage in the use of lift fans mounted in the plane of a wing. Further, the substantially zero static pressure gradient across conduit **20** simplifies the seal design at both root and tip portions of the buckets at these advantages being obtainable while using a constant cross section, untwisted or constant angle design of nozzles, buckets and vanes.

While there has hereinbefore been described a preferred form of the invention, obviously many modifications and variations of the present invention in the use of the flow path in other applications are possible in the light of the above teachings. It is therefore to be understood that within the scope of the appended claims, the invention may be practiced otherwise than as specifically described.

I claim:

1. In a tip turbine fan having turbine buckets peripherally disposed about radially-extending fan blades and rotatable about a central axis,

   a flow path including spaced walls defining a conduit directing motive fluid through said buckets,

   fixed nozzles in said conduit spaced upstream of said buckets,

   said nozzles and buckets being airfoil shaped and having a constant cross section and blade angle from root to tip,

   said flow path having a portion curved to offset the centrifugal force due to the fluid tangential velocity from the nozzles whereby the static pressure gradient across the flow path is substantially zero.

2. Apparatus as described in claim 1 wherein

   the curved portion of said flow path offsetting the centrifugal force extends from at least one-third of the chord distance from the leading edge of the fixed nozzles through the trailing edge of the turbine buckets.

3. Apparatus as described in claim 1 further having fixed airfoil shaped guide vanes having a contsant cross section and blade angle from root to tip and disposed downstream of said buckets and the curved portion of said flow path offsetting the centrifugal force extending from at least one-third of the chord distance from the leading edge of the fixed nozzles through the trailing edge of said guide vanes.

4. Apparatus as described in claim 1 having a scroll fairing into said curved portion of the flow path upstream of said fixed nozzles to discharge motive fluid into said conduit.

5. In a tip turbine fan having turbine buckets peripherally disposed about radially-extending fan blades and rotatable about a central axis,

   a flow path including a pair of spaced walls defining a curved conduit portion directing motive fluid through said buckets,

   fixed nozzles in said conduit spaced upstream of said buckets, said nozzles and buckets being airfoil shaped and having a constant cross section and blade angle from root to tip,

   the radially inner and outer walls of said fluid directing conduit being curved according to the formula:

$$R=\sqrt{R_0+z\tan\theta)^2+x^2}$$

where

R=radial distance to the wall from the central axis of rotation,

R_0=radial distance to the wall at the trailing edge of the bucket from the central axis of rotation,

x and z=the tangential and axial coordinates respectively of a fluid particle on a path from the nozzle through the bucket measured in a rectangular coordinate system having its origin at the point where a fluid particle arrives at the trailing edge of a bucket,

θ=the slope angle of the flow path at the bucket trailing edge,

   whereby the static pressure gradient across the flow path is substantially zero.

6. Apparatus as described in claim 5 wherein the curved portion of the flow path extends from at least one-third of the chord distance from the leading edge of the fixed nozzles through the trailing edge of the turbine buckets.

7. Apparatus as described in claim 5 further having fixed guide vanes of airfoil shape having a constant cross section from root to tip and disposed downstream of said buckets and the curved portion of said flow path extends from at least one-third of the chord distance from the leading edge of the fixed nozzles through the trailing edge of said guide vanes.

8. Apparatus as described in claim 5 having a scroll fairing into said curved portion of the flow path upstream of said fixed nozzles to discharge motive fluid into said conduit.

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