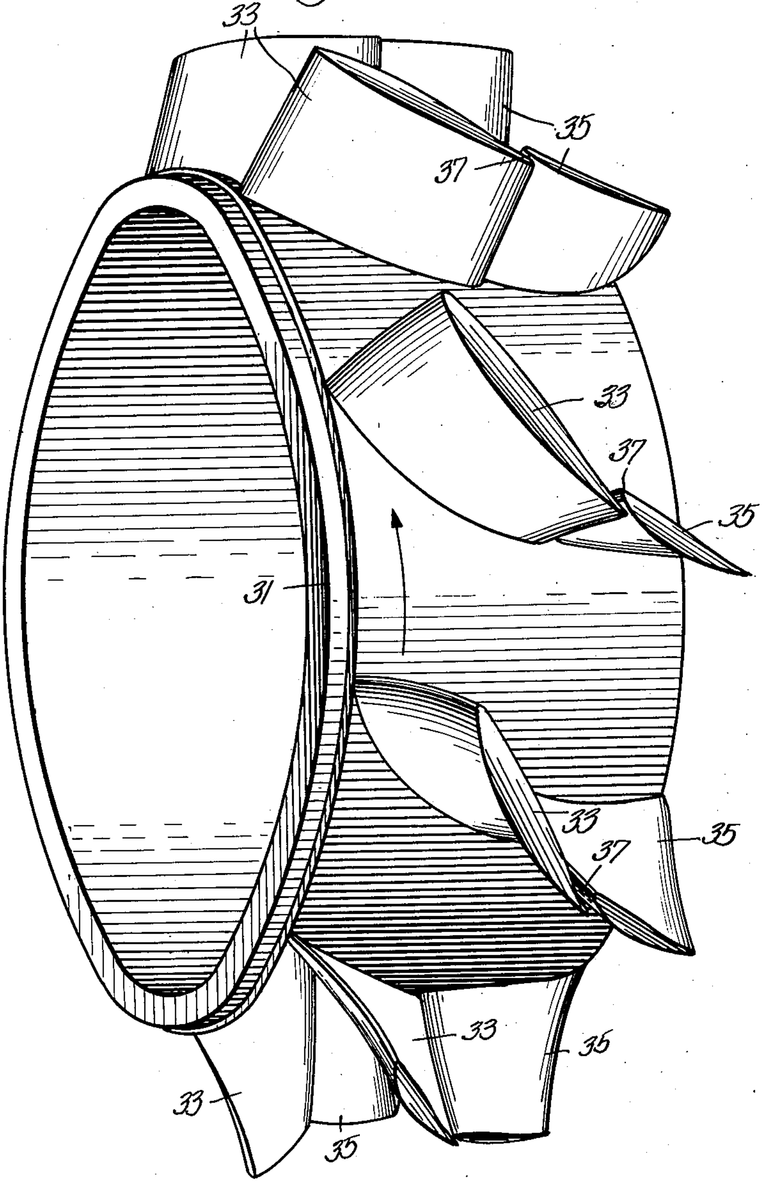
Jan. 29, 1963 **H. E. SHEETS** **3,075,743**

TURBO-MACHINE WITH SLOTTED BLADES

Filed Oct. 20, 1958 8 Sheets-Sheet 1

Fig. 1



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TURBO-MACHINE WITH SLOTTED BLADES

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Fig. 8

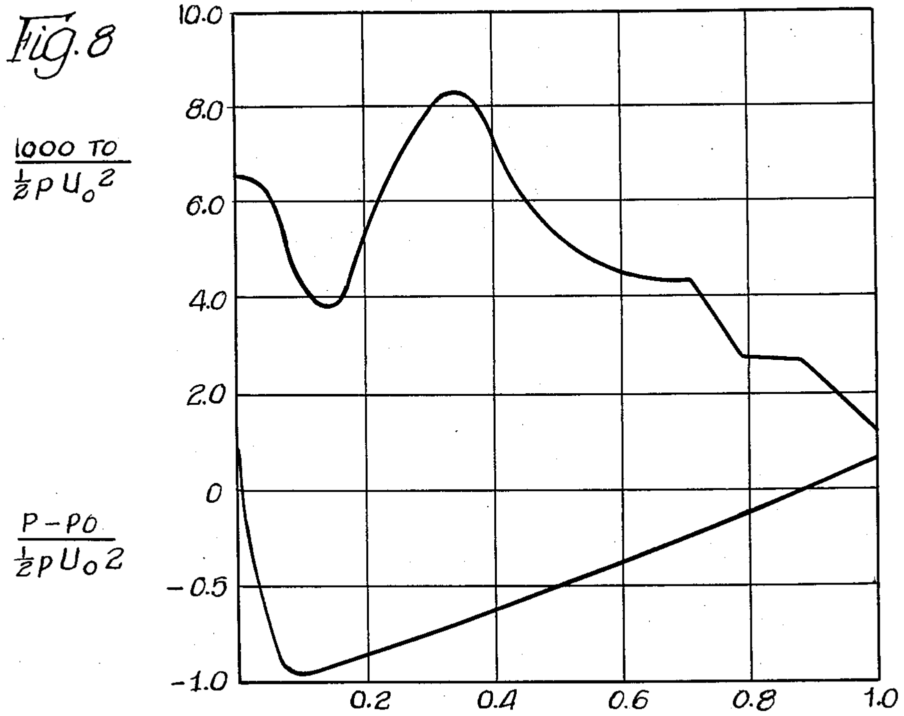

Fig. 2

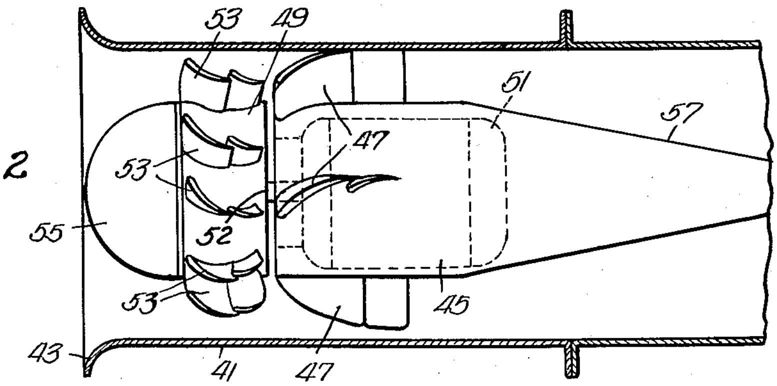

Fig. 3

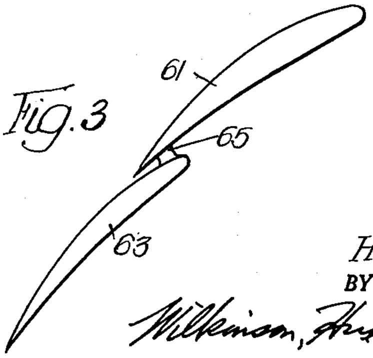

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Fig. 4

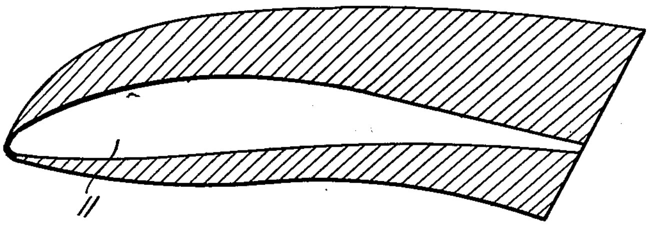


Fig. 5

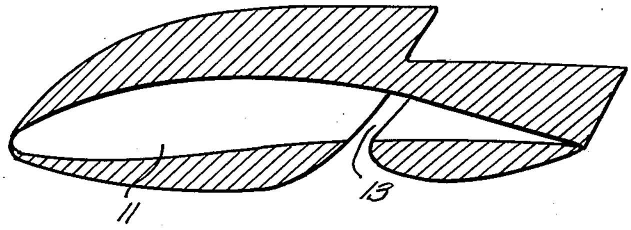


Fig. 6

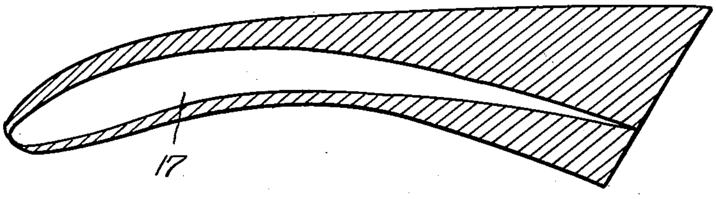
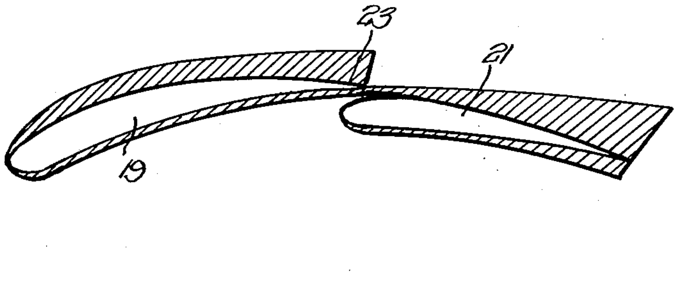


Fig. 7



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TURBO-MACHINE WITH SLOTTED BLADES

Filed Oct. 20, 1958 8 Sheets-Sheet 4

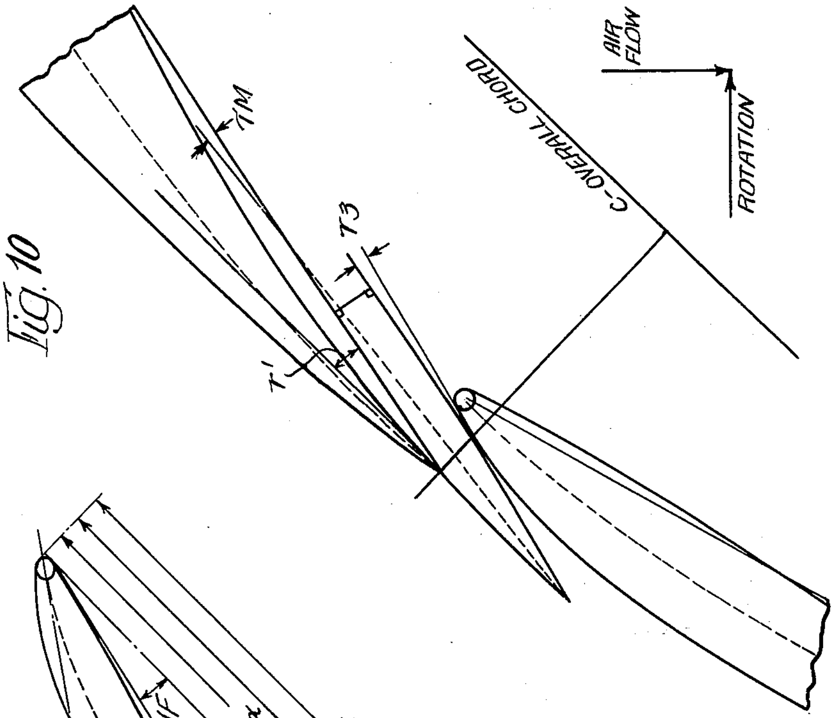

Fig. 10

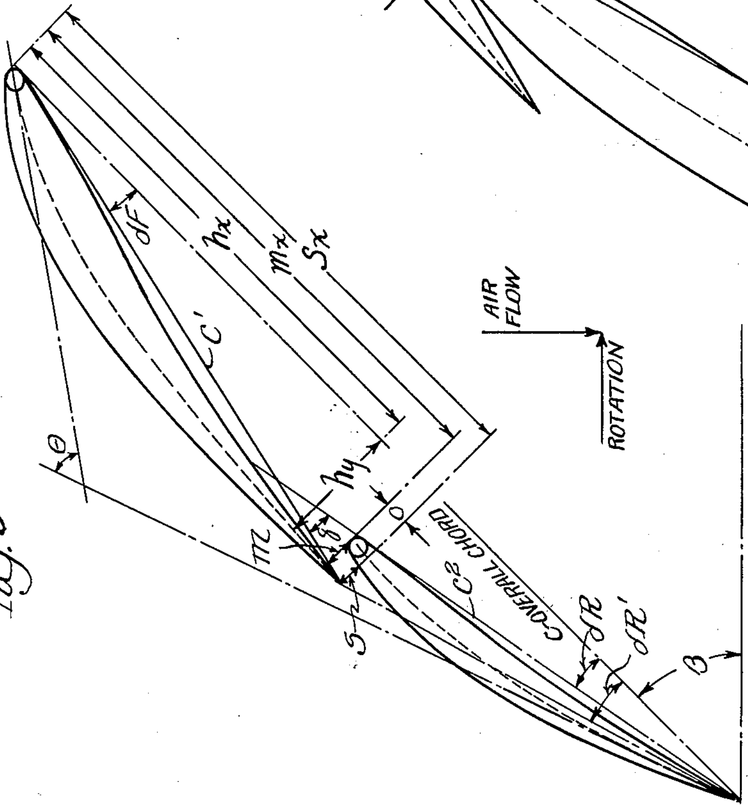

Fig. 9

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TURBO-MACHINE WITH SLOTTED BLADES

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Fig. 15

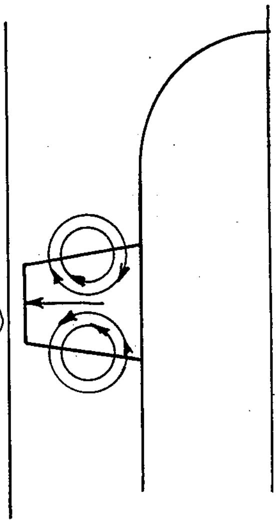


Fig. 16

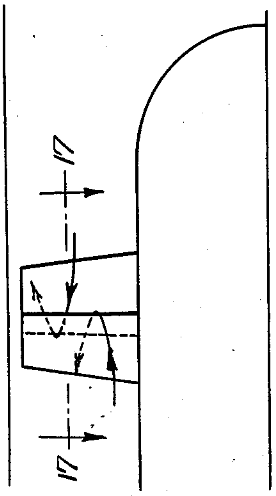


Fig. 17

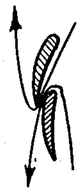
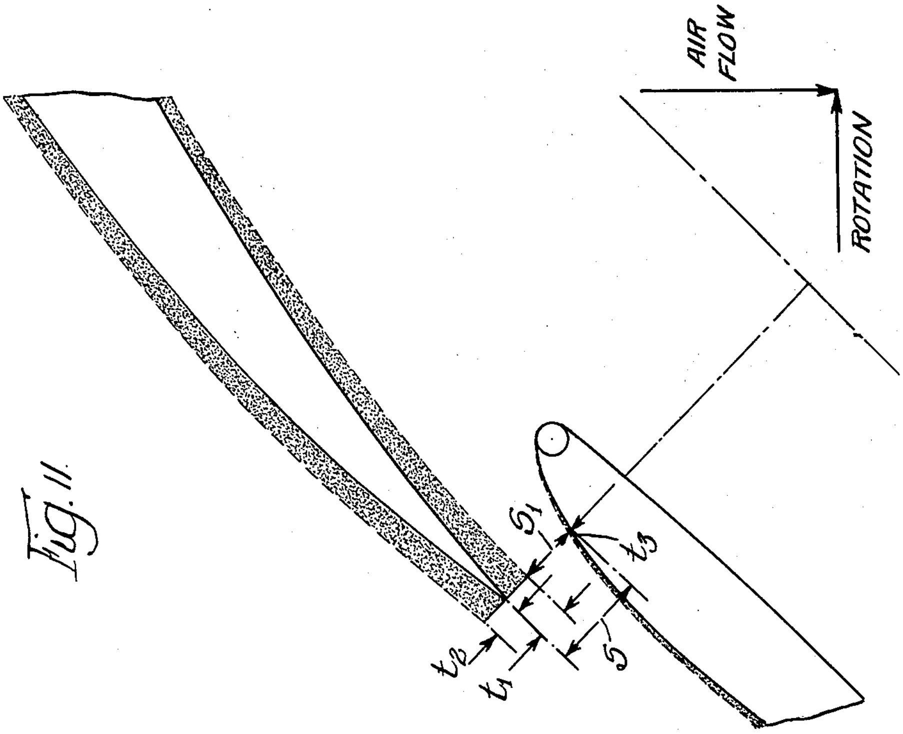


Fig. 11



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TURBO-MACHINE WITH SLOTTED BLADES

Filed Oct. 20, 1958

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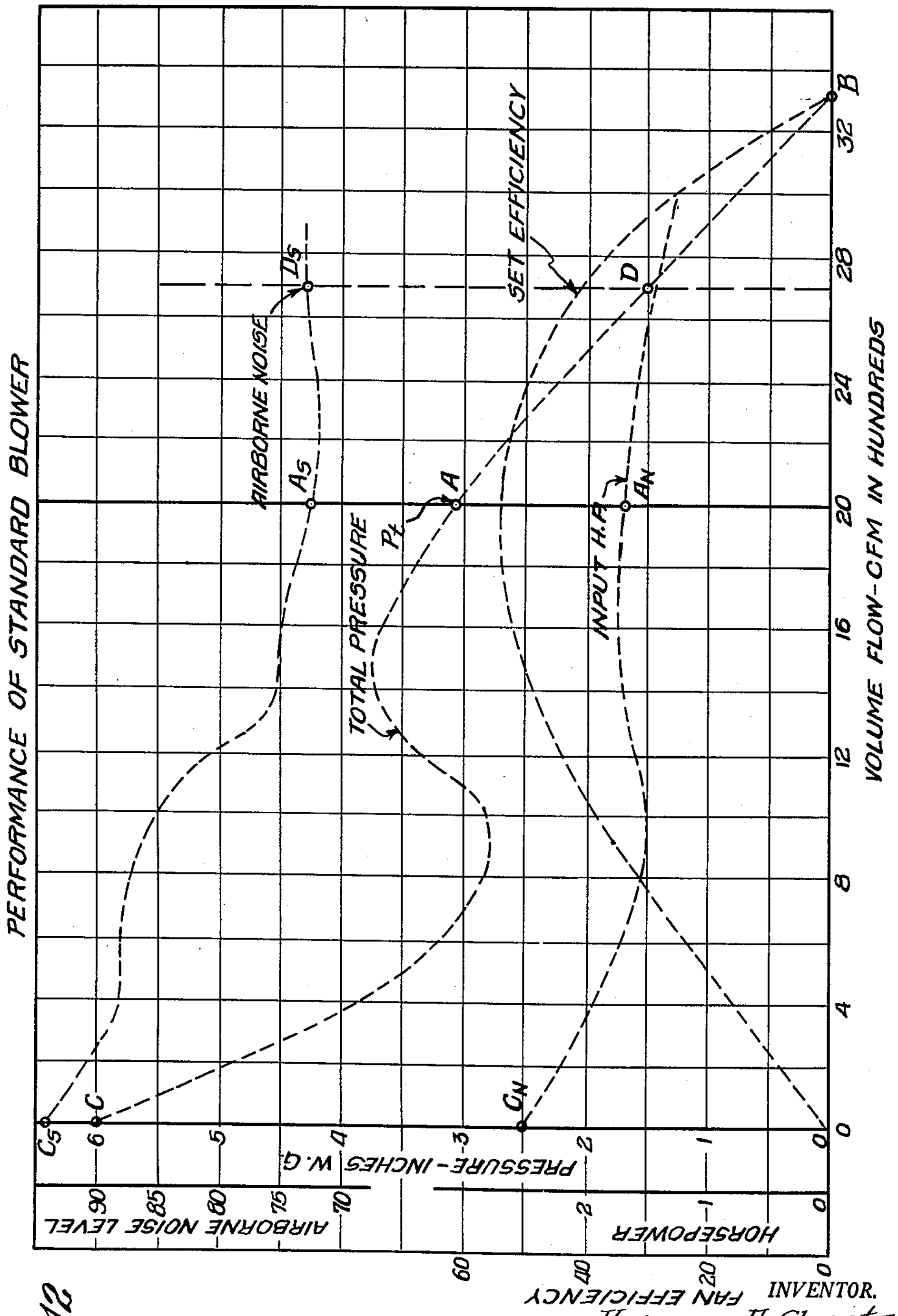

Fig. 12

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TURBO-MACHINE WITH SLOTTED BLADES

Filed Oct. 20, 1958 8 Sheets-Sheet 7

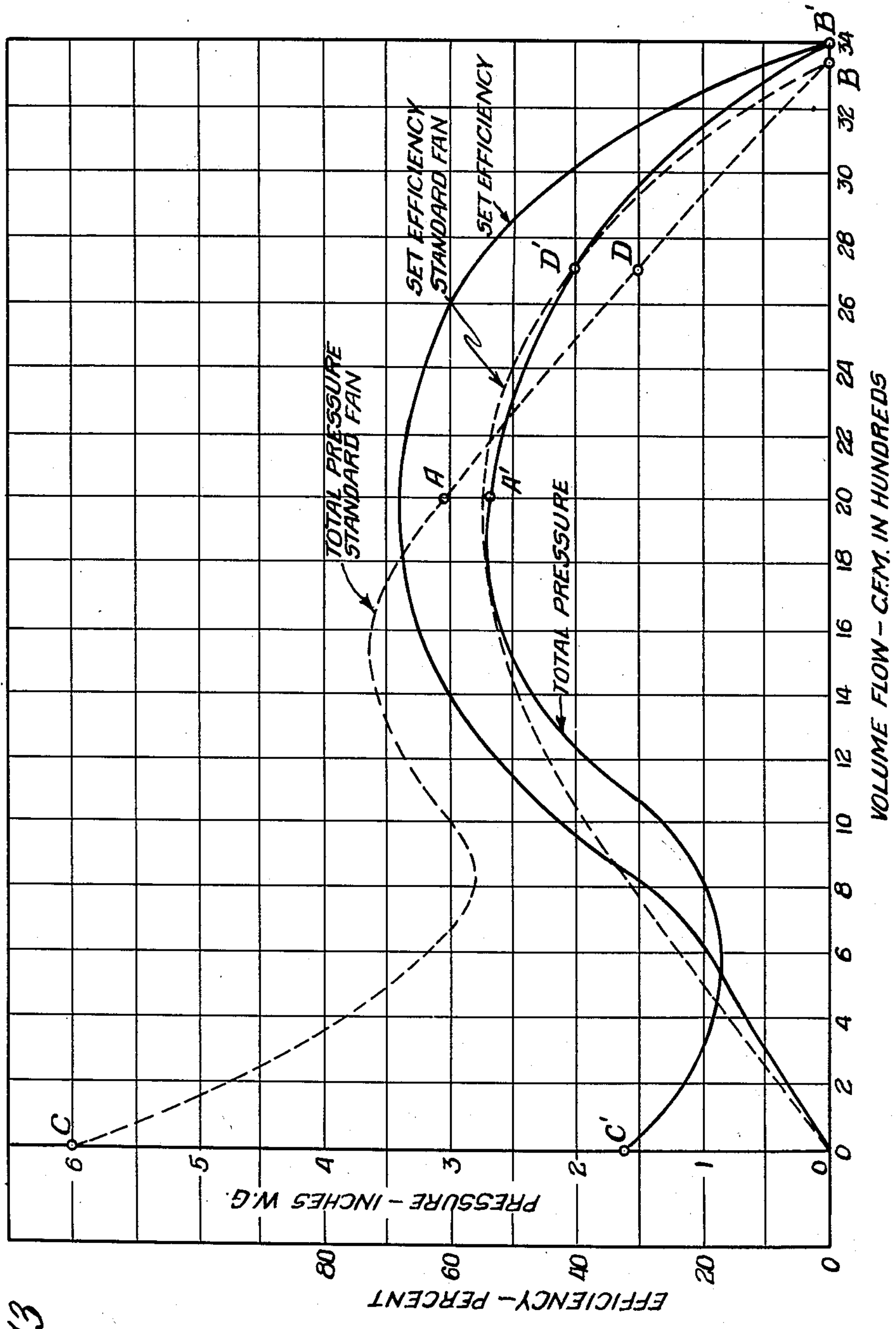

Fig. 13

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TURBO-MACHINE WITH SLOTTED BLADES

Filed Oct. 20, 1958 8 Sheets-Sheet 8

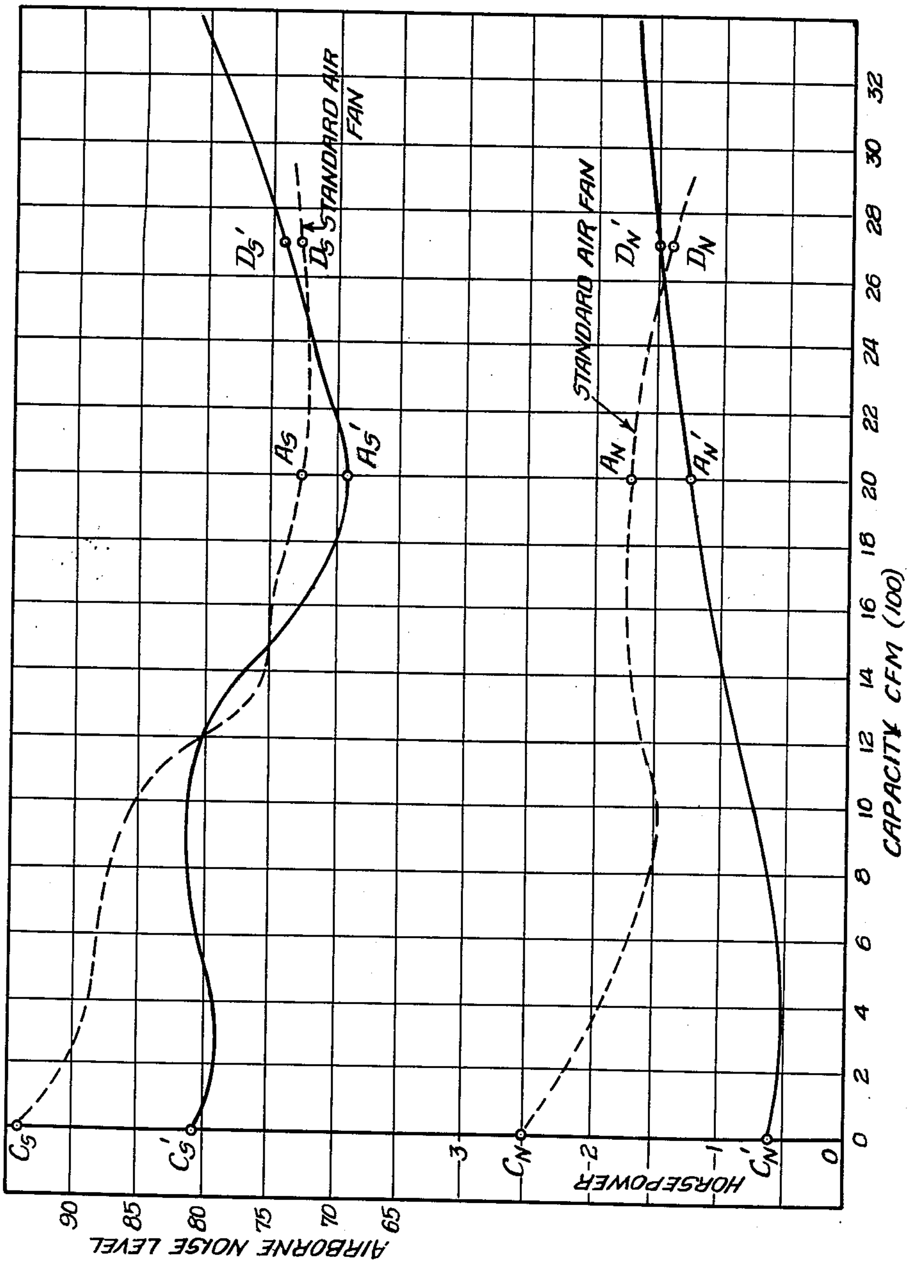

Fig. 14

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TURBO-MACHINE WITH SLOTTED BLADES

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Filed Oct. 20, 1958, Ser. No. 768,490
13 Claims. (Cl. 253—77)

This invention relates to turbo-machines for generating power from the kinetic energy of a fluid or, reversely, producing fluid pressure from mechanical energy. More particularly, the invention relates to turbo-machines of this type having improved blade constructions. Machines of this type include blowers, compressors, pumps, turbines, fluid motors, and the like. The invention specifically relates to turbo-machines having slotted blade constructions which substantially improve the operational characteristics of the machines.

The present application is a continuation-in-part and consolidation of my two prior applications, Serial No. 559,451, filed January 16, 1956, and Serial No 625,050, filed November 29, 1956 now abandoned.

The invention is hereinafter described as being applied to the rotatable or "rotor" blades of an axial flow blower, but the principles of the invention apply generally to the blades of various types of turbo-machines, whether movable or stationary.

Application of the principles of the present invention to the blades of an axial flow blower result in higher pressure output and substantially increased blower efficiency. For example, an axial flow blower utilized in accordance with the present invention has achieved efficiencies of ninety-four percent, with maximum stage efficiency of about ninety-six percent. Maximum efficiencies of prior blowers have been in the neighborhood of eighty-five percent. In addition, the blower of the present invention operates at a lower noise level, and requires less driving horsepower, between the design operating range and the airflow shut-off condition.

The blowers herein considered generally include a shaft, blade-carrying members surrounding the shaft, a plurality of blades arranged on the blade-carrying members, and a casing forming a stationary envelope about the ends of the blades. The machines also include an inlet ahead of the blade-carrying members and an exit diffuser after the blade-carrying members.

My prior Patent No. 2,314,572, issued March 23, 1943, relates generally to slotted blades in turbo-machines, but the blades of this prior patent were constructed and arranged in accordance with earlier airflow theories, prior to the advent of the newly developed boundary layer theories. In contrast, however, the blades of the present invention were conceived by analysis and extensive test in accordance with the modern theories of boundary layer phenomena, to produce turbo-machine blades which achieve considerably increased efficiency while providing still higher pressure output.

Accordingly, it is an object to the present invention to provide a new and improved blade construction for turbo-machines.

Another object of the invention is to provide a turbo-machine blade of the airfoil type having a generally longitudinally extending slot formed from the lower side of the blade to the upper side.

A further object of the invention is to so locate and define the size and contour of such a slot as to provide substantially increased efficiency.

Still another object of the invention is to provide an improved blade for turbo-machines incorporating effective boundary layer control.

A further object of the invention is to provide a turbo-machine blade having a slot located strategically with regard to boundary layer characteristics, for example in a laminar flow airfoil at the point of transition from laminar to turbulent boundary layer, and so dimensioned that the driving jet from this slot is just sufficient to flush downstream all of the boundary layer of the forward blade portion.

A still further object of the invention is to provide a turbo-machine slotted blade construction which extends laminar flow over a larger portion of the blade chord than with standard types of solid airfoil blades and which simultaneously permits larger flow deflections.

An additional object of the invention is to provide a turbo-machine blade construction of this character which permits a considerable increase in the pressure coefficient, or corresponding operation at lower tip speeds for a given pressure increase.

Another object of the invention is to provide a turbo-machine slotted blade construction of the laminar flow airfoil type having more efficient flow characteristics than a similar solid laminar flow airfoil blade.

A further object of the invention is to provide a turbo-machine of low noise level.

Still another object of the invention is to provide an axial flow blower having a low noise level and low driving horsepower required, particularly between the design operating range and the airflow shut-off condition.

A still further object of the invention is to provide an axial flow blower having driving power characteristics which result in substantially lower horsepower required at low capacity and at shut-off, as compared to power requirements in the design operating range.

An additional object of the invention is to provide a blower having a reduced vibrational force output in the range of capacities below the design operating range.

Other objects, features and advantages will be apparent from the following detailed description, taken in conjunction with the accompanying drawings, in which:

FIGURE 1 is a perspective view showing a turbo-machine rotor having a preferred type of blade, according to the present invention, assembled in cascade thereon;

FIGURE 2 is a schematic, longitudinal sectional view of a turbo-machine, including a rotor and a stator, having slotted blades of the present invention;

FIGURE 3 is a diagrammatic end view of a slotted blade of a modified construction;

FIGURE 4 is a diagrammatic illustration of a non-laminar cambered airfoil section illustrating the boundary layer thereon;

FIGURE 5 is a view similar to FIGURE 4, but showing the airfoil provided with a slot and illustrating the resulting change in the boundary layer;

FIGURE 6 is a view similar to FIGURE 4, but illustrating a laminar-flow airfoil section with the boundary layer associated therewith;

FIGURE 7 is a view similar to FIGURE 6, but showing a slotted laminar flow airfoil, like the non-slotted airfoil of FIGURE 6, and illustrating the change in the boundary layer;

FIGURE 8 is a graphic diagram showing frictional intensity and pressure on the upper surface of non-slotted, non-laminar flow airfoil plotted relative to the airfoil chord;

FIGURE 9 is a diagrammatic showing of a slotted blade profile, according to the present invention;

FIGURE 10 is an enlarged fragmentary diagrammatic view showing a portion of the blade of FIGURE 9 on an enlarged scale;

FIGURE 11 is an enlarged, fragmentary diagrammatic view similar to FIGURE 10, but illustrating the boundary layer relationship in the region of the airfoil slot;

FIGURE 12 is a graphic diagram, showing the performance of a standard blower;

FIGURE 13 is a graphic diagram comparing a slotted blade blower, according to the present invention, and a standard blower, in terms of pressure and efficiency relative to flow capacity;

FIGURE 14 is a graphic diagram comparing the blowers of FIGURE 13 in terms of horsepower and airborne noise level as a function of flow capacity;

FIGURE 15 is a schematic illustration of a non-slotted turbo-machine blade operating in the airflow shut-off condition and illustrating the flow components about the blade;

FIGURE 16 is a schematic view similar to FIGURE 15, but illustrating the flow components about a slotted blade, according to the present invention, with the blade operating at the airflow shut-off condition; and

FIGURE 17 is a schematic sectional view taken along line **17—17** of FIGURE 16.

The present invention relates to turbo-machines of essentially the axial flow type. The blades with which the present invention is concerned are generally characterized by the existence of a through flow and circulation flow. The fluid particles follow a flow pattern defined by superimposing the flow of fluid through the blades and a circulation flow around each blade. Because of the superimposing of these flows, pressure difference exists between the upper and lower sides of the blade, with a higher pressure on the lower side of the blade and a lower pressure on the upper side of the blade. The specific geometric shape of the blade and its arrangement or angle of attack within the flow determines the amount of circulation flow which, together with the amount of through flow, determines the amount of the pressure difference between the upper and lower sides of the blade. The pressure difference, in turn, causes a lifting force on the blade, resulting in a blade characteristic defined by lift coefficient and angle of attack. Blades with the above characteristics are generally known as cambered airfoil type blades.

The entire flow process caused by the shape of the blade results in a deflection of flow between blade inlet and exit, the amount of flow deflection being a function of the amount of circulation, through flow and blade arrangement. This flow deflection, in turn, results also in a pressure difference between blade inlet and blade exit, this pressure difference being a pressure increase in the case of a blower or pump, and a pressure decrease in the case of a turbine.

The pressure difference between the upper and lower sides of the blade and the corresponding distribution of pressure causes the flow of fluid to be correspondingly accelerated and decelerated, respectively, in its course from the leading edge to the trailing edge, according to Bernoulli's Law. The sectional shape of the blade and its corresponding circulation flow determine the amount of fluid acceleration-deceleration along the blade surface. The total pressure difference between blade inlet and exit is a function of the amount of circulation flow or its corresponding lift coefficient. However, there is a certain maximum of circulation flow which cannot be exceeded without causing flow disturbances due to boundary layer separation, thus limiting the pressure difference which can be generated between blade inlet and exit.

The substantially improved operation of turbo-machines, according to the present invention, is the direct result of the novel blade configurations which were developed through application of modern boundary layer theories and substantiated by extensive tests. The concept of the present invention is defined in terms of boundary layer conditions on the turbo-machine blades, so that it is well to consider the history and development of the theories underlying boundary layer phenomena.

Fundamentally, fluid flow processes are characterized as viscous, non-viscous, or a combination of the two. For practical purposes the flow at a distance from an airfoil is considered non-viscous, but in the bounary layer the effects of viscosity canot be ignored and the flow must be considered viscous.

The existence of a relatively slow-moving layer of fluid close to the surface of a body in a fluid flow system was discovered about fifty years ago. This relatively slow moving layer of air is referred to as the "boundary layer." At first, bounary layer phenomena were not well enough known to calculate the characteristics of the boundary layer even for the simplest of cases. By the early 1920's the phenomena had been explored sufficiently to permit rough calculation of bounary layers along flat plates in fluid flow of essentially constant velocity and pressure.

It was discovered, and it has now been intensively developed, that a boundary layer is ordinarily laminar at the start and at a certain distance downstream undergoes a transition for a certain limited range until the boundary layer becomes fully turbulent. The flow in the boundary layer can thus be grouped into three different phases, namely, laminar flow, transitional flow and turbulent flow.

In a laminar boundary layer the flow is smooth and without eddies, in a multitude of relatively undisturbed layers varying in velocity from zero at the surface to the free stream velocity at the outer edge of the boundary layer. In a turbulent boundary layer, a large number of relatively small eddies exist so that the flow is no longer in undisturbed layers. These eddies in the turbulent boundary layer induce transfer of momentum from the outer particles of the fluid, moving with relatively high velocity, to the fluid film close to the surface of the airfoil, resulting in a velocity distribution having a higher velocity near the surface. Due to this mechanism of fluid flow, skin friction and energy loss of a turbulent boundary layer is higher than for a comparable laminar boundary layer. A transitional boundary layer is that boundary layer region lying between the end of a laminar boundary layer and the beginning of a fully developed turbulent boundary layer.

Turbulent boundary layers are less inclined to separation than laminar layers because of the increased interchange in momentum in the turbulent layers. If laminar flow separation occurs, the flow may leave the surface of the airfoil permanently or may reattach itself in the turbulent boundary layer. If turbulent flow separation occurs, it can adversely affect the flow through the next row of rotor or stator blades. As the fluid moves over each of the blades, the boundary layer is initially thin in the laminar flow section, thickens as the flow progresses along the surface, and changes to a transitional and then a turbulent boundary layer. The extent of the laminar, transitional and turbulent boundary layers along the airfoil is a function of the blade geometry, blade loading, Reynolds number, and turbulence in the general flow stream. If no separation occurs, the airfoil drag is primarily caused by skin friction and the value of the drag depends mainly on the relative amounts of laminar and turbulent boundary layer flow.

Because of the decreased drag associated with laminar boundary layer flow, it is desirable to maintain laminar flow along an airfoil for as great an extent of the chord length as is possible. In the early 1940's, the first series of low drag, high-critical-speed airfoils were developed and tested by the National Advisory Committee for Aeronautics (NACA). Such low drag airfoils were designed to provide a pronounced reduction in profile drag by reduction of the skin friction through increasing the relative extent of the laminar boundary layer. Such airfoils are now commonly referred to as "laminar flow airfoils." Information concerning such airfoils was first published in 1943 in NACA Report No. 763, "Tests of Airfoils Designed to Delay the Compressibility Burble," by John Stack. This report relates to single laminar flow airfoils of symmetrical cross-section. Subsequently, the theory of laminar flow airfoil was extended to cambered airfoils and reported in 1945 as NACA Report No. 824 entitled, "Summary of Airfoil Data," by Ira H. Abbott, Albert E. von Doenhoff and Louis S. Stivers, Jr.

The newly developed laminar flow airfoils designed by the NACA have configurations which provide a slowly decreasing pressure distribution over a predetermined extension of the chord of the airfoils. The theory has been developed so that it can supply the shape of an airfoil to give a calculated velocity and pressure distribution, including consideration of the boundary layer, in cascades of airfoils in turbo-machinery. Laminar flow airfoils have a laminar boundary layer over a certain extension of the chord to a position where sudden changes in pressure gradient results in transition to a turbulent boundary layer. Such airfoils have been designed with laminar boundary layers to about sixty percent of the blade chord length. There are distinct advantages of low drag when these airfoils are used within the range of optimum conditions for which they are designed.

The laminar flow airfoils developed by the NACA have a common physical characteristic in that the point of maximum thickness always occurs at or farther than 30% of the chord length downstream from the leading edge. Accordingly, thereafter in this specification and in the claims the term "laminar airfoil" is defined as an airfoil in which the maximum thickness occurs at a point at least 30% of the chord length from the leading edge and in which the laminar boundary layer on the upper surface extends over a large portion of the chord length at design operating condition. "Non-laminar airfoils" are defined as all others.

Beginning in about 1947, the newly developed theories concerning the effects of laminar turbulent and transitional boundary layers were discussed in various engineering textbooks. For example, one of the earliest is "Engineering Application of Fluid Mechanics," by J. C. Hunsaker and B. G. Rightmire, 1947.

The new theories of boundary layer flow phenomena were not extended to cascades of airfoils used in turbomachinery until some time later, as set forth in NACA Technical Note 3916, dated February 1957, entitled, "Systematic Two-Dimensional Cascade Tests of NACA 65-Series Compressor Blades at Low Speeds," by L. Joseph Herrig, James C. Emery and John R. Erwin. This treatise originally appeared as a classified NACA Research Memorandum issued in 1951. This report establishes that a laminar flow airfoil which is designed to have a laminar boundary layer up to a predetermined point has, when tested in cascade, a nearly constant pressure distribution up to this point even though the pressure may locally be slightly decreasing or increasing. However, a laminar boundary layer is maintained to approximately this predetermined point even though in cascade the pressure distribution may be slightly increasing.

The invention relates especially to turbo-machines with airfoil type blades of the laminar flow type. For these types of blades, the boundary layer, boundary layer thickness and growth can be determined and controlled. The turbo-machines with laminar flow blades have the lowest drag and the highest efficiency.

The invention is particularly concerned with creating an improved fluid flow process within the boundary layer by means of blades having a slot of special shape and design, which in turn permits the performance of the entire turbo-machine to achieve higher efficiency, or larger pressure differences between inlet and exit, or a combination of both.

Ever since the discovery of the existence of a boundary layer attempts have been made to avoid separation of the boundary layer by means of suction systems, blowing systems, slots or otherwise, and such attempts have been referred to as "boundary layer control." Today much more exact information is available concerning fluid flow process thus permitting calculation of boundary layer thickness and extent of boundary layer. Consequently, it has only recently become possible to scientifically ascertain and calculate slot location and dimension and to include these in the concept of boundary layer control. The present invention is concerned with the scientific formation of slots in turbo-machine blades for improved boundary layer control in the modern concept.

The slotted blade establishes a flow from the lower to the upper side of the airfoil. This results in a sink and boundary layer removal on the lower side of the airfoil, and a source with ejection of fluid on the upper side of the airfoil. In order to achieve minimum drag, pressure distribution in accordance with the latest NACA findings for airfoils in cascade is desirable over the initial part of the airfoil surface upstream of the slot location. On the upper blade surface, a laminar boundary layer is maintained to a predetermined point along the blade chord where ejection of fluid occurs, resulting in addition of energy to the boundary layer and simultaneously in a pressure change. A part of the fluid flows through the slot, according to the invention, and a new impulse is imparted to the fluid particles in the boundary layer on the upper surface, in the area of transition from laminar to turbulent flow, which impulse results in energy addition and establishes quick transition to a turbulent boundary layer.

The quick formation of a turbulent boundary layer at this point on the upper airfoil surface is really advantageous, because the air is thereby given more momentum to follow the rest of the airfoil surface. In a laminar flow airfoil there is of necessity a steep pressure gradient in the turbulent boundary layer, and the flow must advance without separation against this steep pressure gradient. If the transition to a turbulent boundary layer is delayed so much that the laminar boundary layer separates, and stays separated, then the result is an increased drag coefficient. The location and amount of fluid ejection producing engergy addition can be controlled, thus permitting flow without separation against the steep pressure gradient in the region of transition to turbulent flow.

The slotted blade of the present invention permits the design of airfoils with favorable pressure distribution and laminar flow over greater portions of the chord than would otherwise be possible, even for highly cambered airfoils. The lower surface flow sink resulting in removal of the boundary layer thereby extends the range of laminar flow to approximately the trailing edge under design conditions. A pronounced reduction in drag is obtained by the reduction of the skin friction through increasing the relative extent of the laminar boundary layer on the lower airfoil surface.

FIGURE 1 shows in perspective, a rotor having slotted blades according to this invention. The blades are mounted in cascade on the rotor of an axial blower. The rotor is designated **31**, the forward blade portions **33**, the rearward blade portions **35** and the radially extending slots **37**.

FIGURE 2 is a showing of one form of apparatus in which the improved blades may be used. The drawing shows a blower with a tubular housing **41**, having an outwardly flared intake end **43**. A motor housing **45** is supported on guide vanes **47** which are of the slotted design. A rotor **49** is driven by a motor **51** through a drive shaft **52** and carries slotted blades **53**, the tips of which extend to points closely adjacent the inner surface of the housing **41**. The rotor is shown with a hemispherical cap **55**. A conical diffuser **57** is shown extending rearwardly of the motor housing **45**. The showing is somewhat diagrammatic and is illustrative of a form of possible application of the improved blade construction.

FIGURE 3 shows overlapping blade portions **61** and **63** which are joined together at the slot by connecting members **65**. Such members preferably have a relatively small dimension radially of the blade and thus obstruct only small portions of the slots. One or more such connecting members may be used toward the free tip ends of the blade to stiffen the construction.

In FIGURE 4 of the drawings there has been shown a conventional non-laminar type of cambered airfoil **11** with the boundary layer indicated in cross-hatched areas about the airfoil. In FIGURE 5 the same type of airfoil **11** has been shown, but here provided with a slot **13**.

In FIGURE 6 a cambered airfoil **17** of the laminar flow type has been shown together with boundary layers above and below. FIGURE 7 shows a comparable slotted airfoil of the laminar flow type, the airfoil actually consisting of a pair of overlapping smaller airfoils **19** and **21** with the overlap forming a slot **23**. The boundary layers are shown as they are affected by the operation of this slot and it will be apparent that there is a substantial reduction in such areas.

It will be understood that FIGURES 4–7 are schematic only and are not drawn to scale, but they do give a comparative indication as to the boundary layers above and below the airfoils and relative areas from the leading edges to the trailing edges of the airfoils.

FIGURES 9, 10 and 11 are diagrammatic cross-sectional illustrations of a slotted blade according to the present invention, showing the relative positions of the two blade portions and illustrating the slot configuration and location. FIGURE 9 shows the over-all blade configuration, while FIGURES 10 and 11 are enlarged fragmentary illustrations of the slotted portion of the blade. FIGURE 10 specifically illustrates the nozzle-like configuration of the slot and the flow-directing characteristic. FIGURE 11 specifically illustrates the relationship of the boundary layers in the region of the slot for detailed consideration in determining the slot gap or width.

Referring to FIGURE 9, the combined blade is characterized by the magnitude of the camber angle θ, and the physical location of the maximum of the mean camber line relative to the over-all chord c, designated by the abscissa h_x and the ordinate h_y. For the preferred configuration, the maximum camber is located near the rear part of the mean camber line of the forward airfoil. The slotted blade is further defined by the deflection angle δ between the chords of forward and rear airfoil, measuring the deflection of the rear airfoil against the forward airfoil. The angle δF in FIGURE 9 defines the angle between the chord of the forward portion airfoil and the chord of the combined airfoil. The angle δR in FIGURE 9 defines the angle between the chord of the rearward portion airfoil and the chord of the combined airfoil. There is a simple geometric relationship between the angles δ, δF and δR as the chord of the combined, forward and rear airfoil form a triangle. The location of the slot entrance on the lower airfoil surface, representing the flow sink, is defined by the distance m_x. "m" represents the width of the slot inlet, and "s" represents the width at the slot exit. "o" represents the distance of the slot overlap between the forward and rear airfoils. On the upper side of the blade, fluid is ejected at the location s_x, the slot exit, for the purpose of energizing the boundary layer to flow against the steep adverse pressure gradient and to avoid separation.

For further analysis of airfoil drag and boundary layer characteristics, and for the specific development of slotted blades according to the present invention, the effects of the frictional intensity are of particular interest.

Frictional intensity is defined by multiplying the velocity gradient in the boundary layer at the airfoil surface with the viscosity of the air. Thus, frictional intensity can be determined experimentally. FIGURE 8 shows data of pressure distribution and frictional intensity for the upper surface of a non-laminar airfoil, both in dimensionless form by dividing their corresponding values by the value of free stream energy or dynamic pressure $\frac{1}{2}\rho V^2$, where ρ is the free stream density of the air and V is the velocity of the free stream air relative to the airfoil. On the upper surface, frictional intensity has one maximum value near the forward section, and a second and larger maximum value a certain distance downstream relative to the airfoil chord. The transition from laminar to turbulent flow in the boundary layer takes place in the region between these two maxima. For laminar flow airfoils this transition takes place immediately following the point of minimum frictional intensity between these two maxima. Usually the transitional region moves toward the forward section as the blade loading increases. Distribution of normal pressures indicates that the transitional region is frequently situated just downstream to the point of lowest absolute pressure. The distribution of frictional intensity on the lower surface resembles that on the upper surface, but the maximum values are smaller. It appears that the frictional intensity reduces towards the trailing edge, provided that no separation of flow occurs on either the upper or lower surface. It must be remembered that the values for frictional intensity will vary just like the values for pressure distribution with airfoil parameters like camber, thickness, cascade solidity and stagger angle and for the same airfoil it will vary with blade loading or angle of attack. The transition from laminar to turbulent boundary layer occurs on the upper and lower side of the airfoil in the vicinity of the first minimum of frictional intensity. In FIGURE 8 the first minimum of frictional intensity is associated with the normal pressure distribution so as to occur in the area of lowest absolute pressure.

For non-laminar flow airfoils both pressure distribution and frictional intensity as functions of chord length are frequently not as simple as shown in FIGURE 8, and the pressure distribution functions can have a large number of irregularities and even discontinuities. However, for laminar flow airfoils according to the requirements as stated in the NACA reports, the pressure distribution must follow certain laws, thus having a relatively simple relationship over the chord length. The same is true for frictional intensity, which follows the boundary layer velocity distribution at the airfoil surface.

Slot Location

The optimum location of the slot according to the present invention is defined by the boundary layer on both the upper and the lower side of the airfoil.

With respect to slot exit location for laminar flow airfoils at the design condition, it is desirable to maintain laminar flow and a laminar boundary layer to the slot location. Flow through the slot should flush the boundary layer on the upper side of the airfoil downstream and completely disperse it so that a new boundary layer forms over the upper surface downstream of the slot. This results in minimum drag and permits a design of laminar flow airfoils of higher camber and lift coefficient. The slot exit location is determined according to boundary layer conditions and particularly with respect to frictional intensity.

With respect to slot exit location for non-laminar flow airfoils at the design condition, it is desirable to maintain the boundary layer relatively thin to the slot location. To accomplish this the design of the airfoil should give values of pressure distribution and frictional intensity so that the boundary layer remains thin over a large portion of the airfoil, for example, fifty or sixty percent. As is the case with laminar flow airfoils, the flow through the slot should flush the boundary layer on the upper side of the airfoil downstream, and completely disperse it so that a new boundary layer forms over the upper surface downstream of the slot. This results in a higher lift coefficient and simultaneously in a drag coefficient as low or lower than comparable non-slotted airfoils. The exact slot location is again determined according to the principles of boundary layer conditions and frictional intensity.

It is important that slotted airfoils according to the present invention operate satisfactorily over the entire range of operation of the turbo-machine. Consequently, due to the range of angle of attack, the airfoils must be designed so that satisfactory flow is maintained under all conditions. This means, for instance, that the slots of laminar flow airfoils must be so dimensioned that in non-laminar flow conditions, within the operating range of the turbo-machine, the turbulent boundary layer on the upper side of the airfoil is still completely dispersed by the flow through the slot, so that a new boundary layer forms. Furthermore, it is important that the slot be so dimensioned to prevent stalling and other flow irregularities, which would result in unstable flow conditions, since blowers with unstable flow characteristics are generally undesirable.

According to the present invention, in laminar flow airfoils the slot exit on the airfoil's upper surface is located within the transitional region of the boundary layer, said region being located between the two maximum frictional intensity values for the upper surface. For laminar flow airfoils slotted according to the present invention, the transitional region is very short. The transitional region is further defined as that region of the boundary layer which extends downstream from the end of the laminar boundary layer to a point where the turbulent boundary layer has completely replaced the laminar boundary layer. The former point normally coincides with the first minimum frictional intensity value and the latter point normally coincides with the second maximum frictional intensity value. The best results are obtained when the slot exit is located immediately upstream of the second maximum frictional intensity value, a point hereinafter referred to as the "point of transition."

It should be specifically noted that the point of transition for all airfoils can be readily located through the use of frictional intensity data inasmuch as it normally coincides with second maximum of frictional intensity.

For medium Reynolds numbers and for laminar flow air foils in cascade in blowers, the point of transition can also be more roughly ascertained in another manner since it is located downstream from the point of minimum static pressure at a point where the maximum increase in static pressure occurs. Using this information in conjunction with existing blade surface pressure distribution data, such as that contained in NACA Technical Note No. 3916, referred to above, the point of transition for non-slotted airfoils can be located only approximately, i.e., within a ten percent range.

According to the concepts of the present invention, it has been found that the point of transition on a slotted airfoil occurs approximately five to seven percent of the chord length farther downstream than it would on a similar non-slotted airfoil under otherwise identical conditions. It has been observed that a slotted airfoil designed in this manner has about the same flow deflection and velocity distribution characteristics as that of the equivalent non-slotted airfoil. This feature is important since it allows use of the NACA test data for numerous non-slotted airfoils to develop a slotted airfoil having known characteristics. The resulting slotted airfoil provides a quick transition from laminar to turbulent boundary layer flow resulting, consequently, in a narrower range of transitional boundary layer flow. As a result of the extension of the laminar flow boundary layer range and the shortening of the transitional boundary layer range, the slotted airfoil according to this invention results in a reduction in drag and an increase in efficiency.

The advantageous five to seven percent downstream shift of the point of transition in slotted airfoils according to the present invention is the result of the jet effect of flow through the slot. When two fluid streams of different velocities flow side-by-side in the same direction, the streams intermix and the faster moving stream tends to induce increased velocity of the slower moving stream, both upstream and downstream of the point of mixing. In the present instance, one of these streams is the boundary layer on the upper surface of the airfoil while the other is the flow through the slot. It is known that for a flow analysis within the boundary layer, viscous forces cannot be neglected. In addition, the flow through the nozzle-shaped slot has a low Reynolds number compared with the flow over the airfoil. Thus, when the energy of the fluid flow through the slot is added to the viscous flow in the boundary layer traveling in the same direction, this additional energy, when properly added at the proper point, delays the point of transition and moves this point approximately five to seven percent of the chord length farther downstream, when compared with an equivalent non-slotted airfoil.

In my earlier patent, referred to above, a slotted, non-laminar airfoil was disclosed in which the slot exit on the upper surface of the airfoil was intended to be positioned at the point of maximum static pressure increase following the point of minimum static pressure, or at a point about two-thirds the chord length downstream from the leading edge of the airfoil.

In contrast, in accordance with the principles of the present invention, for laminar flow airfoils the slot exit on the upper surface should be located immediately upstream of the second maximum frictional intensity value (in other words, immediately upstream of the point of transition) at the design condition. For non-laminar flow airfoils, according to the present invention, the slot exit should be located a short distance downstream of the second maximum frictional intensity value (point of transition) at the design condition.

When frictional intensity data are not available, for laminar flow airfoils the extent of the laminar boundary layer for the design condition can be calculated in accordance with modern boundary layer theory from the available pressure distribution data. The slot exit on the upper surface is then located at the end of this laminar boundary layer for the design condition. For non-laminar airfoils the slot exit on the upper surface is located approximately five to seven percent of the chord length downstream from the start of the maximum static pressure increase following the point of minimum static pressure at the design condition.

In my prior patent, energy was imparted through the slot merely for the purpose of eliminating stalling and thereby achieving a greater pressure output. This was done at the expense of increased drag and lower overall efficiency. In the present invention, energy is imparted to the boundary layer on the airfoil's upper surface for the purpose of effecting a quick transition from laminar to turbulent boundary layer and for increasing the extent of the laminar boundary layer, thereby achieving both a higher efficiency and a higher pressure output.

An important advance of the present invention is the utilization of the concept of frictional intensity and the relation of pressure distribution data to this concept for slot location as defined above. The importance of frictional data results from a recognition of the fact that the true skin friction drag is the sum of the frictional intensity values over the entire chord. Utilization of frictional intensity data in the manner here taught permits design of an airfoil for minimum drag and maximum efficiency, something which was never previously possible.

The next consideration is the location of the slot inlet on the lower surface of the airfoil. In general, this inlet should be located in the same manner as the slot exit for a laminar flow airfoil, in other words, immediately upstream of the point of transition to turbulent boundary layer on the lower surface.

The entrance on the lower surface provides a sink for the removal of the boundary layer. A new laminar boundary layer forms on that portion of the airfoil's lower surface downstream of the slot entrance and sometimes this new laminar boundary layer extends completely to the trailing edge. This results in a slotted blade having a greater extent of laminar boundary layer over the lower surface than over the upper surface, with a consequent increase in the total laminar boundary layer over the airfoil. Since the amount of skin friction produced in a laminar boundary layer is considerably smaller than that produced in a turbulent boundary layer, a pronounced reduction in drag results.

Consequently, a simultaneous treatment of upper and lower blade surfaces is of distinct advantage. In accordance with the present invention, to achieve optimum boundary layer control on both sides of the airfoil surface, airfoils should be selected in which the transition point on the lower surface at design condition lies either downstream from the transition point on the upper surface or no farther upstream than will permit proper placement of the slot entrance ahead of the slot exit. This results in maximum increase in pressure and blade efficiency. It has been found that this condition exists in many of the NACA 65-Series laminar flow airfoils over a wide range of flow, cascade, solidity and stagger conditions, and accordingly, these laminar flow airfoils are readily provided with slots according to the present invention. Furthermore, the use of this airfoil series makes the application of the invention particularly easy because of the publication of pressure distributions over a wide range of operating conditions, stagger and solidity.

Earlier slotted airfoils did not define the location and requirements for the slot entrance on the lower side of the airfoil, and consequently considerable losses occurred due to high frictional intensity values on the lower airfoil side. With the non-laminar airfoils it is not possible to have a laminar boundary layer on the lower side of the rear airfoil portion of a slotted airfoil if the slot exit is to be located according to the present invention.

Slot Overlap and Flow Direction

In the embodiment of the invention shown in FIGURE 9 the location of the flow sink m_x on the lower side of the airfoil varies and moves farther forward for the higher cambered airfoil section at the hub of the impeller. The same is true for the location of flow exit s_x on the upper side of the combined airfoil. In addition, the amount of overlap is increased with the higher cambered airfoil required at the root of the blades. The larger pressure difference for the higher cambered airfoil would result in a larger amount of flow through the slot if both the slot opening and overlap remained the same.

Referring to FIGURE 10, the angle r' of the lower surface trailing edge of the forward airfoil and the angle $\tau 3$ of the forward part of the upper surface of the rear airfoil at the slot exit have to be carefully selected to permit the flow moving through the slot to properly energize the boundary layer of the combined profile without causing undue drag. All angles τ are shown in FIGURE 10 and are measured with regard to the direction of the chord line of the forward airfoil. The angle τm defines the mean direction of the fluid at the slot exit. This direction is defined by the local value of the angles τ' and $\tau 3$ and the configuration of the slot upstream of the slot exit. The direction of the angle rm relative to both

forward and rear part of the airfoil is important and is defined by effectively creating a nozzle-type configuration at the slot exit so as to produce a fluid flow of predetermined characteristics and to eject it efficiently for proper acceleration of the boundary layer.

The slot must be so directed that the flow of ejected fluid will be in the same direction as that of the fluid which is flowing along the upper surface at the slot exit. When the slot is located between the mid-point of the total chord length and the trailing edge, relatively little overlapping of the two airfoil portions is required, since the fluid flows in a fairly straight path from the lower to the upper surface. However, if the slot should be located upstream of the blade's mid-point, the two airfoil portions must be overlapped to a greater extent in order that the flow through the slot be ejected in the same direction as the flow on the upper surface of the airfoil at the slot exit.

Taking into account all of the variables which relate to slot overlap, it has been found that the overlap o should be within the range of from .5 percent to 5 percent of the over-all chord c. The discharge opening or slot exits must be smaller than the entrance m of the slot to give the necessary nozzle effect. Furthermore, it will be noted that the angle τ' made by the lower surface trailing edge portion of the forward airfoil portion and the chord of said airfoil portion is greater than the angle $\tau 3$ formed by the tangent to the upper surface of the rearward airfoil portions at the slot exit and the same chord. This relationship insures that a flow coming out of the slot is ejected in the proper direction.

Slot Gap or Width

For the following analysis, reference is had to FIGURE 11, which illustrates the combined airfoil in the region of the slot with the associated boundary layers. In this figure t_1 designates the thickness of the boundary layer on the lower surface of the forward airfoil trailing edge portion, t_2 designates the thickness of the boundary layer on the upper surface of the forward airfoil trailing edge portion, and t_3 designates the thickness of the boundary layer on the upper surface of the rearward airfoil leading edge portion at the slot exit. As before, S designates the slot gap at its exit. In addition, S_1 designates the "effective gap" at the slot exit between the boundary layers formed on the lower surface of the forward airfoil and the upper surface of the rearward airfoil.

The principles of jet pumps derived from the book "Centrifugal and Axial Pumps," by A. J. Stepanoff, 1948, beginning on page 414, can be utilized to calculate the area relationships between a jet flow nozzle and the secondary flow induced by this jet flow, for various conditions of pressure and flow. It has been determined from a synthesis of flow theories derived from various scientific treatises, such as "Modern Developments in Fluid Dynamics," by S. Goldstein, Oxford, 1948, and has been verified by extensive test, that these jet pump theories can be applied to the flow conditions in a slotted airfoil according to the present invention.

In the case of a slotted airfoil, the pressure for the driving jet, i.e., the flow through the slot, is relatively low and, consequently, the velocity of the driving jet leaving the slot is relatively low. The fluid mass to be pumped, i.e., the boundary layer on the upper side of the combined airfoil, has a velocity of zero at the airfoil surface and a velocity equal to the main flow at the outer border of the boundary layer. This velocity can be determined from the total pressure and velocity pressure of the combined airfoil. By applying these principles to the actual airfoil test data taken from various NACA Reports, and calculating the mean boundary layer velocities according to Pohlhausen's and Von Karman's equation, published in "Heat Transfer," by A. Jacob, for example, the following table of typical jet flow area ratios can be obtained:

Airfoil	Type	$\frac{A_1}{A_2}$
65(27) 10:45–1	Laminar	1.29
65(21) 10:45–1	do	1.32
65(15) 10:45–1	do	1.43
65(8) 10:45–1	do	1.25
65(21) 10:45–1.5	do	1.00
65(15) 10:45–1.5	do	1.66
65(21) 10:60–1	do	1.43
65(15) 10:60–1	do	1.23
10C4/30C50:45–1	Non-laminar	1.20
10C4/30C50:60–1	do	1.09
NACA 4412: $\alpha=4°$	do	1.14

In the above table, A_1 is the area of the driving jet and A_2 is the area of the induced flow mass at the jet exit. The pressure distribution data for the airfoils listed were taken from NACA Technical Note 3916, referred to above, for the first eight airfoils, from NACA Technical Note 3937, March 1957, for the next two airfoils, and from NACA Technical Report No. 613, 1938, for the last airfoil listed.

From the above table, it will be seen that the average area ratio is as follows:

$$\frac{A_1}{A_2}=1.33 \tag{1}$$

Also from the table it will be seen that the following equation covers the range of area ratios for the various airfoils listed:

$$\frac{A_1}{A_2}=1.33\pm.33 \tag{1a}$$

Considering the slotted airfoil, as shown in FIGURE 11, and applying the principles explained above, the area ratios of the table can be considered as proportional to the effective slot width S_1 at the exit divided by the boundary layer thickness t_2 on the upper surface of the forward airfoil at the same position, so that:

$$\frac{A_1}{A_2}=\frac{S_1}{t_2} \tag{2}$$

From the terminology shown in FIGURE 11, it will be seen that the effective slot width or gap can be expressed as follows:

$$S_1=S-t_1-t_3 \tag{3}$$

For an approximate solution for the slot width, it may be initially assumed that the boundary layer thickness along the airfoil is equal to that of a flat plate. Inasmuch as the boundary layer conditions are identical on both sides of a flat plate, it can be assumed for this approximate solution that the boundary layer thicknesses on both sides of the forward airfoil are the same. To further simplify the calculations, it is assumed that the boundary layer thickness t_3 equals zero because the thickness of the boundary layer is taken very near the leading edge of the rear airfoil portion. With these assumptions, Equation 3 can be simplified to the following:

$$S_1=S-t_2 \tag{4}$$

From the book "Principles of Turbo-machinery," by D. G. Sheperd, 1956, beginning on page 161, and from the book "Boundary Layer Theory," by Dr. Herman Schlichting, 1955, the following formulae for boundary layer thickness are derived:

$$\begin{aligned}\delta L&=\frac{5.2X}{R_{ex}^{1/2}}\ \text{for laminar boundry layer}\\ \delta T&=\frac{.376X}{R_{ex}^{0.2}}\ \text{for turbulent boundary layer}\end{aligned} \tag{5}$$

Where X equals the chord location in inches and R_{ex} equals Reynolds number for this location.

Solving for S_1 in Equation 2, using the average area ratio of Equation 1 and substituting this value of S_1 in Equation 4, the slot exit gap can be simply expressed as follows:

$$S=2.33t_2\ \text{and}\ \frac{S}{C}=2.33\frac{t_2}{C} \tag{6}$$

Taking into account the tolerance accuracy expressed in Equation 1a, the maximum and minimum slot gaps are expressed as follows:

$$\begin{aligned}S\ (\text{minimum})&=2t_2\\ S\ (\text{maximum})&=2.66t_2\end{aligned} \tag{6a}$$

Applying these formulae to several typical ranges of flow velocities and blade chords, the following values of slot gap expressed in terms of percent of total chord were derived for chord positions varying from 25% to 62½% of the total chord.

For all laminar and non-laminar flow airfoils:

$$\frac{S}{C}\ (\text{minimum})=.42\%$$

$$\frac{S}{C}\ (\text{maximum})=5.74\%$$

For laminar flow airfoils:

$$\frac{S}{C}\ (\text{minimum})=.42\%$$

$$\frac{S}{C}\ (\text{maximum})=2.24\%$$

In order to accurately check these results, another series of more thorough calculations were made to determine the actual boundary layer thicknesses for various NACA laminar flow airfoils in cascade for both the concave and convex sides. These detailed analyses were made using the mathematical methods derived in the book by Schlichting, referred to above, and they indicated that the assumptions for the approximate calculation were justified. Therefore, the extensive theoretical analyses for several conditions of flow and chord length for a number of different airfoils indicate that, for all practical cases, the slot exit gap should be within the range of .5 to 5% of the total airfoil chord. The slight minimum and maximum variations from this range in the simplified calculations are explained because the values were calculated on the basis of flat plate boundary layer thicknesses.

Thus, the detailed analyses and synthesis of theories have verified the extensive test results of slotted blade airfoils in cascade, in accordance with the present invention.

To summarize, then, the slot gap is defined reasonably accurately as follows:

$$\begin{aligned}S\ (\text{minimum})&=2t_2\\ S\ (\text{maximum})&=2.66t_2\end{aligned} \tag{6a}$$

The more exact expressions for a slot gap are expressed as follows:

$$S=S_1+t_1+t_3 \tag{3a}$$

$$S=\frac{A_1}{A_2}t_2+t_1+t_3 \tag{3b}$$

$$S\ (\text{minimum})=t_2+t_1+t_3 \tag{3c}$$

or

$$S\ (\text{maximum})=1.66t_2+t_1+t_3 \tag{3d}$$

Slot Direction Relative to Turbo-Machine

An additional feature of the slot configuration is its formation in a straight radial direction with respect to the axis of rotation of the turbo-machine. Inasmuch as the blade speed, with respect to the fluid, increases from root to tip of the blades, decreased camber is provided from root to tip. The radial direction of the slot is to accommodate a certain amount of three-dimensional flow of the fluid in the turbo-machine. If the slot were not radial, the outward boundary layer flow, due to centrifugal force, would cause considerable flow disturbance. When blades of prior turbo-machines were twisted and provided with varying camber, the slots were thrown considerably off radial with resulting flow disturbance.

Reduced Noise Level and Power Requirements

The previous discussion of the slotted blade axial flow blower has been directed generally to improvements in efficiency and output in the design operating range, by use of slotted blades as described. In addition, the invention relates to a blower having low noise level characteristics and low horsepower requirements at operating conditions between the design operating range and the airflow shut-off condition.

The airborne noise level of a blower is a function of the speed of the air flowing over the blades, the blade area and surface smoothness, the boundary layer, the wake and turbulence of the flow. If a blower consists of an impeller having rotating blades and stationary guide vanes, each of the rotating and stationary blades affect the over-all airborne noise output of the blower in accordance with their relative contribution, and the above flow phenomenon relating to noise must be properly considered for both rotating and stationary vanes. The airborne noise level, at the design point, can be reduced by designing the blower for lowest velocity between the rotating impeller blades and the relative airflow, and simultaneously for a low value of absolute velocity over the guide or stationary vanes of the blower. For a certain blade configuration, the lowest noise level is achieved for a predetermined pressure by the lowest air velocities and the smallest blade surface area. Accordingly, a blower with blades generating a high pressure coefficient and comparatively small total blade area is of advantage for low airborne noise level. It results in an inherently lower relative velocity over the blades of the impeller for a given pressure increase.

The structural noise or the vibrational force output of a well-balanced prime mover, and particularly of an electric motor, is a direct function of the horsepower output. Therefore, under otherwise equal conditions of performance and balancing, a more efficient blower has a lower structural noise output because it requires a relatively smaller horsepower input. In addition, if the blower operates within a predetermined range of operating conditions, the vibrational force output can be controlled and predicted, if the horsepower requirements over the desired operating range are known. More specifically, if a blower is desired to operate from the point of maximum efficiency to shut-off, a lower vibrational force output can be achieved at lower capacities, including shut-off, with a horsepower characteristic requiring less input or driving horsepower at lower capacities, including shut-off.

The noise characteristics of the blower are of considerable significance at operating conditions away from the design point or maximum efficiency operating point. FIGURE 12 shows the operating characteristics of a typical axial flow blower, with the design point designated at A. The point of free flow without a duct system is designated as B. The point of shut-off of flow is designated as C. When such a blower is installed in a ventilating system of the recirculating type, there is a certain amount of resistance, consisting of heating or cooling coils and duct friction, inherently built into the system, and, therefore, under such operating conditions, a capacity larger than the flow designated at D can never be obtained. However, by adjusting various controls and dampers in the system, the flow can be adjusted to meet a wide range of requirements. It is usually possible to start from the maximum operating capacity at D and adjust and reduce the flow down to a value of shut-off, as indicated by C. For optimum operating conditions, the capacity of the system shall coincide with the point A of the blower indicating maximum efficiency. For many other operating conditions it may, however, be desirable to operate with smaller flow capacities up to and including shut-off. Therefore, it is of great interest to have low noise level characteristics in the entire flow range from C to D. Most axial flow blowers have characteristics which result in a pressure drop from A to D, and a pressure increase from A to C, as indicated in FIGURE 12. The pressure increase from A to C is also responsible for a corresponding input horsepower increase. FIGURE 12 shows such a power characteristic, indicating higher horsepower consumption at shut-off than at the point of maximum efficiency designated A_n. Typical characteristic curves of axial flow blowers similar to FIGURE 12 are shown in the literature, for instance, FIGURE 120, page 256 of "Fluid Mechanics of Turbo-Machinery" by George Wislicenus, FIGURE 13.8, page 252, and FIGURE 13.19 and 13.20, page 271, of "Turbo-Blowers" by A. J. Stepanoff, Phd.

The airborne noise of the blower shown in FIGURE 12 has the highest value at shut-off point C_s, the lowest value near the design point A_s, and then again slightly increasing values of noise to the point of maximum operating flow at D_s.

This portion of the invention consists of using, with an axial flow blower, a special type of slotted blading which permits considerable improvement of the noise characteristics and the driving horsepower requirements in the practical operating range, as indicated in FIGURE 12 between points C and D.

It has been found that by using slotted blades of special configuration in the impeller alone, or in the impeller and/or guide vanes of an axial flow blower, the pressure characteristics of the blower can be changed so that the pressure from the maximum design point, FIGURE 12, at A, increases only slightly with reduced capacity and then the pressure reduces to a varying degree so that at shut-off, the total pressure is smaller than at the design point or the point of maximum pressure. Depending on the selected design of the slotted blade, the pressure at shut-off can be made to be only two-thirds, one-half, or even less of the pressure at maximum design point A. This change in pressure characteristics of the axial flow blower, in turn, changes the power characteristics of the blower so that an axial blower with such slotted blades has a decrease in power requirements at smaller capacity and at shut-off, as compared with the design point. The decreased power, pressure and noise characteristics resulting from incorporation of a properly designed slot is defined graphically in FIGURES 13 and 14.

FIGURE 13 shows the performance of a slotted blade axial flow blower in terms of pressure and efficiency plotted versus flow capacity. On the same graph, as shown in a dashed line, is the performance of the standard fan producing about the same pressure and capacity in the range of flow between design point A and maximum system flow D. It is noted that the pressure of the slotted blade blower reduces from the design point A′ to shut-off at C′ to about one-half of its value, whereas the standard blower increases its pressure from A to C about 100%. Consequently, the pressure at shut-off is about four times higher for the standard blower than for the slotted blade blower. In most applications, little use can be made of the high shut-off pressure of the standard blower and the high pressure at shut-off is not required. On the other hand, the high pressure at shut-off is responsible for the high airborne noise level. FIGURE 13 also indicates about the same characteristics in efficiency for both blowers.

FIGURE 14 shows the corresponding performance for the same two blowers in terms of horsepower and airborne noise level as function of flow capacity. It is noted that the noise level of the slotted blade blower at zero capacity C'_s is higher than at the point of maximum efficiency A'_s. However, the noise level at zero capacity C'_s is considerably lower than for the standard blower, point C_s. It should be noted that the horsepower requirement of the slotted blade blower at shut-off, point C'_n, is about one-half the horsepower requirement of the slotted blade blower at the design point A'_n. Correspondingly, for the standard blower, the horsepower requirement at shut-off point C_n is about 50% higher than at the design point A_n. The driving horsepower required at design point is higher for the standard blower than for the slotted blade blower due to the higher efficiency of the slotted blade blower. The performance curves indicate that the horsepower requirement for the standard blower at shut-off, point C_n, is about four times as high as for the slotted blade blower point C'_n. Therefore, the structure-borne noise, which varies under otherwise equivalent conditions as a function of the horsepower, as previously pointed out, is considerably less for the blower with slotted blades in the vicinity of shut-off and at low capacity.

It can be stated that for the standard blower the following relationship generally exists between the point of zero flow capacity and design point in regard to pressure and the horsepower characteristics:

$$Pc > Pa \text{ for pressure}$$

and/or

$$Nc > Na \text{ for horsepower}$$

The blower with slotted blades changes the performance characteristics so that the following relationship exists between zero flow capacity and design point in regard to pressure and horespower characteristics:

$$Pc' < Pa' \text{ for pressure}$$

and/or

$$Nc' < Na' \text{ for horsepower}$$

This change in characteristics, in turn, is responsible for the lower airborne and structure-borne noise of the slotted blade blower.

The substantial improvement in the noise characteristics and power requirements is related to the change in the flow pattern caused by a slot designed in accordance with this portion of the invention. When a blower with standard non-slotted blades is operated at low flow capacity, i.e., between the design operating condition and shut-off, radial components of flow are established which change the flow from two dimensional to three dimensional. A specific condition of flow with respect to a non-slotted blade at shut-off is qualitatively shown in FIGURE 15. As illustrated, a radial flow component is formed in the region of the central chord portion of the non-slotted blade, with flow vortexes formed on each side of this radial flow component. Such radial flow components are responsible for the substantial pressure increase at low flow capacity, and the pressure increase causes the high noise level and the increased driving horsepower requirement. Installation of a properly designed slot, extended radially from hub to tip, located approximately at the mid-point of the airfoil eliminates or substantially reduces the radial flow component by permitting the pressure difference between the upper and lower surfaces of the blade to equalize at the slot. The equalizing flow is illustrated in FIGURES 16 and 17 which show a slotted blade, according to the present invention, being operated at shut-off. With the slotted blade, the higher pressure fluid at the lower surface flows through the slot to the reduced pressure on the upper surface, traveling in both directions, to equalize the pressure. The flow is still three dimensional, as shown in FIGURE 16, but inasmuch as the slot is radial, the radial flow component responsible for the pressure increase is substantially reduced. Thus, slotted blades according to the present invention create new, desirable blower characteristics, namely, low pressure and horsepower at shut-off, heretofore not possible with axial flow blowers.

With respect to reducing noise level and horsepower requirements, it has been found by test that slots can have the same gap or slot width derived previously, and the range of slot location can extend between forty percent and seventy-five percent of the total blade chord, with the requirement that the slot must extend in a substantially radial direction for any particular blade design. If, however, the lowest airborne noise levels and power requirements are desired, then laminar flow blades with approximately 50% or more laminar boundary layer should be used and the slot and blade should be dimensioned and located as previously defined.

While the slots may generally have a slot width as previously determined and be located in from forty to seventy-five percent of the total blade chord from the leading edge of the blade, for the greatest efficiency in noise reduction the size and location of the slot should be in a more limited range. The width of the slot should be from two percent to four percent of the total blade chord and should be located in the area from fifty-five percent to seventy percent from the leading edge. If the slot is less than two percent of the chord there is no substantial increase in efficiency over a non-slotted blade, and if it is over six percent of the chord, the effect is substantially that of two adjacent non-slotted blades.

The present invention may be applied to blowers having an impeller only and no guide vanes. In addition, it may be applied to blowers with guide vanes, either upstream or downstream of the impeller. These guide vanes may be either of the slotted or the solid type. The specially designed slot in the impeller blades alone will result in desirable change in pressure, power and noise characteristics. However, slots in both the guide and impeller vanes will further increase these desirable changes.

The specific embodiment of blades which has been shown and described is to be understood to be illustrative only. Variations and modifications may be effected without departing from the scope of the novel concepts of the present invention.

I claim:

1. An axial flow turbo-machine blade having a cross-sectional profile of the laminar airfoil type, said blade including a forward airfoil portion and a rearward airfoil portion with the forward airfoil portion trailing edge section overlapping the rearward airfoil portion leading edge section to form a slot extending generally longitudinally in a downstream direction with respect to the airfoil chord from the lower surface to the upper surface of the airfoil, said slot having its exit in the upper surface at a position located immediately upstream of the point of transition of the boundary layer to fully developed turbulent boundary layer flow at the design operating condition of the blade, the gap at the narrowest point between said airfoil portions being within the range of one time to 1.66 times the thickness of the boundary layer on the upper surface of the trailing edge section of the forward airfoil portion plus the thickness of the boundary layer on the lower surface of the trailing edge section of the forward airfoil portion plus the thickness of the boundary layer on the upper surface of the rearward airfoil portion at the slot exit, where the thickness of said boundary layers are taken at the design operating condition of the blade.

2. An axial flow turbo-machine blade having a cross-sectional profile of the laminar airfoil type, said blade being provided with a slot extending generally longitudinally in a downstream direction with respect to the airfoil chord from the lower surface to the upper surface of the airfoil and having its exit in the upper surface at a position located between the end of the laminar boundary layer and the point of transition of the boundary layer to fully developed turbulent boundary layer flow at the design operating condition of the blade, said slot having a width at

the narrowest point within the range of two times to 2.66 times the thickness of the boundary layer at the location of the slot exit on the upper surface at the design operating condition of the blade.

3. An axial flow turbo-machine blade having a cross-sectional profile of the laminar airfoil type, said blade including a forward airfoil portion and a rearward airfoil portion with the forward airfoil portion trailing edge section overlapping the rearward airfoil portion leading edge section to form a slot extending generally longitudinally in a downstream direction with respect to the airfoil chord from the lower surface to the upper surface of the airfoil, said slot having its exit in the upper surface at a position located between the end of the laminar boundary layer and the point of transition of the boundary layer to fully developed turbulent boundary layer flow at the design operating condition of the blade, the gap between said airfoil portions at the narrowest point being within the range of one time to 1.66 times the thickness of the boundary layer on the upper surface of the trailing edge section of the forward airfoil portion plus the thickness of the boundary layer on the lower surface of the trailing edge section of the forward airfoil portion plus the thickness of the boundary layer on the upper surface of the rearward airfoil portion at the slot exit, where the thicknesses of said boundary layers are taken at the design operating condition of the blade.

4. An axial flow turbo-machine blade having a cross-sectional profile of the laminar airfoil type, said blade including a forward airfoil portion and a rearward airfoil portion with the forward airfoil portion trailing edge section overlapping the rearward airfoil portion leading edge section to form a slot extending generally longitudinally in a downstream direction with respect to the airfoil chord from the lower surface to the upper surface of the airfoil, said slot having its exit in the upper surface at a position located immediately upstream of the point of transition of the boundary layer to fully develop turbulent flow at the design operating condition of the blade, the gap between said airfoil portions at the narrowest point being within the range of two times to 2.66 times the thickness of the boundary layer on the upper surface of the trailing edge section of the forward airfoil portion at the design operating condition of the blade, the gap also being within the range of .5 to 5% of the total chord of the blade and with the overlap of said airfoil portions measured along the chord of the blade being within the range of .5% to 5% of the total chord of the blade.

5. An axial flow turbo-machine blade having a cross-sectional profile of the laminar airfoil type, said blade having a first maximum of frictional intensity on the upper surface and a second maximum of frictional intensity spaced from said first maximum in a downstream chord-wise direction with a first minimum of frictional intensity therebetween at the design operating condition of the blade, and said blade having a forward airfoil portion and a rearward airfoil portion with the forward airfoil portion trailing edge section overlapping the rearward airfoil portion leading edge section to form a slot extending generally longitudinally in a downstream direction with respect to the airfoil chord from the lower surface to the upper surface of the airfoil, said slot having its exit in the upper surface at a position located between said first minimum of frictional intensity and said second maximum of frictional intensity, said slot having a gap between said airfoil portions at the narrowest point within the range of two times to 2.66 times the thickness of the boundary layer on the upper surface of the trailing edge section of the forward airfoil portion at the design operating condition of the blade, the angle made by the lower surface of the forward airfoil portion trailing edge section and the chord of said airfoil portion being greater than the angle formed by the tangent to the upper surface of the rearward airfoil portion at the end of said overlap and said same chord, and with the overlap of said airfoil portions measured along the chord of the blade being within the range of .5% to 5% of the total chord of the blade.

6. An axial flow turbo-machine blade having a cross-sectional profile of the laminar airfoil type, said blade including a forward airfoil portion and a rearward airfoil portion with the forward airfoil portion trailing edge section overlapping the rearward airfoil portion leading edge section to form a slot extending generally longitudinally in a downstream direction with respect to the airfoil chord from the lower surface to the upper surface of the airfoil, said slot having its exit in the upper surface at a position located between the end of the laminar boundary layer and the point of transition of the boundary layer to fully develop turbulent flow at the design operating condition of the blade, said slot having a width at the narrowest point within the range of two times to 2.66 times the thickness of the boundary layer at the location of the slot exit on the upper surface at the design operating condition of the blade, and with said overlap measured along the total chord of the blade being within the range of .5% to 5% of the total chord of the airfoil.

7. In an axial flow turbo-machine including a generally tubular housing having a rotor rotatably mounted therein with a plurality of circumferentially spaced fixed blades on said rotor and with each of said blades having a cross-sectional profile of the laminar airfoil type, the improvement comprising a slot extending generally longitudinally in a downstream direction with respect to the airfoil chord from the lower surface to the upper surface of the airfoil through each of said blades, said blade having a first maximum of frictional intensity on the upper surface and a second maximum of frictional intensity spaced from said first maximum in a downstream chord-wise direction with a first minimum of frictional intensity therebetween at the design operating condition of the turbo-machine, said slot having its exit in the upper surface at a position located between said first minimum of frictional intensity and said second maximum of frictional intensity, said slot exit also being located within a range between 55% and 70% of the total chord of the blade, said slot having a width at the narrowest point within the range of one time to 1.66 times the thickness of the boundary layer on the upper surface of the trailing edge section of the forward airfoil portion plus the thickness of the boundary layer on the lower surface of the trailing edge section of the forward airfoil portion plus the thickness of the boundary layer on the upper surface of the rearward airfoil portion at the slot exit, where the thickness of said boundary layers are taken at the design operating condition of the blade, and said slot also having a width at the narrowest point within the range of from 2% to 4% of the total chord of the blade, whereby the pressure output of the turbo-machine at the airflow shut-off condition is smaller than the pressure output of the turbo-machine at the design operating condition.

8. In an axial flow turbo-machine including a generally tubular housing having a rotor rotatably mounted therein with a plurality of circumferentially fixed blades on said rotor and with each of said blades having a cross-sectional profile of the laminar airfoil type, the improvement comprising a slot extending generally longitudinally in a downstream direction with respect to the airfoil chord from the lower surface to the upper surface of the airfoil through each of said blades, said blade having a first maximum of frictional intensity on the upper surface and a second maximum of frictional intensity spaced from said first maximum in a downstream chord-wise direction with a first minimum of frictional intensity therebetween at the design operating condition of the turbo-machine, said slot having a width at the narrowest point within the range of two times to 2.66 times the thickness of the boundary layer at the location of the slot exit on the upper surface of the blade at the design operating condition of the turbo-

machine, the width of said slot at the narrowest point also being within the range of 2% to 4% of the total blade chord, said slot having its exit in the upper surface at a position located between said first minimum of frictional intensity and said second maximum of frictional intensity, and said slot being located within the range of from 55% to 70% of the total blade chord, whereby the pressure output of the turbo-machine at the airflow shut-off condition is smaller than the pressure output at the design operating condition.

9. In an axial flow turbo-machine including a generally tubular housing having a rotor rotatably mounted therein with a plurality of circumferentially fixed blades on said rotor and with each of said blades having a cross-sectional profile of the laminar airfoil type, the improvements comprising a forward airfoil portion and a rearward airfoil portion of each of said blades with the forward airfoil portion trailing edge section overlapping the rearward airfoil portion leading edge section to form a slot extending generally longitudinally in a downstream direction with respect to the airfoil chord from the lower surface to the upper surface of the airfoil, said blade having a first maximum of frictional intensity on the upper surface and a second maximum of frictional intensity spaced from said first maximum in a downstream chord-wise direction at the design operating condition of the turbo-machine, the exit of said slot being located in the upper surface of the blade immediately upstream of said second maximum of frictional intensity, said slot exit also being located within a range between 55% and 70% of the total chord of the blade, the amount of overlap of the blade portions being within the range of .5% to 5% of the total chord of the blade, the gap between said airfoil portions at the narrowest point being within the range of two times to 2.66 times the thickness of the boundary layer on the upper surface of the trailing edge section of the forward airfoil portion at the design operating condition of the turbo-machine, said gap at the narrowest point also being within the range of from 2% to 4% of the total blade chord, whereby the pressure output of the turbo-machine at the airflow shut-off condition is smaller than the pressure output at the design operating condition.

10. An axial flow turbo-machine blade having a cross-sectional profile of the laminar airfoil type, said blade including a forward airfoil portion and a rearward airfoil portion with the forward airfoil portion trailing edge section overlapping the rearward airfoil portion leading edge section to form a slot extending generally longitudinally in a downstream direction with respect to the airfoil chord from the lower surface to the upper surface of the airfoil, said slot having its exit in the upper surface at a position located between the end of the laminar boundary layer and the point of transition of the boundary layer to fully developed turbulent flow at the design operating condition of the blade, and with said overlap measured along the total chord of the blade being within the range of .5% to 5% of the total chord of the airfoil.

11. In an axial flow turbo-machine including a generally tubular housing having a rotor rotatably mounted therein with a plurality of circumferentially spaced fixed blades on said rotor and with each of said blades having a cross-sectional profile of the laminar airfoil type, the improvement comprising a slot extending generally longitudinally in a downstream direction with respect to the airfoil chord from the lower surface to the upper surface of the airfoil through each of said blades, said blade having a first maximum of frictional intensity on the upper surface and a second maximum of frictional intensity spaced from said first maximum in a downstream chord-wise direction with a first minimum of frictional intensity therebetween at the design operating condition of the turbo-machine, said slot having its exit in the upper surface at a position located between said first minimum of frictional intensity and said second maximum of frictional intensity, said slot exit also being located within a range between 55% and 70% of the total chord of the blade, and said slot also having a width at the narrowest point within the range of from 2% to 4% of the total chord of the blade, whereby the pressure output of the turbo-machine at the airflow shut-off condition is smaller than the pressure output of the turbo-machine at the design operating condition.

12. An axial flow turbo-machine blade having a cross-sectional profile of the laminar airfoil type, said blade being provided with a slot extending generally longitudinally in a downstream direction with respect to the airflow chord from the lower surface to the upper surface of the airfoil and having its exit in the upper surface at a position located between the end of the laminar boundary layer and the point of transition of the boundary layer to fully developed turbulent boundary layer flow at the design operating condition of the blade, said slot having a width at the narrowest point within the range of .5% to 5% of the airfoil chord.

13. An axial flow turbo-machine blade having a cross-sectional profile of the laminar airfoil type, said blade being provided with a slot extending generally longitudinally in a downstream direction with respect to the airfoil chord from the lower surface to the upper surface of the airfoil and having its exit in the upper surface at a position located immediately upstream of the point of transition of the boundary layer to fully developed turbulent boundary layer flow at the design operating condition of the blade, said slot having a width at the narrowest point within the range of .5% to 5% of the airfoil chord.

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UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,075,743 January 29, 1963

Herman E. Sheets

It is hereby certified that error appears in the above numbered patent requiring correction and that the said Letters Patent should read as corrected below.

Column 4, lines 3, 10 and 14, for "bounary", each occurrence, read -- boundary --; column 12, line 23, for "exits" read -- exit s --; column 13, line 67, for "boundry" read -- boundary --; column 19, line 38, and column 20, line 15, for "develop", each occurrence, read -- developed --.

Signed and sealed this 17th day of September 1963.

(SEAL)
Attest:

ERNEST W. SWIDER
Attesting Officer

DAVID L. LADD
Commissioner of Patents