

June 3, 1958

G. E. CHAPMAN
AXIAL FLOW COMPRESSOR

2,837,270

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2 Sheets-Sheet 1

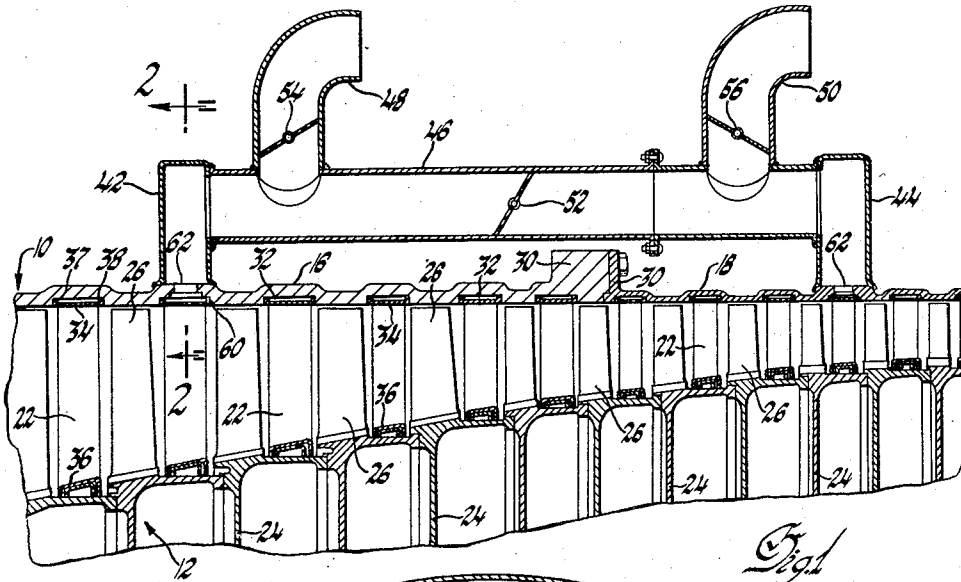


Fig. 1

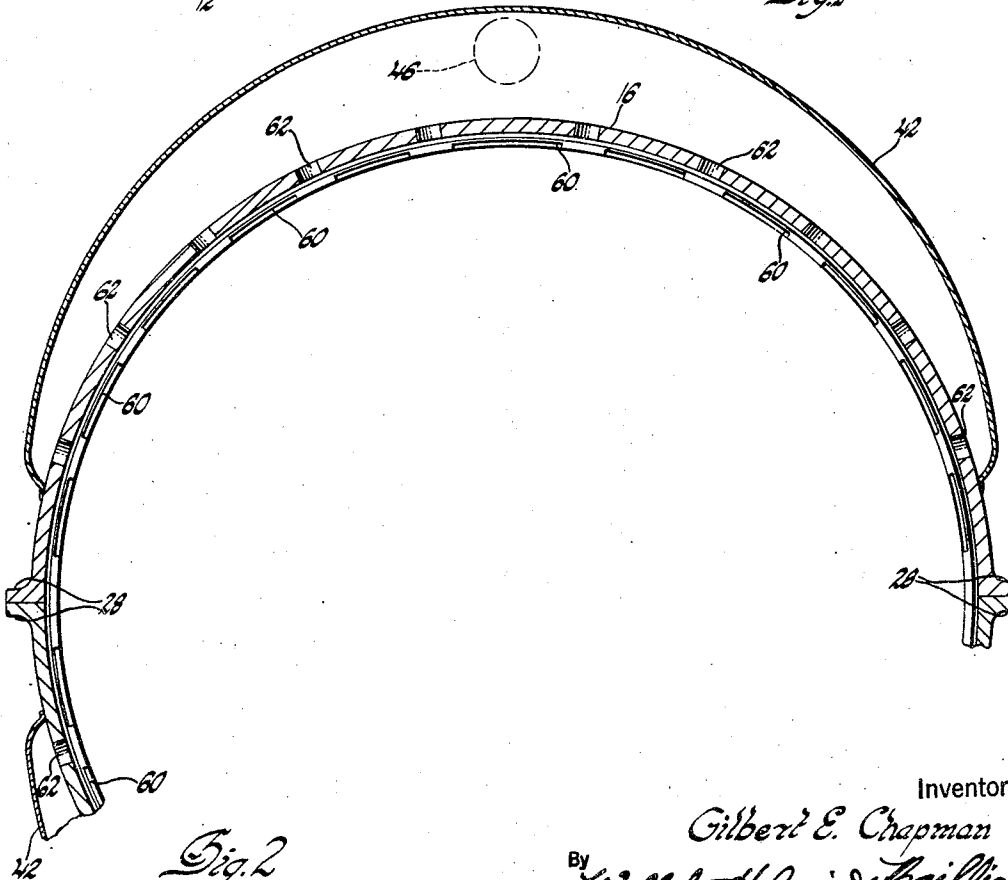


Fig. 2

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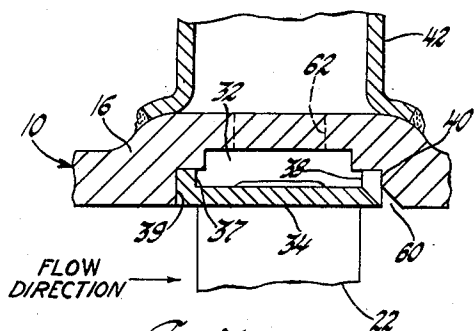


Fig. 3

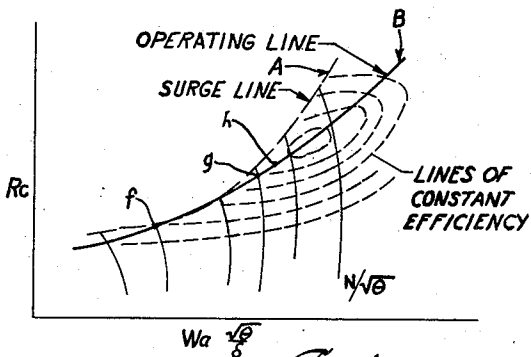


Fig. 4

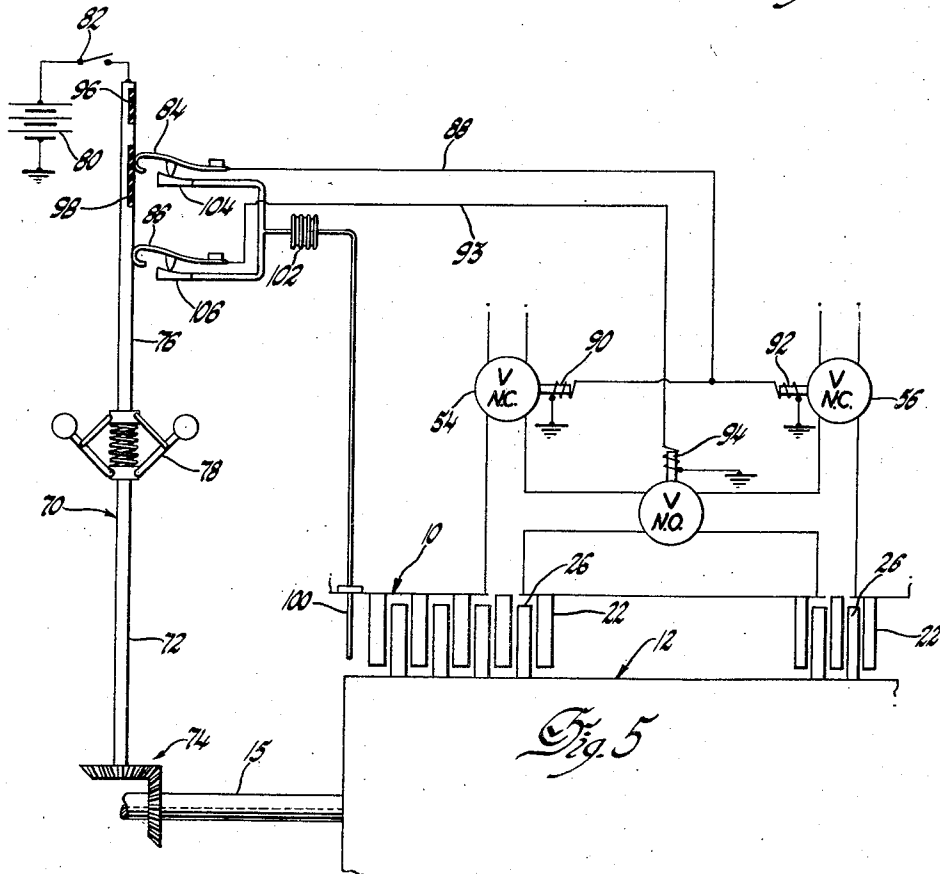


Fig. 5

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AXIAL FLOW COMPRESSOR

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7 Claims. (Cl. 230—115)

My invention relates to multi-stage axial flow compressors for gas turbine engines and the like and, more particularly, to apparatus for improving both the surge characteristics and design speed efficiency of axial flow compressors.

Multi-stage axial flow compressors have an inherent limit of pressure ratio or "surge limit" which varies with the speed of the compressors and with other conditions. When the back pressure of such a compressor installed in a gas turbine engine reaches the surge limit, the flow through the compressor breaks down. The characteristics of an axial flow compressor in a gas turbine engine are matched with the characteristics of turbine in order to obtain maximum efficiency at normal operating or design speed conditions. The compressor thus may be overloaded at lower speeds which must be passed through in accelerating the engine to operating speed, or even under starting conditions.

Even if the operating characteristic is below but very near the surge limit, it may be difficult to accelerate the engine without inducing surge and consequent breakdown of flow. Since the breakdown in compressor performance appears to be primarily a result of too low an axial velocity component of air flow in the earlier stages and too high an axial velocity component of flow in the later stages, under these low speed or starting conditions surge may be eliminated by bleeding air from intermediate stages of the compressor to increase the air flow and hence the axial velocity through the initial stages relative to that in the later stages.

The above may be understood more readily by referring to Fig. 4 herein which depicts the characteristic curve of such a compressor and represents the operating line B and the surge limit line A at which surging of the compressor is encountered. The operating line B and surge limit line A are plotted in terms of the ratio of discharge to inlet pressure ratio (R_c) against the corrected air flow $W\alpha/\sqrt{\theta}$ through the compressor, where the quantity θ (theta) is compressor inlet temperature (degrees Rankine) divided by 518.4 and δ (delta) is compressor inlet pressure in inches of mercury divided by 29.92. The family of generally vertical lines represents corrected speed, $N/\sqrt{\theta}$.

For the characteristic curve illustrated, the operating line B in the low and high speed ranges lies below the surge limit line A and stable operation ensues. In the intermediate speed range, however, the surge limit line lies below the operating line, and highly erratic and unstable operation resulting in surging of the compressor is experienced. As a result, the engine cannot accelerate itself from the low speed range to the normal operating range. By bleeding a sufficient quantity of air from the compressor over this critical speed range, it is possible to raise the surge limit line and lower the operating line so as to obtain stable operation over the entire speed range of the compressor.

Another phenomenon that is particularly undesirable at or near the full design speed of an axial flow compressor is the accumulation along the walls of the compressor casing of a stagnant or slow moving boundary layer of air, the thickness of which increases progressive-

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ly toward the discharge end of the compressor. This layer of air tends to decrease the effective area of the discharge end of the compressor and results in a noticeable impairment of the efficiency thereof. The effect of the boundary layer can be substantially mitigated, however, by accelerating the flow of the boundary layer.

The present invention is directed to a combined compressor air bleed and boundary layer control apparatus and has for its general objective improving both the surge characteristics and the design speed efficiency of an axial flow compressor.

In accordance with my invention, both of the above functions are performed by the same apparatus comprising an arrangement of valved plenum chambers or manifolds mounted on the compressor casing and communicating with the interior of the compressor at selected low and high pressure stages thereof. A control system, which includes a multi-position speed sensitive switch, is provided to control the settings of the manifold valves in such a manner as to permit a sufficient quantity of air to be bled to the atmosphere from selected low and high pressure stages of the compressor over the critical speed range thereof, thereby to control the surge characteristics of the compressor. When the compressor has attained its normal design speed, the manifold valves are arranged to permit bleeding or removal of the slow-moving boundary layer air from a high pressure section of the compressor and reinserting or blowing this air at high velocity into the boundary layer at a low pressure section of the compressor, thereby accelerating the boundary layer and mitigating the effects thereof. The control system also includes apparatus responsive to temperature, say, at the inlet, of the compressor for modifying the operation of the speed sensitive switch so as to compensate for the effects of changes in the compressor temperature on the compressor characteristics.

Other objects, features and advantages of the invention will more fully appear from the following detailed description and drawings wherein:

Fig. 1 is a fragmentary, longitudinal sectional view of an axial flow compressor employing an air bleed and boundary layer control system in accordance with the present invention;

Fig. 2 is a fragmentary, transverse sectional view taken in the plane 2—2 of Fig. 1;

Fig. 3 is an enlarged view of a fragmentary portion of Fig. 1 illustrating the arrangement for removal of air from the interior of the compressor in accordance with a preferred embodiment of the invention;

Fig. 4 is a characteristic curve depicting the operation of a high pressure multi-stage axial flow compressor; and

Fig. 5 is a schematic representation of a form of control system suitable for use with the present invention.

Referring to the drawings, Fig. 1 is a fragmentary showing of a multi-stage axial flow compressor embodying the present invention and comprising a stator 10 and rotor 12. Only that portion of the compressor necessary to understanding the principles of the invention is shown. The stator 10 may be composed of two axially disposed casing members 16 and 18 which confine the low and high pressure sections, respectively, of the compressor and mount a number of axially spaced rings of stator vanes 22 on the interior thereof. The rotor 12, which is enclosed by the stator casing members 16 and 18, comprises a number of spaced disks 24 mounted between a pair of end driving wheels (not shown), the wheels and disks being suitably secured together so as to rotate as a unit. Each of the wheels and disks mounts a ring of rotor blades 26 about the periphery thereof which cooperate with the adjacent rows of stator vanes to form successive axial stages of the compressor.

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Each of the compressor casing members 16 and 18 is constituted by a pair of semi-cylindrical sections provided with longitudinal bolting flanges 28 as shown in Fig. 2. The adjacent ends of the half-sections of the casing members 16 and 18 are provided with bolting flanges 30 about the periphery thereof as shown in Fig. 1. Axially spaced along the inner walls of the casing members 16 and 18 are a number of circumferential grooves 32 for mounting the stator rings. The stator vanes 22 of each of the stator rings are mounted between an outer shroud band 34 and an inner shroud band 36. Each of the outer shroud bands 34 is formed with stub flanges 37, 38 (Figs. 1 and 3) which are seated between the side walls 39, 40 (Fig. 3) of the circumferential grooves 32 in the casing members 16 and 18.

Each half of the compressor constituted by the semi-cylindrical portions of the casing members 16 and 18 has welded or otherwise secured to the exterior thereof a fabricated sheet metal structure comprising a pair of axially spaced manifolds or plenum chambers 42, 44 which are joined by a tubular conduit 46 having a pair of exhaust ports 48, 50 near the opposite ends thereof. A by-pass butterfly valve 52 located centrally of the conduit member 46 and a pair of similar valves 54, 56 in the exhaust ports 48 and 50, respectively, are provided to permit air to be blown from one manifold to the other or to exhaust air externally of the compressor from both manifolds in accordance with the setting of the valves.

Air is extracted from the interior of the compressor into the manifolds 42, 44 around the circumference of selected low and high pressure stages of the compressor through a series of slots 60 (Figs. 2 and 3) which are formed by chamfering portions of the trailing edge or side wall 40 along the circumferential length of the selected grooves and by removing corresponding sections of the after leg or flange 38 of the outer shroud band 34. Air is thus caused to flow into the annular space behind the outer shroud band 34 and the inner wall of the selected ring grooves without interfering with the principal flow of air through the compressor. In order to provide sufficient flow area, the depth of the selected ring grooves may be increased as shown in Fig. 3. A series of spaced ports or openings 62 formed in the compressor casing connects the annular space behind the stator rings of the selected grooves with the respective manifolds 42 and 44. The location of the manifolds 42 and 44 is not critical. For example, however, in a sixteen stage compressor, I prefer to locate them at the outlet of the fourth and twelfth stages.

The valves 52, 54 and 56 may be operated by solenoids or other actuators energized by a control system, a simple form of which is illustrated diagrammatically in Fig. 5. The control system includes speed sensitive means such as a speed responsive switch 70 which comprises a rotatable shaft portion 72 coupled to the compressor rotor shaft 15 through suitable gearing 74 and a conducting rod or slider portion 76 coupled to the shaft portion 72 through a flyball governor 78 that varies the axial position of the conducting rod in accordance with changes in compressor speed. A suitable source of electric power, such as a battery 80, is connected through a switch 82 to the conducting rod 76 which has a pair of spaced sliding contacts 84, 86 bearing on the surface thereof. The contact 84 is connected through line 88 to the armature coils 90, 92 of the normally closed solenoid-opened valves 54, 56, respectively, while contact 86 is connected through line 93 to armature coil 94 of normally open solenoid valve 52. Two insulating segments 96, 98 provided on the conducting rod 76 serve to break the electrical circuits of the valves as the compressor is accelerated or decelerated through its operating range. Slider 76 is illustrated in the zero speed position and moves downward in Fig. 5 as the compressor speed increases.

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The operation of the control system is as follows: Switch 82 is closed to place the control system in operating condition and the compressor is started with all valves closed, the coils 90 and 92 of the solenoid valves being de-energized under starting conditions, and the coil 94 being energized. The characteristics of the compressor follow the operating line B of Fig. 4 as the speed of the machine increases. At a predetermined speed corresponding to point *f* on the operating line, the circuit of the exhaust valves 54 and 56 is closed as the insulating segment 98 moves from under contact 84 and the valves 54, 56 are opened to bleed air from the compressor. Stable operation then occurs as the speed of the compressor increases. Slightly beyond the critical speed range at a predetermined speed corresponding to point *g* on line B, the circuit of valves 54 and 56 is again opened by the insulating segment 96 and the valves are caused to close. Thus, stable operation has been provided through the critical speed range by means of the air bleed arrangement.

At all speeds above that corresponding to point *h*, the by-pass valve 52 is open as insulating segment 98 moves under contact 86 to de-energize solenoid 94 so that air flows from the high pressure end of the compressor to the low pressure end. The boundary layer at the high pressure end is accelerated by bleeding or removing the slow-moving air thereof, and is accelerated at the low pressure end by the blowing action of the high pressure air as this air returns to the low pressure end of the compressor. Thus, the boundary layer is prevented from building up along the compressor casing and the compressor efficiency is improved.

The valves operate in a reverse order during the deceleration of the compressor. Depending upon the compressor characteristics, it may be desirable to maintain the valves 54 and 56 open during starting conditions from zero speed until the point *g* is reached.

In order to compensate for the effects of changes in the compressor inlet temperature, for example, on the compressor surge and operating characteristics, the operation of the speed sensitive switch 70 may be modified in accordance with my invention to maintain the selected positions of *f*, *g* and *h*, irrespective of the value of compressor inlet temperature and hence $\sqrt{\theta}$. This is accomplished by provision of a temperature probe 100 in the inlet of the compressor as shown in Fig. 5. The temperature probe is connected to a pressure responsive device such as a Sylphon bellows 102 which adjusts the position of a pair of camming surfaces 104, 106 to change the position of the slide contacts 84 and 86 relative to the initial position of rod 76.

The cams 104 and 106 are calculated to compensate for the $\sqrt{\theta}$ factor in the $N/\sqrt{\theta}$ term of the characteristic curve of Fig. 4. While the compensation is not rigorously exact, it is sufficient for all practical purposes.

Although a specific embodiment of my invention has been shown and described, it will be understood that it is but illustrative and that various modifications may be made therein without departing from the spirit and scope of the invention.

I claim:

1. In combination, a multi-stage axial flow compressor comprising a stator and a rotor, said stator including an outer casing surrounding said rotor and containing a plurality of axially spaced circumferential grooves within the interior thereof, each of said grooves having an inner wall and a pair of spaced side walls, a ring of stator vanes for each of said grooves including an outer shroud band and a plurality of radially extending stator vanes mounted therein, said shroud band being seated between the side walls of respective ones of said grooves, portions along the circumferential length of at least one of the side walls of at least one of said grooves being chamfered to form a plurality of spaced slots between said one groove and its respective shroud band, ports being formed

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in said compressor casing communicating with said selected grooves, said compressor casing having manifold means thereon connected to said ports.

2. In combination, a multi-stage axial flow compressor comprising a stator and a rotor, said stator including an outer casing surrounding said rotor and containing a plurality of axially spaced circumferential grooves within the interior thereof, each of said grooves having an inner wall and a pair of spaced side walls, a ring of stator vanes for each of said grooves including an outer shroud band and a plurality of radially extending stator vanes mounted therein, said shroud band being seated between the side walls of respective ones of said grooves, portions along the circumferential length of one of the side walls of selected ones of said grooves being chamfered to form a plurality of spaced slots between each of said selected grooves and its respective shroud band, ports being formed in said compressor casing communicating with said selected grooves, and manifold means mounted on said compressor casing connected to said ports.

3. In combination, a multi-stage axial flow compressor comprising a stator and a rotor, said stator including an outer casing surrounding said rotor and containing a plurality of axially spaced circumferential grooves within the interior thereof, each of said grooves having an inner wall and a pair of spaced side walls, a ring of stator vanes for each of said grooves including an outer shroud band and a plurality of radially extending stator vanes mounted therein, said shroud band being seated between the side walls of respective ones of said grooves, portions along the circumferential length of one of the side walls of selected ones of said grooves being chamfered and corresponding portions of the shroud bands seated in said selected grooves being removed to form a plurality of spaced slots between each of said selected grooves and its respective shroud band, ports being formed in said compressor casing communicating with said selected grooves, and manifold means mounted on said compressor casing connected to said ports.

4. In combination, a multi-stage axial flow compressor comprising a stator and a rotor, said stator including an outer casing surrounding said rotor and containing a plurality of axially spaced circumferential grooves within the interior thereof, each of said grooves having an inner wall and a pair of spaced side walls, a ring of stator vanes for each of said grooves including an outer shroud band and a plurality of radially extending stator vanes mounted therein, said shroud band being seated between the side walls of respective ones of said grooves, portions along the circumferential length of one of the side walls of at least one of said grooves being chamfered to form a plurality of spaced slots between said groove and its respective shroud band, ports being formed in said compressor casing communicating with said groove, exhaust means mounted on said compressor casing connected to said ports, conduit means connected between said ports for conducting air from high pressure to low pressure stages of said compressor, valve means in said exhaust means and in said conduit means, and speed responsive control means for controlling the position of said valve means over the operating speed range of the compressor.

5. In combination, a multi-stage axial flow compressor comprising a stator and a rotor, said stator including an outer casing surrounding said rotor and containing a plurality of axially spaced circumferential grooves within the interior thereof, each of said grooves having an inner wall and a pair of spaced side walls, a ring of stator vanes for each of said grooves including an outer shroud band and a plurality of radially extending stator vanes mounted therein, said shroud band being seated between the side walls of respective ones of said grooves, portions along the circumferential length of one of the side walls of at least one of said grooves being chamfered to form a plurality of spaced slots between said one groove and its

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respective shroud band, ports being formed in said compressor casing communicating with said groove, exhaust means mounted on said compressor casing connected to said ports, conduit means connected between said ports for conducting air from high pressure to low pressure stages of said compressor, valve means in said exhaust means and in said conduit means, and control means including speed responsive means for controlling the position of said valve means over the operating range of the compressor, means responsive to temperature in the compressor, and means operatively connected with said temperature responsive means and said speed responsive means and affecting operation of said valve means in accordance with the effect of temperature changes in the operating characteristics of the compressor.

6. A multi-stage axial flow compressor compressing, in combination, a rotor and a stator having a casing surrounding the rotor, said stator casing having a plurality of axially spaced circumferential grooves formed within the interior boundary thereof and further having a plurality of openings extending therethrough and communicating with at least one of said grooves therein, a ring of stator vanes for each of said grooves, each of said rings including an outer shroud band seated in a respective one of said grooves and a plurality of radially extending stator vanes mounted in each of said bands, said one of said grooves having portions of the edge thereof relieved to form a plurality of spaced slots between said one groove and its respective shroud band, and exhaust means on said compressor casing communicating with the interior of the compressor through said ports and slotted grooves.

7. In combination, a multi-stage axial flow air compressor comprising a rotor and a stator having a casing surrounding the rotor, said stator casing having at least two axially spaced ports formed therein communicating interiorly with the compressor at a low pressure stage and at a high pressure stage respectively, exhaust conduit means connecting each of said ports to atmosphere for exhausting air from said stages, by-pass conduit means connecting across said exhaust conduit means for conducting air from said high pressure stage to said low pressure stage, separate valve means in both of said exhaust conduit means and in said by-pass conduit means, the compressor being subject to surge at intermediate speeds unless air bled to atmosphere at such speeds and being subject to the accumulation of a substantially stagnant boundary layer of air along the inner wall of said stator casing at high speeds unless the boundary layer of air is accelerated in some fashion at such speeds, and an automatic control including compressor speed sensitive means for controlling the position of said three separate valve means, said control including first means maintaining both of said exhaust valve means open and said by-pass valve means closed at intermediate speeds whereby said surge is avoided by air bleeding said stages through said exhaust conduit means and said control including second means maintaining both of said exhaust valve means closed and said by-pass valve means open at high speeds whereby said accumulation of a stagnant boundary layer of air is avoided by transferring air from the boundary layer at said high pressure stage to the boundary layer at said low pressure stage through said by-pass conduit means.

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