April 10, 1962 G. M. LEWIS 3,029,011

ROTARY COMPRESSORS OR TURBINES

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Fig. 1.

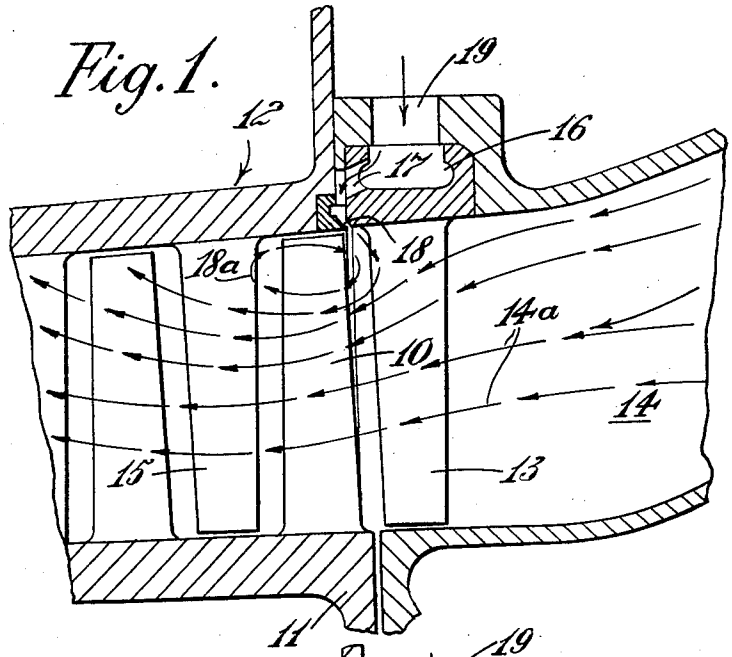
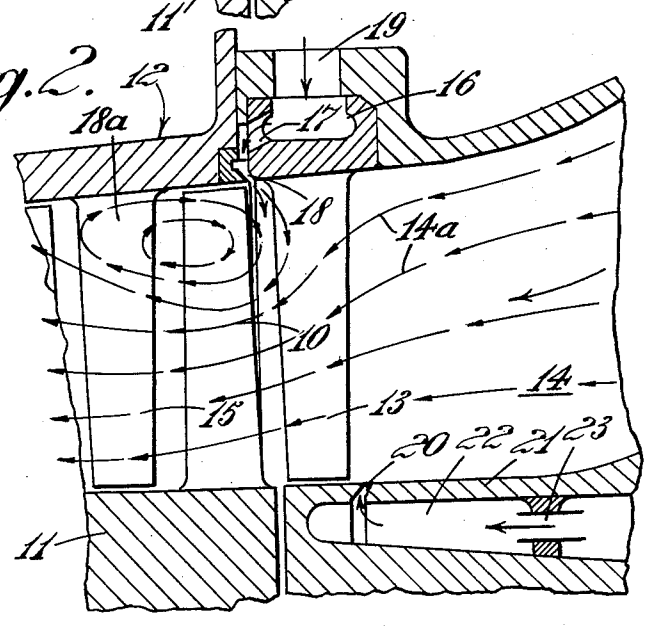


Fig. 2.

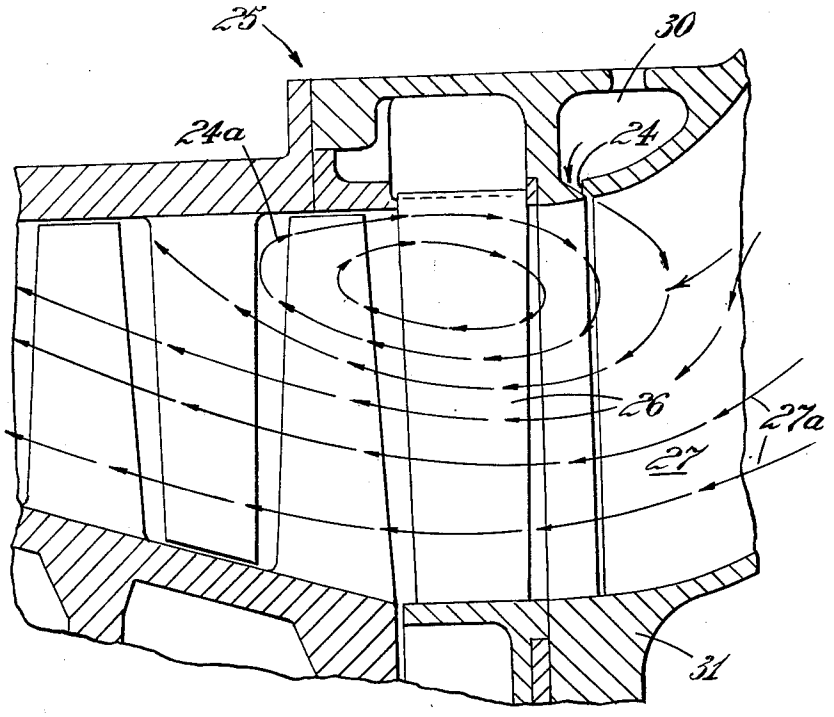


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Fig. 3



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ROTARY COMPRESSORS OR TURBINES

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1 Claim. (Cl. 230—114)

This invention relates to axial flow rotary compressors and turbines using a gaseous medium (hereinafter referred to as gas), and in the case of such compressors has as its main object to provide a means of stabilising the operation of the compressor when the speed of rotation differs substantially from the optimum operating speed, usually referred to as the "designed speed." The invention is applicable to single and multi-stage compressors as well as single and multi-stage turbines and more especially, although not exclusively, to the compressors and turbines of axial flow gas turbine engines. As is well known, in a multi-stage compressor or turbine each stage comprises a ring of moving blades and a ring of stationary blades.

With multi-stage, axial flow, rotary compressors at speeds of rotation below the designed speed, when the pressure rise per stage is less than the designed pressure rise, the reduction in axial velocity of the main gas flow at the entry to the compressor results in the moving blades of the initial stages of the compressor operating at an increasing angle of incidence until, when the speed of rotation has been reduced sufficiently, the blades become stalled. A blade ring does not however stall simultaneously over its whole area, but initially only certain parts stall, the axial velocity falling substantially in these parts so that the main flow is concentrated in the unstalled parts and a sufficient axial velocity is maintained in the unstalled parts to delay further their stalling. The rate at which the stalling spreads, and the extent of the blading affected is a measure of the severity of the stalling.

One object of the present invention is to provide means whereby the axial velocity of the gas flow past a blade ring approaching a stalled or partially stalled condition may be increased whereby the stalling is delayed and the speed range increased. This effect is achieved, according to the invention, by reducing the effective cross-sectional area of the gas flow passage upstream of the blade ring, and the invention can be used for this purpose in turbines as well as compressors.

According to the present invention in an axial flow, rotary gas compressor or turbine having a plurality of blade rings, there is provided an annular slot or an annular series of slots in a wall of the gas flow passage of the compressor or turbine on the upstream side of and adjacent a blade ring, and supply means for supplying the slot or slots with gas under pressure always greater than the pressure in the gas flow passage in the region of the slot or slots, the slot or slots being arranged to inject gas so supplied to them into the gas flow passage with a component of motion which is directed upstream against the main gas flow through the gas flow passage, to reduce the effective flow area of the gas flow passage in the region of the slot or slots and thereby to increase the velocity of the gas flow through the gas flow passage downstream of the slot or slots.

In the case of a compressor, the stalling or partial stalling of the early stage blading may, or may not precipitate full compressor surge, depending on the severity of the stall in the early stages. In cases where the early stage stall is sufficiently violent, the compressor is unable to operate with these stages in their stalled state over a certain range of r.p.m., and a "kink" in the surge line results, the surge line being that line on a plot of compression

ratio against mass gas flow at various constant rotational speeds which divides the area of the plot corresponding to possible operating conditions of the compressor from the area in which stable operation cannot take place. The existence of such a "kink" in the surge line has the disadvantage that the compressor has to be operated in general at a condition further from the surge line, and therefore at less efficiency, in order to avoid crossing the surge line at the "kink."

It has been observed that in most axial flow compressors stalling of the first ring of moving blades commences in zones spaced around the circumference of the ring at the tips of the blades, such zones moving around to produce what is known as a rotating stall pattern, and that compressors behaving in this way often exhibit the above described undesirable "kink" in their surge lines. On the other hand, the first moving blade rings of compressors having certain features of design, for example rather large blade tip clearances, tend to stall at the tips evenly all round the circumference of the blade ring, and it has been observed that with these compressors the "kink" in the surge line is much less marked.

Unfortunately the features of design which tend to produce this characteristic behaviour also usually tend to reduce the efficiency of the compressor at its designed speed.

According to a feature of the present invention, however, it has been found that by positioning said slot or slots immediately upstream of the blade tips of a rotor blade ring, the interference with the main gas flow caused by injection of the gas through said slot or slots promotes stalling at the blade tips of said rotor blade ring. By adopting this feature of the invention therefore circumferentially distributed tip stalling may be promoted in any moving blade ring of the compressor, and it has been found possible by this means to reduce the undesirable "kink" in the surge line of the compressor.

Three embodiments of the present invention will now be described, merely by way of example and with reference to the accompanying drawings, whereof

FIGURE 1 is a partial cross sectional elevation of one multi-stage axial flow rotary gas compressor according to the invention,

FIGURE 2 is a partial cross sectional elevation of another construction of multi-stage axial flow rotary gas compressor according to the invention, and

FIGURE 3 is a partial cross sectional elevation of yet another construction of multi-stage axial flow rotary gas compressor according to the invention.

Referring to FIGURE 1, the moving or rotor blades of the compressor, the first ring of which is indicated at **10**, are carried on a drum **11** mounted for rotation inside a stationary casing **12** which casing carries rings of stationary blades, the first ring **13** of which is in an annular air intake **14** of the compressor upstream of the first rotor blade ring, and forms an entry guide blade ring to the compressor, and the subsequent rings **15** of which are positioned alternately with the rotor blade rings in well known manner.

In the construction being described the longest blades of the compressor are at the entry end and are represented by the entry guide blades **13**, while the shortest blades are at the discharge end of the compressor, the blades being made progressively shorter from the entry to the discharge end.

According to the invention gas under pressure is tapped off from an intermediate stage of the compressor or from the compressor delivery and passed through conduit means, part of which is indicated at **19**, to an annular gallery **16** in the stationary casing **12**, the annular gallery surrounding the ring of entry guide blades **13**. The

gallery 16 communicates by a number of passages 17 with an annular slot 18 formed in the casing 12 immediately upstream of the blade tips of the blades of the first ring 10 of rotor blades. Instead of the annular slot 18 there may be provided an annular series of slots in the casing 12 immediately upstream of the ring 10.

The annular slot 18 may be of a nozzle formation and is arranged to inject the gas which is supplied to it with a component of motion which is directed upstream against the main gas flow through the gas flow passage of the compressor. In the example at present being described the slot 18 is arranged to inject gas at an angle of about 60° to a plane normal to the rotational axis of the rotor 11.

The flow of tapped-off gas supplied to the slot 18 through the conduit means is controlled by a valve (not shown) in the conduit means previously described and the flow of tapped off gas may amount to about 2% of the total gas flow through the compressor.

The flow control valve is preferably of the kind which closes progressively with increase of speed of the compressor and vice versa, although in the case where the compressor forms part of a gas turbine engine the valve may be made to close progressively with increase in the rate of delivery of fuel to the engine and vice versa.

Where the invention is applied to an axial flow rotary gas turbine as later described the valve is preferably of the kind which closes progressively with increase of speed of the turbine or again where the turbine forms part of the gas turbine engine with increase in the delivery of fuel to the engine.

In the example at present being described, assuming that there is no injection of gas from the slot 18, when the speed of the compressor is reduced sufficiently below the designed speed, there is a tendency for the gas flow in the main gas flow passage of the compressor to be reversed over the blade tips of the first rotor blade ring and to form vortices. As already stated however, this usually occurs in patches and a rotating pattern is formed.

By injecting gas through the slot 18 energy is added to the vortices adjacent the blade tips of the rotor blade ring 10 so that these vortices join up and become stabilised in the form of a single toroidal vortex. The injection effect ensures that all the blade tips in the first rotor blade ring are substantially encircled by the toroidal vortex and results in the development of a stalled zone of relatively uniform annular shape and this in turn results in a smooth transition to the fully stalled condition. In addition, the injected air creates a dead zone, occupied by the toroidal vortex, with the result that the effective cross-sectional area of the main gas flow passage of the compressor at the first rotor blade ring is reduced. By reducing the effective cross-sectional area of the main gas flow passage in this region the velocity of gas flow over the blades of the first rotor blade ring and the blade rings downstream of the first rotor blade ring is increased, and this has the effect of improving the effective matching of the inlet stages of the compressor with the rest of the compressor stages with the result that a wider flow range is possible before surging occurs.

In the example now being described therefore the present invention may be seen to operate in two ways

(*a*) by effectively improving the matching of the compressor stages at speeds below the designed speed and reducing the compressor capacity, thereby moving the surge line in the direction of lower flow, and

(*b*) by promoting and stabilising the partly stalled condition in the initial stage of the compressor, resulting in removal of the "kink" in the surge line.

With multi-stage axial flow rotary gas compressors and turbines gas may be injected into the main gas flow passage at more than one blade ring, but in the case of a compressor the best results appear to occur when the injection is made so as to promote the formation of blade tip vortices at the rotor blade ring having the longest blades as just described. It will be appreciated however that the operation of the invention as described at (*a*) above may be achieved by arranging an annular slot such as 18 on the upstream side of and adjacent the entry guide blades 13 so that injection of gas through the slot causes the effective cross-sectional area of the gas flow passage upstream of the entry guide blade ring to be reduced, and thereby the velocity of gas flow over the blading of the compressor to be increased. The slot is positioned within about a blade length of the guide blades, the blade length being that of the guide blades. An example of an arrangement in which a slot such as 18 is positioned on the upstream side and adjacent the entry guide blade ring of a compressor is later described with reference to FIGURES 2 and 3.

In the case where the injection of air is to take place immediately upstream of a rotor blade ring it is possible to apply the invention also or alternatively to the shortest rotor blades of the compressor described with reference to FIGURE 1 so that the tips of these blades are stalled at speeds of rotation of the compressor above the designed speed when the pressure rise per stage is greater than the design pressure rise. Such a case might arise where maximum efficiency of the compressor is designed to occur at partial loading.

Referring now to FIGURE 2 in which the same reference numerals are used to indicate parts already described with reference to FIGURE 1, there is provided in this case, as previously mentioned, an annular slot 20 formed in structure 21 defining the inner wall of the annular air intake 14 to the compressor. The structure 21 is formed with an annular gallery 22 which is communicated by conduit means part of which is shown at 23 with an intermediate stage or the delivery end of the compressor, valve means being provided in the conduit means which valve may be of the kind previously described.

The slot 20 which is of nozzle formation, is located on the upstream side of and adjacent the ring of entry guide blades 13, and is arranged to inject gas supplied to the gallery 22 into the air intake 14 of the compressor with a component of motion upstream against the main gas flow through the air intake, in the present example at an angle of about 60° to the rotational axis of the rotor 11.

As in the previous case the annular slot 20 may if desired be replaced by an annular series of slots, and the slot 20 is provided in addition to the slot 18 which is positioned as previously described.

During operation of the compressor at the speed below its designed speed the injection of gas through the slot 20 reduces the effective cross-sectional area of the annular air intake to the compressor in the region of the slot with the result that the velocity of gas flow over the blading of the compressor is increased, the matching of the compressor stages thereby being improved and the compressor capacity being reduced thereby moving the surge line in the direction of lower flow.

In the case of an axial-flow rotary gas compressor where a slot such as 20 as described with reference to FIGURE 2 only is provided, the slot may be formed in the outer casing structure on the upstream side of and adjacent the entry guide blades to the compressor. Such a construction is shown in FIGURE 3 to which reference will now be made. In this case an annular slot 24 having a nozzle formation is formed in the outer casing structure 25 of the compressor which outer casing structure supports a ring of entry guide blades 26 at the entry end of the compressor and also subsequent stator rings of the compressor stages in well known manner.

The slot 24 is supplied with gas from an annular gallery 30 formed in the outer casing structure, the gallery 30 being communicated with an intermediate stage or the delivery end of the compressor by conduit means (not

shown) the conduit means including a valve to control the flow of tapped off gas through the conduit means which valve may be of the kind hereinbefore described.

The slot **24** is, as before, arranged to inject gas with a component of motion which is directed upstream against the main gas flow through the air intake **27** to the compressor, in the present example at an angle of 60° to the axis of the compressor rotor.

In order further to increase the restriction of the effective cross-sectional area of the air intake of the compressor described with reference to FIGURE 3 by the injection of gas into the intake a further annular slot may be formed in the structure **31** defining the inner wall of the intake **27**, the slot in the structure **31** lying in the same radial plane as the slot **24**, and being arranged to inject gas supplied to it into the intake with a component of motion directed upstream as before, means being provided to supply the second slot with gas under pressure from an intermediate stage or the delivery end of the compressor.

The range over which the valve controlling the supply of gas to any particular slot or annular series of slots is arranged to be open depends on the position of the compressor operating line without gas injection through the slot in relation to the "kink" in the surge line of the compressor. The valve is arranged to open over that range of the operating line of the compressor without gas injection which approaches the "kink" in the surge line. This range may be an initial range or an intermediate range.

As previously indicated the present invention may be applied to an axial flow rotary gas turbine. Where the invention is applied to such a turbine it is preferred that the injection of gas into the main gas flow passage of the turbine be arranged to occur between a stator blade ring and the next downstream rotor blade ring. The gas to be injected is preferably tapped from the main gas flow passage of the turbine or a gas turbine engine of which the turbine forms a part and is, of course, injected at a pressure higher than that of the gas flow at the place of injection with a component of motion which is directed upstream against the main gas flow through the gas flow passage of the turbine. When the tapping is not feasible or desirable, gas may be taken from another source but must be injected under a sufficient pressure to deflect the main gas flow to the desired extent.

By injecting gas into the gas flow passage of an axial flow rotary gas turbine in the manner described, the effective cross-sectional area of the main gas flow passage of the turbine is reduced in the region at which the injection takes place, and the velocity of the gas flow over the turbine blading downstream of the region is increased. This has the effect of reducing the capacity of the turbine and may be used, for example, to improve the matching of a rotary axial flow gas turbine of a gas turbine engine with a compressor of the engine when the turbine is running at a speed below its designed speed.

In FIGURES 1 and 2 of the drawings, the resultant flow pattern of the gases is indicated at **14***a* and **18***a*. At **18***a* is indicated the fluid barrier set up by the gas injected into the gas flow passage **14** through the slot formation **18** and at **14***a* is indicated the resultant flow of gas through the passage **14** which is produced by the barrier **18***a*.

In FIGURE 3 of the drawings, the resultant flow pattern of the gases is indicated at **24***a* and **27***a*. At **24***a* is indicated the fluid barrier set up by the gas injected into the gas flow passage **27** through the slot formation **24** and at **27***a* is indicated the resultant flow of gas through the passage **27** which is produced by the barrier **24***a*.

In the drawings the blades have been shown as non-shrouded blades. The invention is however applicable to axial flow, rotary compressors and turbines having shrouded as well as non-shrouded blades.

I claim:

A rotary axial flow bladed power conversion machine comprising inner and outer walls defining an annular gas flow passage, and a plurality of blade rings contained in said passage, there being in one of said walls, immediately upstream of the leading edge of the blades of a rotor blade ring, an annular slot formation which is coaxial with said passage and has a discharge opening slanted in an upstream direction and transverse to the annular gas flow passage and which serves for injecting into said gas flow passage during operation of the machine gas having an upstream component of velocity greater than the downstream component of velocity of the gas in said gas flow passage and under sufficient pressure to substantially deflect the main gas flow, the slot formation being defined at least in part by bounding surfaces which have a directive effect on the injected gas, said surfaces directing the injected gas with a component of motion upstream in the gas flow passage whereby the effective flow area of the gas flow passage in the region of the slot formation is reduced and the velocity of the gas flow through the gas flow passage downstream of the slot formation and through the blade ring is increased.

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