This invention relates to high-pressure compressors whose rotors run with a peripheral speed higher than that of sound and whose blades have radially directed cross-sections in planes normal to the rotor axes to take the centrifugal forces without bending.

Since the rotors, and particularly the blades, of such high-pressure compressors are stressed to the maximum permissible limit under present practice, the rotors have been made with purely radial extension of both the blades and the flow. The blades and the disks connecting them have been shaped as bodies projecting from the hub with uniform resistance to centrifugal forces. The blade passages thereby end in the radial direction. In this way an outlet triangle of velocities is formed in which the absolute velocity of outlet of the compressed gas is greater than the peripheral speed of the blades, and therefore greater than the velocity of sound.

When the velocity of sound is reached, disturbances caused by Mach's pressure waves become observable and have a very detrimental effect on the efficiency of the compressor. It was therefore necessary in the described high-pressure compressors either to keep the peripheral speed of the rotor blades lower than the velocity of sound, being content with the lower pressures generated, or to accept the drawback of the disturbances which are abruptly introduced at a peripheral speed exceeding the velocity of sound.

According to the present invention, the blade passages are set to define a direction of flow obliquely warped with respect to the rotor axis, the blades being bent backwards to such an extent that the absolute velocity of the compressed medium at the outlet does not exceed the velocity of sound, at least not to that extent at which Mach's pressure waves are formed.

Since the height of the compression pressure of the product depends on the peripheral component of outlet speed and the peripheral speed of the rotor, and the peripheral speed of the rotor can be increased very considerably beyond the speed of sound (over 400 m./sec.) when all parts are set exactly radially and are given the appropriate shapes of this invention, a compression ratio of at least 2.0 can be reached by the invention in a single-stage machine without adversely affecting its overall efficiency.

The general semi-axial form of rotor resulting from the application of this invention has been previously known for slow-speed compressors in which the blades, consisting of sheet iron welded to the hub, are set in such a manner that their cross-sections at right angles to the axis of rotation are directed radially. In this way certain advantages were obtained for the machining of the plate and for the welding. However, for the phenomena of flow taking place far below the velocity of sound this general semi-axial shape is of no significance. It is only with the adoption in a semi-axial rotor of the specific shapes of this invention that, in compressors in which the peripheral speed of the blades exceeds the velocity of sound, the effect is obtained that the occurrence of Mach's pressure waves in connection with the velocity of sound is avoided and the efficiency is thereby improved.

In a semi-axial rotor formed according to the invention, intermediate blades may also be arranged or the blades may be discontinuous and staggered. In these ways a further improvement of the rotor efficiency may be obtained, in that they further avoid the increased risk of turbulence which occurs when the velocity of sound is exceeded.

The invention is explained in detail below with the help of the accompanying drawings, in which:

Fig. 1 shows in a simplified manner one example of execution of a high-pressure compressor according to the invention in longitudinal section;

Figs. 2 and 3 show the rotor of the high-pressure compressor according to Fig. 1 in plan and in cross-section;

Figs. 4 and 5 illustrate, in positions similar to Figs. 2 and 3, a rotor with intermediate blades;

Figs. 6 and 7 illustrate likewise a rotor with discontinuous and staggered blades; and

Figs. 8 and 9 are geometrical figures to illustrate the manner of deriving the blade curvature.

The compressor according to Fig. 1 has a rotor 1 with integral blades 2, made up from the solid, for instance by forging and milling, and arranged overhung on shaft 3. The air or other gas to be compressed is drawn in from the passage 4 and discharged in the compressed state through the spiral casing 5.

In service the blades 2 (Figs. 2 and 3) of the rotor 1 run with a peripheral speed which exceeds the velocity of sound at least at the outlet edges 6. In order to be able to withstand the elevated centrifugal forces thus produced without bending, the blades 2 are made in such a way that all sections lying at right angles to the axis of the rotor e. g. I—I, II—II, III—III, extend exactly in a radial direction, e. g. in the direction of the radii
The sections taken on the lines I—I, II—II, III—III of Fig. 3 give the plane blade sections marked I, II and II, respectively, in Fig. 2.

The direction of flow in the passages between the blades is not radial but is inclined with respect to the rotor axis X in the direction of the arrow 7. Because of this, it is possible to so bend the blades backwards with respect to the direction of rotation 8, that the absolute velocity of the compressed medium at the outlet does not exceed the velocity of sound.

The shape which the middle surface of the blade then assumes is one of a screw surface with a pitch either constant or changeable along the rotor, one requirement being that the middle line of the blade shall be curved backwards with respect to the directions of the flow and the rotation. By "middle line of the blade" is to be understood a line drawn on the middle surface of the blade in the middle between the inner limit of the blade at the hub and the outer limit of the blade, this line consequently running in the direction of the flow, i.e. somewhat like the arrow 7 in Fig. 2.

This shape results, at service rotation speeds, in which the blade tip speed exceeds the velocity of sound, in an outlet angle for the blades (with relation to the peripheral direction) whose cosine is greater than the ratio of the relative velocity of the medium to twice the peripheral velocity of the blade tip. In order to show how a screw line of constant or variable pitch and of constant or variable diameter may be employed to define the middle line of the blade on an actual rotor, reference is made to Figs. 8 and 9, which apply common geometrical construction methods to a rotor of this invention:

The middle lines of the blades of the rotors illustrated in Figs. 1–7 lie on a surface of revolution, whose axis of revolution is identical with the axis of rotation X of the rotor. A cone tangential to this surface in the radius r is drawn in Fig. 8. It is tangential to one of the blade middle lines at the point A and has, as half apex angle, the angle γ (gamma). In cylindrical coordinates the locus of the point A is defined by the point of intersection F in which the transverse plane—containing the point A and situated at a right angle to the axis of rotation X—cuts the axis of rotation, further by the radius r and finally by the angle which the meridian plane containing the radius r makes with a meridian plane chosen as initial plane.

Now, if the transverse plane is displaced by the differential value dx in the X direction, the radius r turns through the differential angle value \( \frac{\Delta}{2\pi} \) (d alpha) and thereby generates a small part of the screw surface through which the middle surface of the blade is formed.

If this screw surface were continued with a constant pitch and cut with a coaxial cylindrical surface, the ordinary screw-line, drawn dashed in Fig. 8, would be obtained. If it were cut with the conical surface drawn in Fig. 8, the conical screw line of constant pitch would be obtained; it is drawn solid. If the transverse plane is moved further in the X direction through the distance r/2, not only the screw surface has completed a half turn, but the same holds good for the ordinary screw line, and for the conical screw line as it is shown in the drawing, whereby s defines itself as the screw pitch prevailing at the point A of the middle line of the blade, which middle line is not drawn in Fig. 8.

Thus the differential equation of the screw surface,

\[ ds = s \frac{da}{2\pi} \]

is obtained, in which s may be variable in the z direction and r does not appear, since r has the value AF only for the point A, but, for all parts of the screw surface that lie outside the point A, remains still free to be chosen as desired.

The middle line of the blade lies on this screw surface thus defined which forms the middle surface of the blade, and it now remains to investigate what relations must exist between the pitch s, the radius r of the middle line of the blade and the angle γ as half apex angle of the cone touching this middle line, in order that this middle line may have the required backwards curvature. For this purpose, in Fig. 8 at the point A on the conical screw line shown non-dotted, and thus also on the middle line of the blade not shown there, the tangent AD is drawn, the length AD being considered to be infinitely small, so that the perpendicular dropped from the point D on to the meridian plane passing through A represents the tangent at the point A to the parallel-circle passing through A. This tangent DB consequently represents the direction of the peripheral velocity at the point A, while the tangent AD represents the direction of the middle line of the blade and therefore the direction of the relative velocity of the delivered medium led along both sides of the blade. These two tangents include the angle \( \beta \) (beta) (see Fig. 9). AB is the generating line of the cone, AC the generating line of the cylinder, and the angle BAC is therefore the angle γ as half apex angle of the cone. AE is the tangent at the point A to the cylindrical screw line, drawn in broken lines. BCED is a rectangle, and the angles BCA and DEA are right angles. The angle CEA is marked \( \beta' \). From Fig. 9 the following trigonometrical relations are obtained:

\[ \tan \beta = \frac{AB}{BD} \]
\[ \tan \beta' = \frac{AC}{CB} = \frac{AC}{BD}, \quad \cos \gamma = \frac{AC}{BD} \]

If the cylinder is developed in a plane, the following relations are obtained:

\[ \tan \beta' = \frac{s}{2\pi r} \]
where \( r \) = radius of the cylinder.

Substituting this relation into the formula

\[ \tan \beta' = \tan \beta \cos \gamma \]

we have

\[ \tan \beta = \frac{s}{2\pi r \cos \gamma} \]

Backwards curving of the middle line of the blade requires that the angle \( \beta \) must continually diminish with displacement in the X direction. Consequently, if the indices 1 and 2 signify two transverse planes of the rotor, such that with displacement in the X direction the transverse
plane is passed through before the transverse plane, the requirement must be fulfilled that
\[ \beta_2 < \beta_1 \text{ or that } \tan \beta_2 < \tan \beta_1 \]
Consequently also the following relations hold good:
\[ \frac{s_2}{s_1} \frac{1}{2 \pi \theta_2 \cos \gamma_2} < \frac{s_1}{s_2} \frac{1}{2 \pi \theta_1 \cos \gamma_1} \]
from which we finally have:
\[ \frac{s_1 r_2 \cos \gamma_2}{s_2 r_1 \cos \gamma_1} > 1 \]
If the pitch of the blade is kept constant,
\[ \frac{s_2}{s_1} = 1 \]
and the formula:
\[ \frac{r_2 \cos \gamma_1}{r_1 \cos \gamma_1} > 1 \]
is obtained.

If on the other hand, the rotor is conical, i.e. the angle \( \gamma \) is constant, the form of the equation:
\[ \frac{s_1}{s_2} \frac{1}{\theta_2} > 1 \]
is obtained.

This backwards bending makes it possible to have a compression ratio of more than 2.0 within a single stage, without having to put up with disturbances through Mach's pressure waves, which occur in the region above the velocity of sound.

The rotor according to Figs. 4 and 5 has additional intermediate blades 9 arranged between the main blades 2; the intermediate blades give a better guiding to the flow of the medium which is to be compressed, and thereby prevent, within the flow passages, a non-uniform distribution of the medium which is to be compressed.

The rotor according to Figs. 6 and 7 has blades 10 which are interrupted at the spaces 11 and are continued in staggered arrangement. In this way turbulence, which could very well occur at the high speeds used, is prevented.

It is possible under certain conditions of working to let the velocity of flow of the compressed medium increase slightly beyond the velocity of sound without any disturbances being caused by Mach's pressure waves.

I claim:

1. A rotor for a centrifugal gas compressor to be operated at peripheral velocities above the speed of sound for fitted rotation about an axis, one end of said rotor being of smaller diameter than the other, the outer surface of said rotor having longitudinally-extending channels obliquely warped with respect to the rotor axis arranged to receive gas to be compressed at the smaller end of said rotor and to discharge compressed gas at the larger end of said rotor, said channels being defined in part by blades which have radially extending cross-sections and in the flow direction curve backwards from the direction of rotation to form angles to planes of revolution at right angles to the rotor axis decreasing toward the larger end of said rotor, the middle lines of said blades forming a surface of revolution, the middle surfaces of said blades conforming substantially to a surface having the equation:
\[ dz = \frac{s \cdot da}{2 \pi} \]
and the dimensions of the rotor being such that
\[ \frac{s_1 r_2 \cos \gamma_2}{s_2 r_1 \cos \gamma_1} > 1 \]
in which \( dz \) is a distance along the rotor axis toward said larger end, \( s \) is the lead or pitch, \( dz \) is the angle through which the blade surface has turned in distance \( dx \), \( r \) is the radius, \( \gamma \) is the half apex angle of the cone tangent the surface of revolution formed by the blade middle lines at any plane of revolution, and the subscripts 1 and 2 designate any successive planes of revolution taken along the rotor axis toward said larger end.

2. A rotor as claimed in claim 1, the blades of which have constant pitch such that:
\[ \frac{s_2 r_2 \cos \gamma_1}{s_1 r_1 \cos \gamma_1} > 1 \]

3. A rotor as claimed in claim 1, the rotor body of which is formed as a cone such that:
\[ \frac{s_1 r_2 \cos \gamma_1}{s_2 r_1 \cos \gamma_1} > 1 \]

4. A rotor as claimed in claim 1 in which the blades extend from substantially the small end of the rotor to substantially the large end of the rotor.

5. A rotor as claimed in claim 1 in which the blades which define in part the longitudinally-extending peripheral passages of the rotor are discontinuous and staggered.

WALTER KILKENNANN.

REFERENCES CITED

The following references are of record in the file of this patent:

UNITED STATES PATENTS

<table>
<thead>
<tr>
<th>Number</th>
<th>Name</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>991,134</td>
<td>Capell</td>
<td>May 2, 1911</td>
</tr>
<tr>
<td>1,029,554</td>
<td>Neumayer</td>
<td>June 11, 1912</td>
</tr>
<tr>
<td>1,717,694</td>
<td>Kraut</td>
<td>June 13, 1929</td>
</tr>
<tr>
<td>1,838,126</td>
<td>Sperry</td>
<td>Dec. 29, 1931</td>
</tr>
<tr>
<td>1,959,703</td>
<td>Birman</td>
<td>May 22, 1934</td>
</tr>
<tr>
<td>2,407,469</td>
<td>Birman</td>
<td>Sept. 10, 1946</td>
</tr>
</tbody>
</table>