

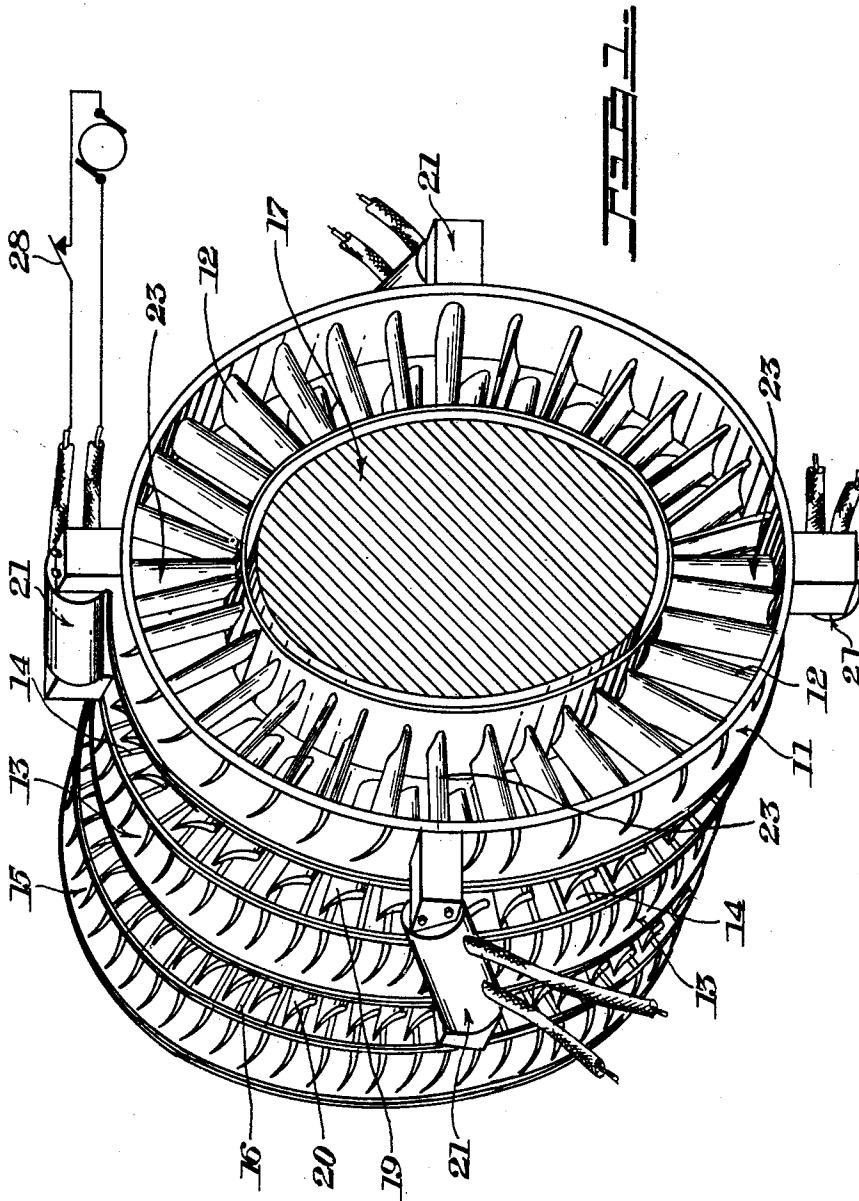
Feb. 1, 1955

D. G. HENSHAW  
ROTARY COMPRESSOR

2,701,092

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3 Sheets-Sheet 1



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FIG. 2.

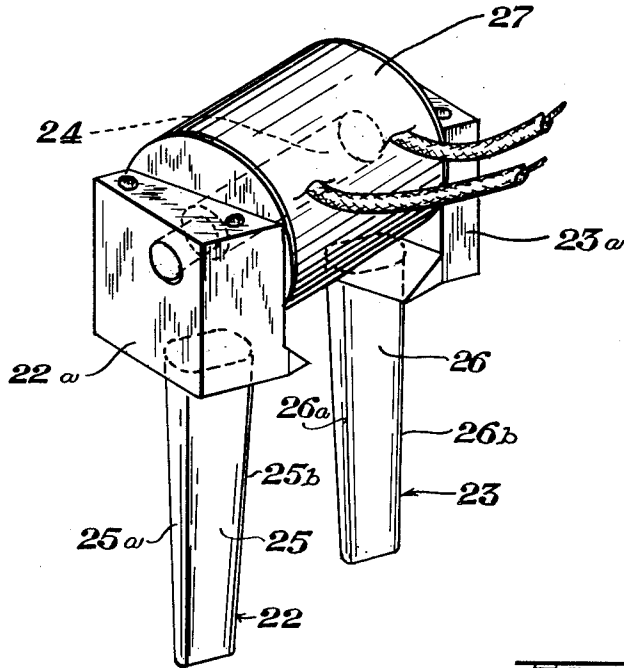
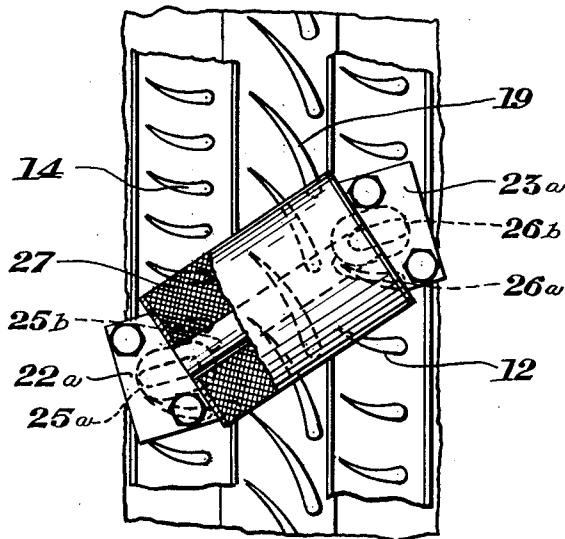


FIG. 3.



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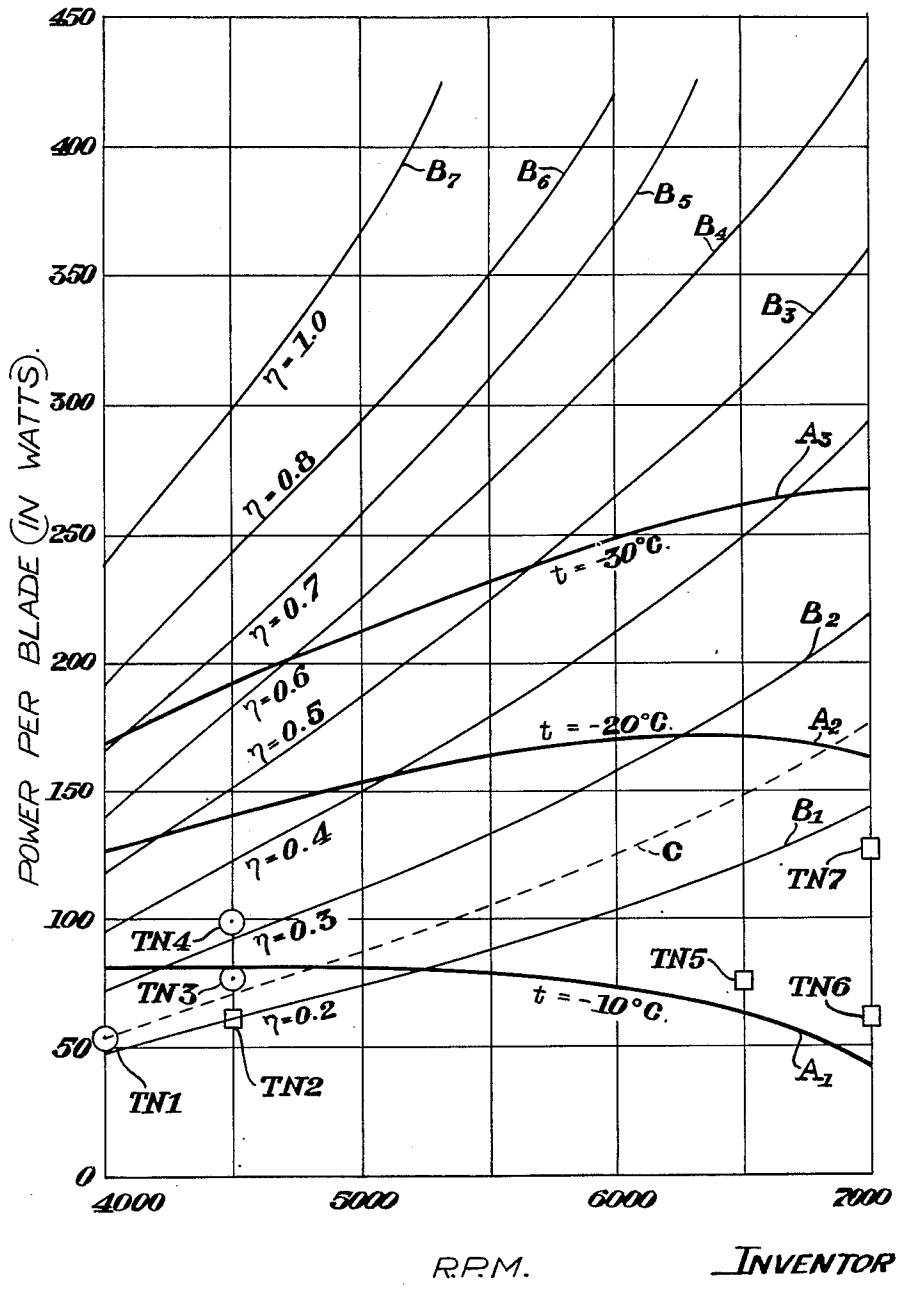
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FIG. 4



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## ROTARY COMPRESSOR

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Claims priority, application Great Britain  
October 25, 1949

2 Claims. (Cl. 230—122)

This invention is for improvements in or relating to rotary compressors and is concerned, more particularly, with high speed multi-stage axial flow compressors of the kind employed in gas turbine and/or jet propulsion engines, and with anti- and de-icing means therefor.

It has been determined that under atmospheric icing conditions the initial compression stages of high speed axial flow compressors of the kind referred to are liable to accumulate ice. Such accretions of ice may produce hazardous operating conditions and, by decreasing the efficiency of the compressor and engine may result in mechanical damage to the compressor blading and may also tend to set up dangerous vibration from out-of-balance loading of the rotor.

An object of the present invention is to provide in a rotary compressor, anti- and de-icing means which is essentially simple in construction, easy to maintain and which is readily adjustable to an operative or to an inoperative condition, as may instantly be required.

By the expression "anti- and de-icing means" as herein employed is to be understood means which is effective both to prevent the formation of ice upon the rotor blades and to permit the removal of ice after its formation.

According to the invention, in a rotary compressor comprising a stator structure including guide and stator vanes arranged in rings separated by a narrow gap and a bladed rotor mounted for rotation in the gap, there is provided electro-magnetic anti- and de-icing means comprising a pair of magnetisable pole-pieces extending radially one in each of the guide and stator vane rings, a magnetisable yoke bridging outer ends of the pole-pieces, an energising winding about the yoke whereby to provide an energisable magnetic circuit which extends through the yoke and pole-pieces and across the gap therebetween and electrically-conductive rotor blading in the gap.

More particularly, the invention includes in a multi-stage axial flow rotary compressor including a stator structure having a guide vane ring, a plurality of stator vane rings, the guide and stator vane rings being separated by narrow gaps, and a bladed rotor mounted for rotation in the gaps, electro-magnetic anti- and de-icing means comprising a pair of magnetisable pole-pieces extending radially one in each of contiguous rings of the stator structure, a magnetisable yoke bridging outer ends of the pole-pieces, an energising winding about the yoke whereby to provide an energisable magnetic circuit which extends through the yoke and pole-pieces and across the gap therebetween and electrically conductive rotor blading in the gap intermediate the said contiguous rings.

Upon energising the electro-magnetic circuit in the foregoing arrangements, a magnetic field is created which extends across the air gap between the pole-pieces. Upon rotation of the rotor, the electrically conductive rotor blades continually cut the magnetic field so that the rotor blades are thereby subjected to a continual fluctuation in magnetic field intensity. Eddy currents are thereby induced in the rotor blades and heat is produced which can be arranged to be sufficient to maintain the rotor blades at such a temperature as will keep the rotor blades clear of ice accretions. Energisation of the electro-magnetic circuit will, of course, impose drag in the compressor proportional to the energising current but, nevertheless, under non-icing conditions the magnetic circuit may readily be de-energised and the compressor there-

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upon subject only to such slight drag from the magnetic circuit as may arise from residual magnetic flux therein.

For reasons referred to hereinafter, it is preferred that the rotor blades be made of a non-magnetic material.

Optimum heating efficiency requires that the magnetic field be at right angles to the rotor blades and it is accordingly a feature of the invention so to arrange the pole-pieces that the magnetic field therebetween crosses the rotor blades approximately at right angles to the chord of the blades passing between the pole-pieces.

In a preferred embodiment of the invention, a plurality of magnetic circuits as set forth above are arranged circumferentially about the stator in approximate equidistant spacing as may be permitted by the physical disposition of other components of the compressor.

In a multi-stage axial-flow compressor, it may not be sufficient to heat only the rotor blades working between the guide and first stator vane ring or between the first and second stator rings; two or more magnetic circuits as set forth above may, therefore, be arranged axially of the stator, for example bridging the guide and first stator vane ring, and bridging the first and second stator vane rings, and so on. Generally, however, it should be found sufficient to employ the magnetic circuits only in the first two or three stages of the compressor. The preceding arrangement is preferably used in combination with further magnetic circuits disposed circumferentially about the stator in approximate equidistant spacing therearound.

A specific embodiment of the invention applied to a multi-stage axial-flow compressor will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 is a fragmentary diagrammatic perspective view of the initial stages of an axial flow compressor, including anti- and de-icing means pursuant to the invention.

Figure 2 is a perspective view of the anti- and de-icing means,

Figure 3 is a diagrammatic top plan view showing the general direction of the magnetic flux in relation to the angle of pitch and rotational direction of the rotor blades, and

Figure 4 is a graph showing certain calculated and experimentally-determined results employing the anti-icing means of Figure 2.

Referring to Figure 1, the multi-stage compressor comprises a fixed guide vane ring assembly 11 having radially directed guide vanes 12 spaced about the ring, a fixed first stator vane ring assembly 13 having radial spaced stator vanes 14 and a fixed second stator vane ring assembly 15 with radial spaced stator vanes 16. The compressor is of conventional construction and is to be understood as having a plurality of stator rings, of which only the first two are illustrated, the various vane ring assemblies being mounted within a fixed outer casing, not shown. The ring assemblies are, as usual, disposed in spaced parallel planes and are arranged concentrically about a rotor assembly, indicated generally at 17, contiguous rings of vanes such as 11, 13 and 15 being separated each by an annular air space or gap encircling the rotor assembly. Annular arrays of radially disposed rotor blades 19, 20 work within the annular air gaps and upon rotation of the rotor, impel air from an inlet position at the right of the device and force it under compression through the labyrinth of vanes axially of the compressor to an outlet position at the left of the device.

The anti- and de-icing means in accordance with the invention comprises an electro-magnetic unit indicated by the general reference 21. The construction of the unit appears more clearly in Figure 2 and will be seen to consist of a U-shaped electro-magnet having similar blade-like legs indicated by the general references 22 and 23, constituting pole-pieces, which extend rigidly at right angles from cheeks 22a and 23a which are rigidly secured to the ends of a yoke bar 24. The pole-pieces 22 and 23 are formed with substantially flat opposite faces 25 and 26 respectively, which merge into rounded fore-and-aft edges 25a, 25b and 26a, 26b. The pole faces 25 and 26 lie in substantially parallel planes athwart a

general plane containing the pole-pieces. A multiple-wound energising coil 27 surrounds the yoke 24 between the cheeks 22a, 23a and is connectable to a direct current source through a switch 28 (Figure 1).

In the present embodiment of the invention, four magnetic units 21 are disposed in equidistant spacing circumferentially about the compressor as shown in Figure 1. The units are secured to the compressor casing by bolts passing through the cheeks 22a, 23a, the yokes 24 lying outside the compressor casing so as to bridge the internal annular air gap between the guide and first stator vane rings. The pole-pieces 22 and 23 extend radially into the first stator and the guide vane rings each pole-piece 23 being fitted in the guide vane ring in position between adjacent guide vanes or occupying a position which otherwise would be taken up by a guide vane so necessitating the removal or displacement of an adjacent guide vane. The pole-pieces 22 are similarly fitted in the first stator vane ring. Preferably, the energising coils of the magnetic units are so connected that the polarity of the magnetic units reverses from one unit to the next in the circumferential direction of the rings.

The arrangement of the pole-pieces 23 and 22 in the guide and stator rings is shown more clearly in Figure 3 from which the pole-pieces may be seen to be staggered in the rings and to be separated in a circumferential direction by a distance predetermined in relation to the angle or pitch of the rotor blades which is such as to ensure that the magnetic field between the adjacent edges 25b and 26a of the pole-pieces crosses the axis of the rotor so as to intersect the rotor blades 19 passing between the pole-pieces approximately at right angles to the chord of the blades 19 when positioned in the gap between the pole-pieces.

Upon energising the electro-magnetic units, magnetic fields are set up in circuits which, in each unit, extend between the pole-pieces 22, 23 across the annular air gap intermediate the guide and first stator vane rings and are completed externally of the compressor casing through the yokes 24. At least those rotor blades working between the guide and first stator vane rings are electrically conductive and may be made either of a non-magnetic material, such as a high tensile aluminium alloy, for example of the "Dural" type or the more recent "75S" types, or austenitic steel, or of a magnetic material, such as mild steel or high tensile steel. It is preferred to use a non-magnetic material for these blades to minimise magnetic skin effect in the blades so securing better uniformity of heating, and also to reduce residual magnetic drag when the magnetic units are de-energised.

Upon rotation of the rotor, the rotor blades 19 cut the magnetic field of each magnetic circuit approximately at right angles to their chord so that, in a complete cycle of rotation, each blade 19 in the first compressor stage experiences four electro-magnetic linkages with the magnetic fields which, in the preferred arrangement also change direction in passing from one unit to the next. Eddy currents are thereby induced in the blades 19 which generate heat in the blades and maintain the blades at a temperature, depending upon the energising current in the electro-magnetic units, which may be arranged to be sufficient to keep the blades in an ice-free condition.

Experimental tests have been made with an installation, as described above, applied in a Jumo 004 jet-engine. Four electromagnetic units were installed at quarter points around the compressor, one pole-piece of each magnet being disposed in the guide vane ring and the other pole-piece in the first stator ring and otherwise arranged as shown in Figure 3.

The electro-magnetic units were designed having regard to calculated power requirements for anti-icing protection of the rotor blade at various revolutions per minute and ambient air conditions. In these calculations certain assumptions were made as follows:

(a) The rotor blades should be maintained at +5° C. in order to prevent icing. This value was chosen to allow for a factor of safety and also to allow for any unevenness in heating.

(b) The kinetic heating was assumed to be constant over the blade.

(c) The blade was assumed to be completely wetted and the total area of the rotor was taken as the area from which evaporation took place.

(d) The free water concentration was assumed to be 1 gram per cubic meter under all temperature conditions.

(e) The water caught by the rotor blades was assumed to be the ratio of the area swept out by the rotor blades to the total inlet area times the total water entering the compressor.

For a sinusoidally varying magnetic field, it may be shown that the power produced in a cylinder with its axis along the axis of the magnetic field is equal to:

$$P = \frac{t}{16} \cdot \frac{1}{10} \cdot 16 \cdot H^2 \cdot \rho \cdot \omega^2 \cdot r^4 \quad (1)$$

where

P=power in watts

t=thickness of cylinder in cms.

$\rho$ =resistivity in ohm cms.

H=magnetic field

$\omega$ =frequency in radians/sec.

r=radius of cylinder in cms.

The derivation of Equation 1 was based on the following assumptions:

(i) That the field strength H is a function of the radius only and not of the length,

(ii) That H is a periodic function of the form,

$$H = H \cdot \max. \cos \omega T.$$

(iii) That the material is non-magnetic, i. e.  $\mu=1$ .

However, for the blades of a jet engine the power produced in a rotor blade will differ from that given in Equation 1 by a multiplicative constant " $\eta$ " which will be dependent only on the geometry of the compressor. This constant may be termed the induction efficiency and must be found experimentally. The power produced per blade may, therefore, be re-written as:

$$P = \eta \cdot \frac{t}{16} \cdot \frac{1}{10} \cdot 16 \cdot H^2 \cdot \rho \cdot \omega^2 \cdot r^4 \quad (2)$$

The value of the "induction efficiency" for the Jumo 004 jet-engine was not known and as a starting point was assumed to be 1 and a factor of safety used. The required magnetic field calculated using Equation 2 for the worst design conditions were found to be 530 Gauss based upon the following data:

P=170 watts

t=0.144 inch (average thickness)

$\omega = 2 \times \frac{2 \times 4000}{60}$  radians/sec.

r=1.95 inches (chord of rotor blades)

$\rho = 5 \times 10^{-6}$  ohm cms.

The electro-magnetic units were made of Birmingham soft iron (the best available substitute for Swedish iron) and were wound with approximately 1250 turns of No. 19 magnet wire. When energised at 5 amperes and 24 volts, the magnetic field measured at three points along the pole-pieces was found not to be uniform over the length of the magnet owing to installation difficulties, but yielded an average value of 600 Gauss.

The value of  $\eta$  was determined approximately by running at various revolutions per minutes (R. P. M.) under different temperature conditions and by observing when the rotor blades were maintained free of ice.

The test procedure was as follows:

The Jumo jet-engine with ducting in place was started and idled at 3000 R. P. M. until warmed up. During this time, temperature conditions became steady. The R. P. M. were then adjusted to the test R. P. M. and maintained at this speed for 3 minutes. Power and temperature readings were recorded at the end of the 3 minute periods. Water was then sprayed into the air intake through spray nozzles of the air/water type in an amount of approximately 1 gram/cubic meter of air for periods varying from 2 to 5 minutes during which time the various components iced up. The engine was then stopped, the ducting was removed and the rotor icing inspected.

Sixty-eight test runs were carried out including, for comparison purposes, a datum run (electro-magnets de-energised) and a power run (electro-magnets energised) for each test condition. For a successful anti-icing run,

it was postulated that the rotor blades must have been iced for the datum run and clear for the power run.

The results of those tests where anti- or de-icing properties noted, are recorded in the following table:

Table of test results

Test No.	Run No.	R. P. M.	Magnet Current, Amperes	Inlet Air Temp. (° C.)	Observations	Rating
1	33	4,000	0	-5.6	1/16" ice on leading edge, ice on pressure face.	Power not sufficient for complete clearance.
	34	4,000	5	-7.25	Very few blades with ice shedding apparent.	
	35	4,000	0	-7.75	1/16" ice on leading edge, ice on pressure face.	
	36	4,500	0	-7.8	1/16" ice on leading edge, ice on pressure face and trailing edge.	
2	37	4,500	5	-8.4	No ice on blades—blades wet.	Power sufficient for complete clearance.
	38	4,500	0	-8.4	1/8" ice on leading edge, ice on pressure face and trailing edge.	
3	48	4,500	0	-9.5	3/8"-1/16" ice on leading edge, ice on pressure face.	Power not sufficient for complete clearance.
	49	4,500	5	-9.5	Very light icing, tips of leading edge clear.	
4	23	4,500	0	-13.9	1/8" ice on leading edge, ice on pressure face.	Do.
	24	4,500	5	-13.3	Very few blades with ice.	
5	25	4,500	0	-13.3	1/8" ice on leading edge, ice on pressure face.	Power sufficient for complete clearance.
	59	6,500	0	-11.1	1/16" ice on leading edge, ice on pressure face spotty.	
	60	6,500	5	-11.1	No ice on blades—blades wet.	
6	57	7,000	0	-11.6	1/32" ice on leading edge and trailing edge.	Do.
	58	7,000	5	-11.1	No ice on blades—blades wet.	
7	53	7,000	0	-16.6	1/32" ice on leading and trailing edge.	Do.
	54	7,000	5	-17.7	No ice on blades—perhaps spot here and there.	
	55	7,000	0	-17.7	1/32" ice on leading and trailing edge.	

The above results may be divided into two classes, namely:

Class 1, including all those tests where the power developed was sufficient for anti-icing purposes, i. e. Test Nos. 2, 5, 6 and 7 of the above table, and

Class 2, all those tests where the power produced was insufficient for complete anti-icing but was sufficient for shedding or partial anti-icing, i. e. Test Nos. 1, 3, and 4.

To evaluate the efficiency of the apparatus, a plot was made as shown in Figure 4, of the calculated power required for icing prevention, namely, curves A<sub>1</sub>, A<sub>2</sub> and A<sub>3</sub> plotted for constant air inlet temperatures of -10° C., -20° C. and -30° C. respectively, and of the power produced as determined theoretically from Equation 2 for various values of  $\eta$ , namely, curves B<sub>1</sub> to B<sub>7</sub> for values of  $\eta=0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8$  and  $1.0$ , respectively.

For a given value of  $\eta$ , anti-icing protection should be afforded for all points on the graph to the right of the related theoretical produced power curve B<sub>1</sub> to B<sub>7</sub>. Thus, if any particular calculated power requirement curve A<sub>1</sub>, A<sub>2</sub> or A<sub>3</sub> lies to the right and below any particular power produced curve B<sub>1</sub> to B<sub>7</sub>, then icing protection should be afforded at the temperature conditions of the calculated power requirement curve, whereas if the particular curve A lies above and to the left of the selected curve B, then no protection should be afforded.

The test results given in the foregoing table are also plotted in Figure 4 as square points TN<sub>2</sub>, TN<sub>5</sub>, TN<sub>6</sub> and TN<sub>7</sub> related, respectively, to Test Nos. 2, 5, 6 and 7 of class 1 and as circular points TN<sub>1</sub>, TN<sub>3</sub> and TN<sub>4</sub> related, respectively, to the Test Nos. 1, 3 and 4 of class 2. A dotted-line curve C separating the two groups of points for classes 1 and 2 is also shown. Curve C accordingly represents the approximate division line between successful anti-icing and incomplete anti-icing in the above tests. Curve C should have the same shape as the theoretical produced power curves B<sub>1</sub>, B<sub>2</sub>, and B<sub>3</sub> and its position in relation to those curves should determine the efficiency factor  $\eta$  for the electro-magnetic units employed. The value of  $\eta$  so determined will be seen to be approximately 0.23.

From Figure 4 it may be concluded that, for the jet-engine employed, an efficiency factor  $\eta=0.7$  is required

to provide anti-icing protection for temperatures down to -30° C. and for R. P. M. greater than 4000. The electro-magnetic unit described above may be considered for the purpose of comparison, as having an efficiency

factor of 0.23 which is adequate in the above arrangement to provide icing protection down to approximately -6° C. at 4000 R. P. M. and down to approximately -20° C. at a little below 7000 R. P. M.

While the foregoing tests did not, under all atmospheric and power operating conditions, show completely satisfactory anti- and de-icing of the compressor of the Jumo 004 jet engine, they nevertheless illustrate that complete protection may be achieved with any particular compressor by applying the above theoretical considerations in the preliminary design of the electro-magnetic units and by thereafter making an initial experimental determination of the efficiency factor  $\eta$ , as described. For example, it is apparent from the foregoing that the icing protection of the Jumo 004 compressor could be enhanced by increasing the field strength of the electro-magnetic units. For complete protection of the Jumo 004 compressor down to air inlet temperature of -30° C., the  $\eta$  value must be raised from 0.23 to 0.7 which requires that the field strength should be increased from 600 Gauss to a value of

$$\left(\frac{0.7}{0.23}\right)^{\frac{1}{2}} \cdot 600 = 1025 \text{ Gauss}$$

This field strength value may be attained by increasing the section of the magnetic material, by using a material of higher permeability and by increasing the ampere-turns of the energising coil. Alternatively, or in addition, the number of electro-magnetic units may also be increased so, in effect, to raise the  $\eta$  value. If four more units be added then the  $\eta$  value will in effect rise from 0.23 to 0.92 which, in the engine considered, will supply protection under all atmospheric conditions likely to be encountered in practice.

Icing of the rotor blades of jet engines is generally most severe in the compression stage immediately following the guide ring. The phenomenon may, however, extend also to later stages of the compressor and while in the foregoing specific embodiment of the invention the electro-magnetic units have been described only as applied to the first compression stage, it should nevertheless be understood that anti-icing protection may simi-

larly be applied to one or more later stages of the compressor.

In order that the aero-dynamic flow conditions in the compressor be disturbed as little as possible by the presence of the anti- and de-icing means, the pole-pieces of the electro-magnetic units are preferably shaped as nearly as possible like the guide or stator vanes in the ring in which they are fitted.

In an arrangement employing a plurality of electro-magnetic units in two or more stages of and spaced circumferentially about the compressor, the units are preferably located in approximately the same circumferential positions in successive stages so to provide units in successive stages in approximate alignment with the axis of the compressor. The energising coils of the units are then preferably connected so that like magnetic poles of adjacent units in successive stages are located together in the same stator ring.

While the invention has been described with reference to the use of a direct current power source for energising the electro-magnetic units it should be understood that an alternating current source may alternatively be employed, preferably of a high frequency, such as 400 cycles per second.

What I claim as my invention is:

1. In a multi-stage axial flow rotary compressor including a stator structure having a guide vane ring, an adjacent stator vane ring, the guide vane ring and the adjacent stator vane ring being separated by a narrow gap, and a rotor carrying electrically conductive rotor blading, said blading being disposed for rotation in said gap and being arranged at an angle with respect to the rotor axis; electromagnetic anti- and de-icing means compris-

ing a pair of magnetizable pole-pieces, one of said pole-pieces extending radially into said guide vane ring and the other extending radially into said adjacent stator vane ring, a magnetizable yoke bridging the outer ends of the pole-pieces, an energising winding about the yoke whereby to provide an energisable magnetic circuit which extends through the yoke and pole-pieces and across said narrow gap, said electrically conductive rotor blading being formed from non-magnetic metallic material, said pole-pieces being staggered circumferentially with respect to each other and being separated circumferentially of the stator by a distance so related to the angle of pitch of the rotor blading that a magnetic field between the pole-pieces in the circuit across the gap extends approximately at right angles to the chord of the rotor blading when positioned between the pole-pieces.

2. In a rotary compressor as defined in claim 1, a plurality of said electro-magnetic means disposed circumferentially about said stator structure in approximately equidistant spacing therearound.

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