The vortex tube has no moving parts and its simplicity makes it an attractive form of refrigerator when a source of compressed air is available. The drawback is that this device has a low efficiency.

The proposed application involves passing compressed air, from a jet engine, through a precooler and a vortex tube to the ventilated suit.

Investigations show that the temperature of the air entering the ventilated suit is decreased as engine compression ratio and precooler efficiency are increased.

Increase of the aircraft's forward speed will result in decreased cooling until a maximum Mach number is reached above which the ventilated suit cooling requirement, of 115°F, can no longer be satisfied.

The maximum permissible Mach number, for an aircraft flying at sea level under the maximum ambient tropical temperature of 85°C, has been calculated over a range of compression ratios, 3 - 15 and precooler efficiencies, 75 - 100 per cent. These results are plotted in figures 6 and 7.

It is found that a practical application requires a precooler efficiency of not less than 80 per cent.

The maximum permissible Mach numbers for a precooler of 90 per cent efficiency are tabulated below.

<table>
<thead>
<tr>
<th>Compression Ratio</th>
<th>5</th>
<th>7.5</th>
<th>10</th>
<th>12.5</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Mach No.</td>
<td>.64</td>
<td>.75</td>
<td>.85</td>
<td>.93</td>
<td>.99</td>
</tr>
</tbody>
</table>

It should be stressed that the above results apply only to the original form of the Hilsch vortex tube. It is hoped that revised forms of the tube will prove to have superior characteristics.
INDEX

1.0 NOTATION
   1.1 Vortex Tube Notation
   1.2 Jet Engine Notation

2.0 INTRODUCTION
   2.1 The Vortex Tube
   2.2 Application of the Vortex Tube

3.0 LAYOUT OF COOLING SYSTEM
   3.1 Compressor
   3.2 Precooler
   3.3 Vortex Tube and Ventilated Suit
   3.4 Control of Cooling to Ventilated Suit

4.0 VOXRET TUBE PERFORMANCE
   4.1 Choice of performance data
   4.2 Typical performance of vortex tube
   4.3 Performance of Hilsch Tube at Max. Temperature drop

5.0 VENTILATED SUIT REQUIREMENTS

6.0 PRELIMINARY CALCULATION ON THE COOLING SYSTEM
   6.1 Assumptions
   6.2 Calculations
   6.3 Preliminary Conclusions

7.0 GENERAL CALCULATION ON THE COOLING SYSTEM
   7.1 Scope of Calculation
   7.2 Engine Calculations
   7.3 Precooler
   7.4 Vortex Tube
   7.5 Ventilated Suit Requirements

8.0 GENERAL CONCLUSIONS

9.0 REFERENCES

10.0 FIGURES 1 - 7

/1.0 Notation...
1.0 NOTATION

1.1 Vortex Tube

\( P_i \) Inlet pressure
\( P_c \) Cold outlet pressure
\( T_i \) Inlet temperature
\( T_o \) Cold outlet temperature
\( T_H \) Hot outlet temperature
\( \Delta T_c \equiv (T_i - T_c) \).
\( m_i \) Mass flow of air entering vortex tube

\[ m_o = \frac{m_i}{1.07} \text{ lb/sq.in.} \times \sqrt{\frac{T_i}{288}} \]

\( \mu \equiv \frac{\text{cold mass flow}}{\text{inlet mass flow}} \)

\( T_{ambient} \) Atmospheric temperature
\( A_i \) Area of inlet
\( M \) Mach number

1.2 Jet Engine

\( \eta_i \) Intake adiabatic efficiency
\( \eta_c \) Compressor adiabatic efficiency
\( R_i \) Intake compression ratio
\( R_c \) Engine compression ratio
\( \Delta T_{\text{intake}} \) Temperature rise through intake
\( \Delta T_{\text{compressor}} \) Temperature rise through compressor
\( R_{cc} \) Engine compression ratio under standard static conditions.
2.0 **INTRODUCTION**

2.1 **The Vortex Tube**

A simplified diagram of the vortex tube is shown in figure 2. It consists of a device for separating compressed air into a hot and a cold stream at some low pressure. The compressed air is injected tangentially into the main vortex tube at the end next to the cold outlet and diaphragm. The other end of the main tube is partly closed by an adjustable valve. The incoming air sets up a vortex within the main tube. Thus, near the inlet chamber, the vortex consists of a cold low pressure core which is surrounded by a periphery at a higher temperature and pressure. The control valve is partially closed to give a pressure gradient along the tube and so force some of the cold air out through the cold outlet. The remaining air escapes past the valve as a hot stream.

The proportion and temperature of the cold air, for a given inlet pressure, are determined by the setting of the hot valve. In the extreme case of the valve being fully open, air is sucked in through the cold outlet from atmosphere. For any given valve setting increased cooling may be obtained by increasing the pressure of the inlet air.

2.2 **Application of the Vortex Tube**

Because of its simplicity and lack of moving parts the vortex tube device presents an attractive form of refrigeration which has low initial cost, is reliable and requires little or no maintenance. From 1946 and for several following years, particularly in the U.S.A., these qualities stimulated the initial enthusiasm for many research investigations. Unfortunately the device proved to have a very low efficiency and the running costs, to provide the compressed air, made it an uneconomical proposition, for almost all practical applications, when competing with standard types of refrigerators.

The need to cool high speed jet powered aircraft has again revived interest in the vortex tube. With this application a source of high pressure air is already available at the jet engine's compressor and therefore the over-riding factor of operating cost is no longer important. If the vortex tube is able to supply sufficient air at the required temperature then its simplicity will make it a rival to the refrigeration turbine which is at present used for aircraft cooling. Although for low inlet pressures the refrigeration turbine delivers air at a much lower temperature, for very high inlet pressures the...
temperature drop of the vortex tube may approach that of the refrigeration turbine.

The following investigation is carried out to determine whether a vortex tube would be capable of meeting the requirements for a ventilated suit system of cooling in a jet powered aircraft.

3.0 LAYOUT OF COOLING SYSTEM

The general layout of the cooling system is shown in figure 1.

3.1 Compressor

A bleed from the jet compressor supplies the system with high pressure air. Owing to compression this air may have a temperature which is of the order 300 - 400°C whilst the air entering the ventilated suit is required at 45°C. Neither the vortex tube nor the refrigeration turbine is capable of producing this large temperature drop and it is therefore necessary to insert a pre-cooler between the compressor and the vortex tube.

3.2 Pre-cooler

The pre-cooler is of the air to air type. It is at this point in the system that the largest temperature drop occurs and it will therefore be important to use a pre-cooler with a high thermal efficiency. A second detail to note is that the cooling fluid is the free stream air at its stagnation temperature. Under the hottest sea level tropical conditions, when an aircraft is travelling at a Mach No. = 1, this stagnation temperature will exceed atmospheric ambient temperature by about 64°C and the difference increases more rapidly with further increase of Mach No. Thus there will be an upper speed limit, to the use of the vortex tube cooler, unless some other form of pre-cooler is devised which does not rely on the free stream stagnation temperature for cooling.

3.3 Vortex Tube and Ventilated Suit

The pre-cooled air next passes to the vortex tube where it is separated into a hot and a cold stream. The cold stream flows to cool the ventilated suit whilst the hot air is rejected unless required for some other heating purpose. Back pressure on the vortex cold outlet will reduce the cooling and it is therefore advantageous to reduce pressure losses through the suit.
to a minimum and to connect the air outlet from the suit to the lowest available pressure.

3.4 Control of Cooling to Ventilated Suit

The rate of cooling in a ventilated suit is mainly dependent on the temperature, rate of flow and humidity of the inlet air. Although the humidity is not easily controllable, the first two factors may be readily varied by:

(a) Altering the inlet pressure to the vortex tube
(b) Altering the back pressure at the cold outlet
(c) Altering the valve setting at the hot outlet.

Method (a) or (b) could be accomplished by the insertion of a control valve between the precooler and the vortex tube or between the vortex tube and the ventilated suit, respectively. In both cases the temperature of the cooling air would decrease as its rate of flow increased. Method (c) is not so straightforward as later examination of figure 3 will show. In this case the maximum temperature drop occurs at an optimum rate of flow and hence an increased temperature drop could be accompanied by either an increase or a decrease of cold air flow. Method (b) appears the most suitable for the wearer of the ventilated suit to control.

4.0 VORTEX TUBE PERFORMANCE

4.1 Choice of performance data

The vortex tube was discovered by G.J. Ranque in France and brief performance details are mentioned in a patent \(^1\) and a paper \(^2\) published in 1931 and 1933. The next publication \(^3\) came after the end of the Second World War, in 1946, when it was disclosed that C.W. Hilsch had been carrying out research on this device at Erlangen University in Germany. Although Hilsch's paper was the second to be published and although probably about fifty subsequent ones have discussed the device, this paper still remains one of the most systematic and comprehensive works which is available on the vortex tube's performance.

Apart from the introduction of the multi-nozzle inlet chamber, by Fulton \(^4\), there has been little improvement in performance. Some improvement has been made at the lower inlet pressures but, at the higher pressures, no consistent improvements have been claimed. For the purpose of these calculations...

/Hilsch's ...
Hilsch's results will be used. The dimensions of Hilsch's tube were chosen to give a compromise between a tube which would deliver a small fraction of cold air at a low temperature and one which would give greater cooling by delivering a larger cold flow at some higher temperature. In this respect our calculations may underestimate the available temperature drop since we are interested only in the former type of cooling. On the other hand, it is remarkable that no other investigators have made appreciable improvements on Hilsch's results.

4.2 Typical performance of the vortex tube

Figure 3 gives typical performance curves and illustrates the main features. The lower diagram shows the variation of the hot stream temperature, \( T_H \), and the cold stream temperature, \( T_C' \), with respect to the cold flow ratio, \( \mu \), for various constant pressure ratios \( p_1/p_0' \). The inlet temperature is denoted by \( T_1' \), the inlet pressure by \( p_1' \), and the cold outlet pressure by \( p_C' \). For constant inlet pressure the value of \( \mu \) is determined by the valve setting at the hot stream outlet; for example, \( \mu = 1 \), when the valve is fully closed. Although the results, quoted were for \( p_C' = \) atmospheric pressure, the curves have been plotted in terms of the pressure ratio \( p_1'/p_C' \) and not \( p_1' \). This is reasonable since no performance figures are available to show the effect of varying \( p_C' \) without varying \( p_1'/p_C' \). It is only qualitatively known that increase of \( p_C' \) decreases the temperature drop.

It will be seen that increasing the inlet pressure will increase the temperature drop and that for a given inlet pressure there is a certain value of \( \mu \) for which a maximum temperature drop occurs. For higher inlet pressures this value of \( \mu \) decreases. For each inlet pressure it will be necessary to alter the valve setting if the point of maximum temperature drop is required.

In some applications a larger cold flow may be required with a smaller temperature drop. In the top diagram of figure 3 the temperature drop \( \Delta T_C' \) is multiplied by the cold flow ratio, \( \mu \), giving the 'specific refrigeration', \( \mu \Delta T_C' \), which is plotted against \( \mu \). It will be seen that a maximum of \( \mu \Delta T_C' \) occurs at about \( \mu = 6 \) and the value decreases slightly for higher inlet pressures. The point of maximum \( \mu \Delta T_C' \) is the optimum working point for maximum heat extraction from a source at temperature, \( T_1' \).

These two distinct applications of the vortex tube require different hot valve settings and tube dimensions. To
obtain a large temperature drop it is better to use a smaller cold orifice than that used for maximum heat extraction.

4.3 Performance of the Hilsch Vortex Tube at Maximum Temperature Drop

Hilsch gives performance results for three different tube sizes. He found that the tube performance increases slightly with increase of tube size. These results have been interpolated and general performance curves, at maximum temperature drop, are given in figure 4.

The maximum temperature drop divided by the inlet temperature, i.e. $\frac{\Delta T_c}{T_1}$ max., is plotted against the area of the inlet orifice, $A'_1$, for various pressure ratios, $\frac{p_1}{p_c}$. Superimposed are curves of 'equivalent mass flows', $m_o$. To obtain the true inlet mass flow, $m_1$, it is necessary to multiply by a factor which corrects for outlet pressure and inlet temperature. The expression is

$$m_1 = m_o \times \frac{p_0}{14.7 \text{ lb./sq.in.}} \times \sqrt{\frac{288}{T_1}}.$$  

A curve of the cold flow fraction, $\mu$, at maximum temperature drop, against $p_1/p_c$ is given in figure 5.

The cold outlet flow is found by multiplying $m_1$ from figure 4 by $\mu$, found from figure 5. We thus know the amount of air which is bled from the jet compressor and the amount which will pass to the ventilated suit.

When applying the general curves to the ventilated suit problem it will be necessary to make two assumptions which have not yet been experimentally verified. Firstly we will assume that $\Delta T_c$ max. is a function of $p_1/p_c$ and secondly that $\Delta T_c$ max. is proportional to $T_1$,

$$\frac{\Delta T_c}{T_1} \text{ max.} = f\left(\frac{p_1}{p_c}\right)$$

for any given tube.

No investigations of the first assumption have been reported and usually $p_c$ is at atmospheric pressure. Some investigators have varied $T_1$, but their object was the elimination of condensation errors due to the use of wet air and therefore these results are unreliable for checking the second assumption. Further experimental work is required.

/5.0 ...
5.0 VENTILATED SUIT REQUIREMENTS

Each suit requires an air supply of 6 cu.ft./min. (3.7 lb./min.) at a temperature not greater than 115°F (46.1°C) and there will be a pressure loss through the suit of 6 lb./sq.in.

The wearer of a ventilated suit will experience increased cooling if dry air is supplied. It was at first hoped that a vortex tube might also act as a water separator. One investigator states that very little or no drying occurs and it will therefore be necessary to fit a water separator in the system if dry air is required.

6.0 PRELIMINARY CALCULATION ON THE COOLING SYSTEM

The following short calculation was suggested as a preliminary check on the system's practicability.

6.1 Assumptions

Tentative assumptions were:-

(a) Air pressure at compressor = 200 lb./sq.in.
(b) Air temperature at compressor = 350°C
(c) Allowable bleed from compressor = 6 lb./min.
(d) Thermal efficiency of intercooler = 75 per cent.
(e) Aircraft's Mach No. = 0.8
(f) Ambient temperature at sea level = 25°C
(g) Suit discharges air at pressure = 14.7 lb./sq.in.

6.2 Calculations

(i) Free stream stagnation temp. = \( T_{\text{ambient}} (1 + \frac{2}{M^2}) \)
   = 336°C. (65°C)

(ii) Temperature drop through intercooler = (Compressor temperature - Stagnation temperature) \times 75\text{ per cent}
   = 215 K.

(iii) Temperature of air entering vortex tube, \( T_i = 408°C \) (135°C)

(iv) \( \frac{p_i}{p_c} = \frac{200}{14.7 + 6} = 9.8 \)

(v) \( '\text{Equivalent mass flow} \quad m_o = m_i \left( \frac{14.7}{14.7 + 6} \right) \sqrt{\frac{T_i}{288}} \)
   = 5.06 lb./min.

/(vi) ...
(vi) From (iv) and (v) and using figure 4,
\[ \frac{T_o}{T_i} = 0.218, \quad A_1 = 0.025 \text{ sq.in.} \]

(vii) From (iii) and (vi), temperature of cold air to suit,
\[ T_o = 46^\circ \text{C}. \]

(viii) Cold air ratio, \( \mu \), from figure 5 = 0.258

(ix) Cold air flow = \( n_1 \times \mu \)
\[ = 1.55 \text{ lb./min.} \]

(x) Maximum number of suits = 4.

6.3 Preliminary Conclusions
In this particular case it appears that the vortex tube system is just able to fulfill the cooling requirements and that there is sufficient air to supply four ventilated suits.

The calculations will now be extended to more general cases under tropical sea level conditions.

7.0 GENERAL CALCULATION ON VORTEX COOLING SYSTEM

7.1 Scope of Calculations
The object of the calculation was to determine the effects of engine compression ratio, precooler thermal efficiency and Mach Number when the aircraft was flying at sea level under the hottest tropical conditions, namely - ambient temperature = 45\(^\circ\)C.

7.2 Calculation of pressure and temperature at engine compressor
It will be assumed that the aircraft's engine has an axial compressor with a pitot intake. In this case, the adiabatic intake efficiency, \( \eta_i \), and the adiabatic compression efficiency, \( \eta_o \), will lie in the range.
\[ 0.9 < \eta_i < 1.0 \]
\[ 0.83 < \eta_o < 0.87. \]

In the following example it will be assumed that.
\[ \eta_i = 95 \text{ per cent} \]
\[ \eta_o = 86 \text{ per cent}. \]
For an aircraft at Mach No., \( M \), and ambient temperature, let the compression ratios of intake and compressor be denoted by \( R_1 \) and \( R_c \) respectively.

Therefore pressure at compressor \( = R_1 \times R_c \times \) Atmospheric pressure. Let \( R_{i0} \) and \( R_{co} \) be the compression ratios under standard static conditions. \( (R_{co} \) is the engine variable which is required in the general calculations).

Intake temperature rise, \( \Delta T_{\text{intake}} = \frac{T_{\text{ambient}}}{\eta_1} (R_1^{286} - 1) \) \ ..........(1)

\[ = T_{\text{ambient}} \left( 1 + \frac{.288}{286} \right) \] \ ..........(2)

Compressor temperature rise, \( \Delta T_{\text{compressor}} = \frac{T_{\text{ambient}} + \Delta T_{\text{intake}}}{\eta_c} (R_c^{286} - 1) \) \ ..........(3)

In the above expressions \( R_c \) and \( R_1 \) are not independent variables. In order to introduce \( R_{co} \) it is often assumed that the compressor temperature rise, \( T_{\text{compressor}} \), is independent of altitude or forward speed and that \( \eta_1 \) and \( \eta_c \) are constant.

Therefore \[ \Delta T_{\text{compressor}} = \frac{T_{\text{ambient}}}{\eta_c} \] \ ..........(4)

Temperature at compressor bleed = \( T_{\text{ambient}} + \Delta T_{\text{intake}} + \Delta T_{\text{compressor}} \) (The last two terms are obtained from (2) and (4).)

Pressure available at compressor bleed = Atmospheric pressure \( (R_1 \times R_c) \) (\( R_1 \) is obtainable from equation (1) and (2), \( R_c \) is obtainable from equation (3) and (4) with the aid of (2).)

The available temperature and pressure at the compressor bleed were calculated using

\[ \begin{align*}
T_{\text{ambient}} &= 45^\circ C \\
\eta_1 &= 95 \text{ per cent} \\
\eta_c &= 86 \text{ per cent}
\end{align*} \]

for a range of forward speeds, \( 0 \leq M \leq 1.0 \), and engine compression ratios, \( 3.0 \leq R_{co} \leq 15.0 \).
7.3 Precooler

The preliminary calculation in section 6.0 assumed that the precooler had a thermal efficiency of 75 per cent. A somewhat higher figure of 90 per cent is mentioned in reference 5. In order to include both figures and to indicate the theoretical maximum, an efficiency range of 75 per cent - 100 per cent has been investigated.

7.4 Vortex Tube

Figure 4 was used to calculate the cold air temperature for the various ranges of Mach Number, Compression Ratio and Precooler Efficiency.

The back pressure on the cold outlet was assumed to be $P_0 = .447 + .6 = 20.7$ lb./sq.in. and the tube size corresponded to an inlet area, $A_1 = .03$ sq.in.

7.5 Ventilated Suit Requirements

The suit must be supplied with cooling air at a temperature not greater than $115^\circ F$. The highest Mach Number, at which this requirement was satisfied, is shown in figures 6 and 7 for various compression ratios and precooler efficiencies. Figure 6 plots maximum permissible Mach Number against engine compression ratio for precooler efficiencies of 80, 85, 90, 95 and 100 per cent. Even under static conditions and with a compression ratio as high as 15, it was not possible to meet the cooling requirements using a 75 per cent efficient precooler. For precooler efficiencies between 75 and 80 per cent the curves are rather flat and there is only slight increase of maximum permissible Mach Number with increase of compression ratio. A table of representative values for higher precooler efficiencies is given below.

<table>
<thead>
<tr>
<th>Maxima Permissible Mach No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression Ratio</td>
</tr>
<tr>
<td>Precooler Eff. = 80$%$</td>
</tr>
<tr>
<td>= 90$%$</td>
</tr>
<tr>
<td>= 95$%$</td>
</tr>
</tbody>
</table>

In figure 6 the slopes of the curves decrease with increase of compression ratio. Assuming an indefinite increase of the latter, for a precooler efficiency of 90 per cent, it is unlikely that the maximum permissible Mach Number would exceed 1.05. It will be seen that a practical application of the
system requires both a high compression ratio and a high efficiency precooler. The maximum permissible Mach Number has been replotted against precooler efficiency, in figure 7, for engine compression ratios of 2.5, 5.0, 7.5, 10.0, 12.5 and 15.0. It seems desirable to use a precooler whose efficiency is at least 80 per cent for any practical applications.

8.0 GENERAL CONCLUSIONS

The preliminary calculations for an aircraft travelling at a Mach No. of 0.8 at sea level with an ambient temperature of 25°C and precooler of 75 per cent efficiency, shows that the vortex tube system was just able to meet the cooling requirements of a ventilated suit.

More general calculations, for a sea level maximum tropical temperature of 45°C, showed that increased cooling was obtained by either increasing the engine compression ratio or the precooler efficiency. Adverse cooling is obtained by increasing the speed of the aircraft and figures 6 and 7 give the maximum permissible Mach Number for any compression ratio and precooler efficiency, which permits the fulfilment of the cooling requirements.

A practical vortex tube cooling system will necessitate the use of high efficiency precooler and high engine compression ratios. A precooler thermal efficiency of less than 80 per cent will be unacceptable except at very low speeds. An efficiency of 90 per cent will permit a maximum Mach Number of 0.75 for a compression ratio of 7.5 and the Mach Number will rise to about 1.00 for a compression ratio of 15. It therefore appears that the vortex tube system of cooling could have practical applications provided the speed of the aircraft does not exceed the maximum determined by the compression ratio and precooler efficiency.

The general performance curves for the Hilsch Vortex Tube at maximum temperature drop, given in figures 4 and 5, can be used to investigate the effects on the cooling system of other variables such as altitude and ambient temperature changes.

More recent investigators have reported vortex tube temperature drops which are an improvement on those given by Hilsch. These improvements are usually accompanied by a reduced cold flow ratio and, although the results are somewhat inconsistent, it appears that there may be some possibility of designing a vortex tube which has a superior performance to that given in figure 4.

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APPLICATION OF THE VORTEX TUBE TO VENTILATED SUIT COOLING.

FIG. 1.

JET ENGINE

COMPRSSOR.

PRECOOLER.

VENTILATED SUIT.

VORTEX TUBE.

FIG. 2.

Simplified Vortex Tube.

COLD AIRT

inlet chamber.

main tube.

adjustable valve.

COLD AIRT

cold outlet & diaphragm.

single inlet & spiral alternatives.

multi-nozzle inlet chamber.

HOT AIRT
FIG. 3

TYPICAL HILSCH VORTEX TUBE

(VARIATION OF PERFORMANCE WITH COLD AIR FLOW RATIO)
**Fig. 4**

**Performance of Hilsch Vortex Tube at Max. Temperature Drop**

- $P_i$ - Inlet stagnation pressure
- $A_i$ - Inlet area
- $P_c$ - Cold exit static pressure
- $m_c$ - Mass flow into tube
- $T_i$ - Inlet stagnation temperature
- $m_o = m_i \left( \frac{1.47}{288} \right)$

**$\Delta T_e$** - Temperature drop of cold air

- $m_o = \frac{\Delta T_e}{T_i}$

**Graphical Data**

- **Inlet Area** vs. **Temperature Drop**
- **Inlet Area** vs. **Mass Flow Rate**
COLD FLOW RATIO FROM HILSCH VORTEX TUBE
AT MAX. TEMPERATURE DROP.
MAX PERMISSIBLE MACH NO. \nu COMPRESSION RATIO

FOR VENTILATED SUIT AIR SUPPLY \geq 115^\circ F.

Conditions:
- Sea level max. tropical temp. = 45^\circ C.
- Engine intake efficiency = 95%.
- Compression efficiency = 96%.
- Precooler thermal efficiency = 80, 85, 90, 95, 100%.

FIG 6
FIG. 7

MAX PERMISSIBLE MACH NO V. PRECOOLER EFFICIENCY
FOR VENTILATED SUIT AIR SUPPLY ≥115°F.

Conditions:
- Sea level max tropical temp. = 45°C
- " pressure = 14.7 lb/sq.in.
- Engine intake efficiency = 95%
- " compression efficiency = 86%
- " compression ratio = 2.5, 5.0, 7.5, 10.0, 12.5, 15.0.

MACH NO

70% 80% 90% 100%

PRECOOLER THERMAL EFFICIENCY

ENGINE COMPRESSION RATIO

15.0 12.5 10.0 7.5 5.0 2.5
Improvements in the Performance of a Vortex Tube

Summary

The object of this note is to indicate how the vortex tube experiments at the College of Aeronautics will contribute towards the design of a tube with increased cooling performance.

1. Introduction

The vortex tube has two distinct applications. It may be used to deliver air at the lowest possible temperature or to deliver the largest quantity of refrigerant. These two requirements are not compatible in one tube. In the first application the tube is designed to deliver a small quantity of air at the lowest temperature whilst in the second a much larger quantity is delivered at a slightly higher temperature.

In the ventilated suit application it is necessary that the temperature of the cold air shall not exceed a given value, namely 115 - 125°F. If this cooling requirement can be met by the second case instead of the first then either more ventilated suits can be supplied from the one vortex tube or a smaller tube will be sufficient. As the forward speed of the aircraft increases it is found that larger temperature drops are required across the vortex tube and eventually tube of the first type must be used. For still higher aircraft speeds, it is not possible to satisfy the cooling requirements unless inlet pressure to the vortex is increased.

2. Investigations to improve Vortex Tube cooling.

Three vortex tubes have been constructed as part of the investigations at the College.

Vortex tube No.1 is a simple laboratory demonstration model.

Vortex tube No.2 (see figure 5) was constructed for visual investigations of the flow within the vortex. Typical shadowgraphs taken with a high speed camera are shown in figure 4.

Vortex tube No.3 was designed to investigate the effects of the many variables which control the cooling performance of a vortex tube.

During the interval, between the completion of the visual flow experiments and the construction of vortex tube No.3, vortex tube No.2 was adapted to test modifications which might increase the maximum temperature drop. These modifications were ...
were based on the observation that the temperature drop between
the inlet and the axis of the vortex was about 20-30% greater
than that between the inlet and the cold outlet. This cold
region extended over several diameters along the vortex axis.
In carrying out the visual tests it was found necessary to
shorten the vortex tube to obtain clear pictures. It appeared
that the cooling performance was not appreciably affected when
a tube of only 6 diameters in length was used.

3. Modifications to Vortex Tube No.2.

The modifications which were tried are illustrated in
figures 2(i) - 2(v).

Figure 2(i) - Unmodified tube with supersonic inlet.

The results for maximum temperature drop are plotted
against the pressure ratio across the inlet and the cold outlet,
in figure 1. Between pressure ratios of 2 to 4.5 the temperature
drop exceeds Hilsch's results by 10-20%. The temperature drop
ceases to increase at a pressure ratio of 5 and the tube is
inferior to Hilsch's above a ratio of 5.5.

Figure 2(ii) - Axial jet to induce cold air towards the
cold outlet.

The object was to induce cold air towards the cold outlet
by means of an axial air jet. The cooling results were not
significantly different from the results for the unmodified tube.

Figure 2(iii) - Recirculation and heat exchange through
an axial pipe.

The principle was to cool air which passed along an axial
tube and which was recirculated by means of an ejector. The
object of this arrangement was to avoid the decreased cooling
which occurs when back pressure is applied to the cold outlet
of a conventional tube. The results obtained by this modification
were not as good as those for an unmodified tube.

Figure 2(iv) - Open ended axial tube.

Figure 2(v) - Perforated axial tube.

The object of these two modifications was to tap off air
at points away from the cold outlet.

The cooling results are only slightly below those for the
unmodified tube (see figure 1). The perforated tube has the
advantage that the cold flow may leave in both directions and
the exit area may be effectively doubled.

It will be concluded from the above experiments that none

/ of the ...
of the methods tried are suitable for producing significant increases in temperature drop of the vortex tube.

4. Vortex Tube systems using Cascade and Precooling.

Increased cooling can be obtained if several vortex tubes are coupled in series and if cold air is fed back to cool the inlet air. Provided the performance characteristics of each vortex tube in the cascade are known, then the result of combining several tubes and heat exchangers may be calculated.

Many combinations are possible and the performances have been calculated for three simple systems which are illustrated in figure 3(i), 3(ii) and 3(iii).

**Figure 3(i) - Cascade.**

This cascade system gave the same temperature drop as a single vortex tube. The same results were obtained if more than two vortex tubes were used in the system. (This interesting conclusion suggested that for a single tube

$$\left( \frac{T_i}{T_{\text{cool}}} \right) = \left( \frac{T_i}{T_C} \right)$$

and this has been verified by the results carried out on Vortex Tube No. 3.)

**Figure 3(ii) - Inlet Precooling.**

In this system part of the cold air is fed back to a heat exchanger which cools the inlet air. The calculation showed that a greater temperature drop is obtained if a tube is incorporated whose unmodified characteristics are not of the maximum temperature drop type but of the large refrigerant type. For an ideal heat exchanger, the results indicate that at a pressure ratio of 5.5 (see figure 1) the temperature drop could be increased by about 60%.

**Figure 3(iii) - Cascade and Inlet Precooling.**

In this method the cold air of the first tube is used to precool the inlet air of the succeeding tube. The process may be repeated for any number of tubes. Using two tubes and an ideal heat exchanger it was found the temperature drop could be increased by about 60%, as for the previous system.

It will be seen that the inclusion of a heat exchanger in a vortex cascade system will give large increases in the temperature drop. This increased performance is obtained at the expense of decreased cold flow and with the added complication of heat exchangers.
5. Vortex Tube No. 3.

Although countless ad hoc investigations have been carried out on the vortex tube, (reference - 'Bibliography and Survey of Vortex Tube' C. of A. Note No.9), very few investigators have carried out a systematic investigation of all the controlling parameters in the design of a conventional tube.

Vortex Tube No. 3 (see figures 6, 7, 8) was designed to investigate the effect on performance of many of the design and operating variables. The variables are listed below and some of the design ones are shown in figure 9.

Design parameters.
1. Size and shape of inlet nozzles.
2. Size of cold outlet.
3. Length of vortex pipe.

Operating variables.
1. Inlet pressure.
2. Hot valve setting.
3. Cold outlet pressure.
4. Hot valve pressure.
5. Inlet temperature.

The tests, now proceeding on Vortex Tube No. 3, are intended to provide optimum design data for a tube giving either maximum temperature drop, maximum refrigerant or any required compromise. The tests will indicate how the performance is altered by variations of inlet and external pressures (e.g. in aircraft cooling applications). The results will be directly required in the calculation of the cooling performance of the cascade and heat exchanger vortex system.

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