T H E   C O L L E G E   O F   A E R O N A U T I C S

C R A N F I E L D

A Note on the Application of the Vortex Tube

to Ventilated Suits

-by-

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SUMMARY

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 $115^{\circ}F$, can no longer be satisfied.

The maximum permissible Mach number, for an aircraft flying at sea level under the maximum ambient tropical temperature of $45^{\circ}C$, 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. -

Compression Ratio	= 5	7.5	10	12.5	15
Max. Mach No.	= .64	.75	.85	.93	.99

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.

MEP

I N D E X

1.0 NOTATION

1.1 Vortex Tube

p_i Inlet pressure

p_c Cold outlet pressure

T_i Inlet temperature

T_c Cold outlet temperature

T_H Hot outlet temperature

$\triangle T_c$ $\equiv (T_i - T_c)$.

m_i Mass flow of air entering vortex tube

$$m_o \equiv m_i \left(\frac{14.7}{p_c \text{ lb./sq.in.}} \times \sqrt{\frac{T_i \, ^oK}{288}} \right)$$

μ $\equiv \dfrac{\text{cold mass flow}}{\text{inlet mass flow}}$

$T_{ambient}$ Atmospheric temperature

A_i Area of inlet

M Mach number

1.2 Jet Engine

η_i Intake adiabatic efficiency

η_c Compressor adiabatic efficiency

R_i Intake compression ratio

R_c Engine compression ratio

$\triangle T_{intake}$ Temperature rise through intake

$\triangle T_{compressor}$ Temperature rise through compressor

R_{co} Engine compression ratio under standard static conditions.

2.0 INTRODUCTION

2.1 The Vortex Tube

A simplified diagram of the vortex tube in 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 46°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 precooler between the compressor and the vortex tube.

3.2 Precooler

The precooler 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 precooler 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 precooler is devised which does not rely on the free stream stagnation temperature for cooling.

3.3 Vortex Tube and Ventilated Suit

The precooled 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 straight forward 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, μ, for various constant pressure ratios p_i/p_c. The inlet temperature is denoted by T_i, the inlet pressure by p_i and the cold outlet pressure by p_c. For constant inlet pressure the value of μ 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_i/p_c and not p_i. This is reasonable since no performance figures are available to show the effect of varying p_c without varying p_i/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 μ for which a maximum temperature drop occurs. For higher inlet pressures this value of μ 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 $\triangle T_c$ is multiplied by the cold flow ratio, μ, giving the 'specific refrigeration', $\mu \triangle T_c$, which is plotted against μ. It will be seen that a maximum of $\mu \triangle T_c$ occurs at about $\mu = 6$ and the value decreases slightly for higher inlet pressures. The point of maximum $\mu \triangle T_c$ is the optimum working point for maximum heat extraction from a source at temperature, T_i.

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 temper-
ature drop, are given in figure 4.

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

$$m_i \; = \; m_o X \frac{p_c}{14.7} \; \text{lb./sq.in.} \; X \; \sqrt{\frac{288}{T_i \, ^\circ K}} \; .$$

A curve of the cold flow fraction, μ, at maximum temperature
drop, against p_i/p_c is given in figure 5.
The cold outlet flow is found by multiplying m_i from figure 4
by μ, 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 ΔT_c max. is a function of p_i/p_c and secondly
that ΔT_c max. is proportional to T_i,

i.e. $\qquad \frac{\Delta T_c \; max.}{T_i} \; = \; f\left(\frac{p_i}{p_c}\right)$

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_i, 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 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. $= T_{ambient} \, (1 + .2M^2)$

$$= 336^\circ K. \quad (63^\circ C)$$

(ii) Temperature drop through intercooler = (Compressor
temperature - Stagnation temperature) X 75 per cent

$$215^\circ K.$$

(iii) Temperature of air entering vortex tube, $T_i = 408^\circ K$ ($135^\circ C$)

(iv) Pressure ratio across tube, $\dfrac{p_i}{p_c} = \dfrac{200}{14.7+6} = 9.8$

(v) 'Equivalent mass flow $m_o = m_i \, \dfrac{14.7}{p_c \, \text{lb./sq.in.}} \, X \sqrt{\dfrac{T_i \,^\circ K}{288}}$

$$= 5.06 \text{ lb./min.}$$

/(vi) ...

(vi)   From (iv) and (v) and using figure 4,

$$\frac{\triangle T_c}{T_i} = .218 , \quad A_i = .025 \text{ sq.in.}$$

(vii)   From (iii) and (vi), temperature of cold air to suit,

$$T_c = 46^\circ C.$$

(viii)   Cold air ratio, μ, from figure 5 = .258

(ix)   Cold air flow = $m_i \times \mu$
                          = 1.55 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 fulfil 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, η_i, and the adiabatic compression efficiency, η_c, will lie in the range.-

$$0.9 < \eta_i < 1.0$$
$$0.83 < \eta_c < 0.87.$$

In the following example it will be assumed that.-

$$\eta_i = 95 \text{ per cent}$$
$$\eta_c = 86 \text{ per cent.}$$

/For an ...

For an aircraft at Mach No., M, and ambient temperature, $T_{ambient}$, let the compression ratios of intake and compressor be denoted by R_i and R_c respectively.

Therefore pressure at compressor = R_i x R_c x Atmospheric pressure. Let R_{io} 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, $\triangle T_{intake}$,

$$= \frac{T_{ambient}}{\eta_i} (R_i^{.286} - 1) \qquad \dots\dots\dots (1)$$

$$= T_{ambient} (1 + .2M^2) \qquad \dots\dots\dots (2)$$

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

$$\dots\dots\dots (3)$$

In the above expressions R_c and R_i are not independent variables. In order to introduce R_{co} it is often assumed that the compressor temperature rise, $T_{compressor}$, is independent of altitude or forward speed and that η_i and η_c are constant.

Therefore $\triangle T_{compressor} = \frac{T_{ambient\ standard}}{\eta_c} (R_{co}^{.286}-1) \dots (4)$

Temperature at compressor bleed = $T_{ambient} + \triangle T_{intake} + \triangle T_{compressor}$

(The last two terms are obtained from (2) and (4).

Pressure available at compressor bleed = Atmospheric pressure $(R_i$ x $R_c)$

(R_i 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

$$\begin{cases} T_{ambient} = 45^\circ C \\ \eta_i = 95 \text{ per cent} \\ \eta_c = 86 \text{ per cent} \end{cases}$$

for a range of forward speeds, $0 < M < 1.0$, and engine compression ratios, $3.0 < R_{co} < 15.0$.

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_c = 14.7 + 6 = 20.7 lb./sq.in. and the tube size corresponded
to an inlet area, A_i = .03 sq.in.

7.5 Ventilated Suit Requirements

The suit must be supplied with cooling air at a temper-
ature not greater than 115°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.-

Maximum Permissible Mach No.

Compression Ratio	= 7.5	10.0	12.5	15.0
Precooler Eff. = 80%	.21	.25	.29	.33
= 90%	.73	.85	.93	.99
= 95%	.88	1.02	1.11	1.16

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 ...

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 $25^{\circ}C$ 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 $45^{\circ}C$, 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 precoolers 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.

9.0 REFERENCES

1. G.J. Ranque   French Patent applied for Dec. 1931, issued 1932. (U.S.A. Patent applied for Dec. 1932, issued March 1934. Patent No. 1,952,281. 'Method and Apparatus for Obtaining from a Fluid under Pressure Two Currents of Fluids at Different Temperatures'.)

2. G.J. Ranque   'Experiences Sur la Détente Giratoire Avec Productions Simultanées d'un Echappement d'Air Chaud et d'un Échappement d'Air Froid'. No. 342. Bulletin Bi-Mensuel 2nd June, 1933, pp.1125-1155. Jnl. de Physique et Le Radium, 7^E Serie 4, 1933.

3. R. Hilsch   'Die Expansion von Gasen im Zentrifugalfed als Kälteprogess' Zeitsch fur Naturforshung Vol.1 No. 4, pp.208-214. April 1946. (Translation in Review of Scientific Instruments Vol. 18, pp.108-113, February 1947).

4. C.D. Fulton   'Ranque's Tube'. Journal of ASRE 'Refrigerating Engineering', May 1950, pp.473-479.

5. E.W. Still   'Temperature Control of Jet-Engined Aircraft'. Jnl. R.Ae.S., Feb. 1953, p.93.

FIG. I.

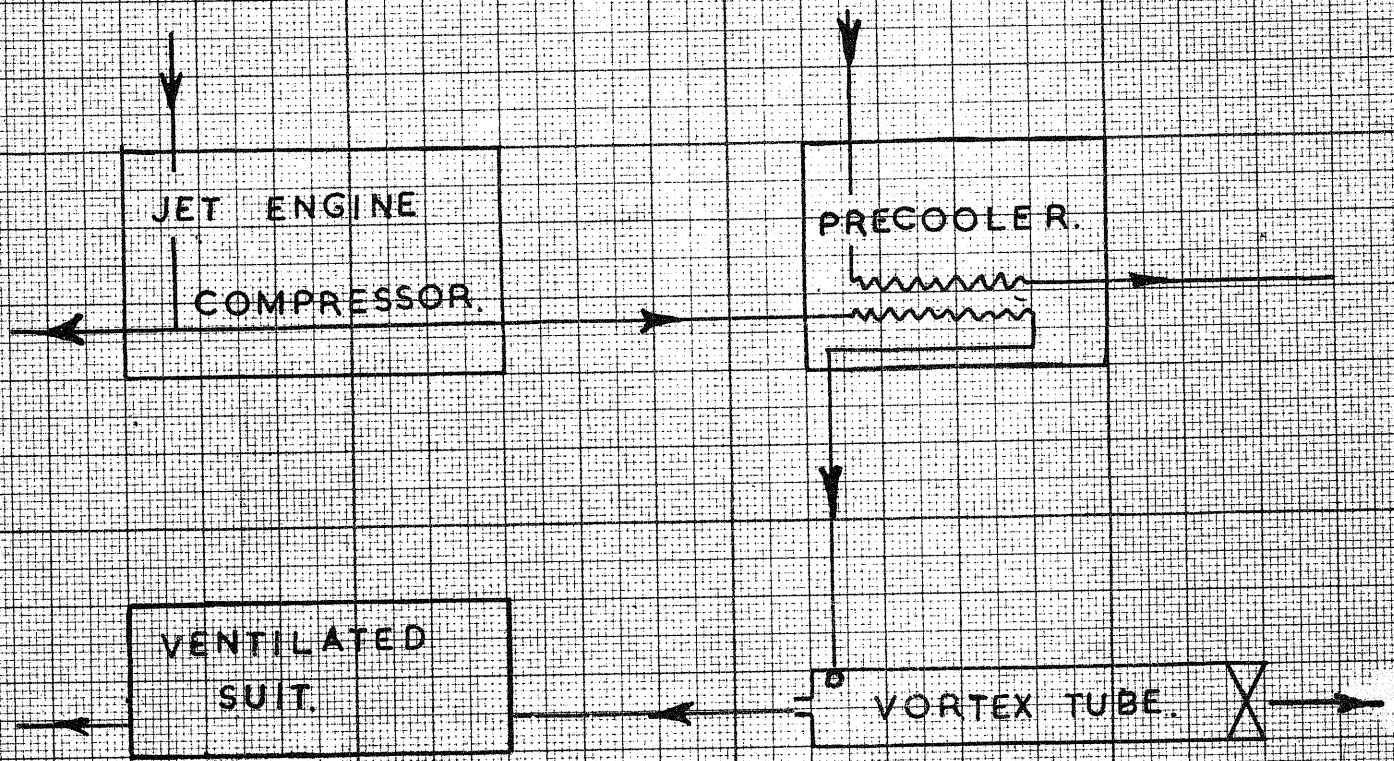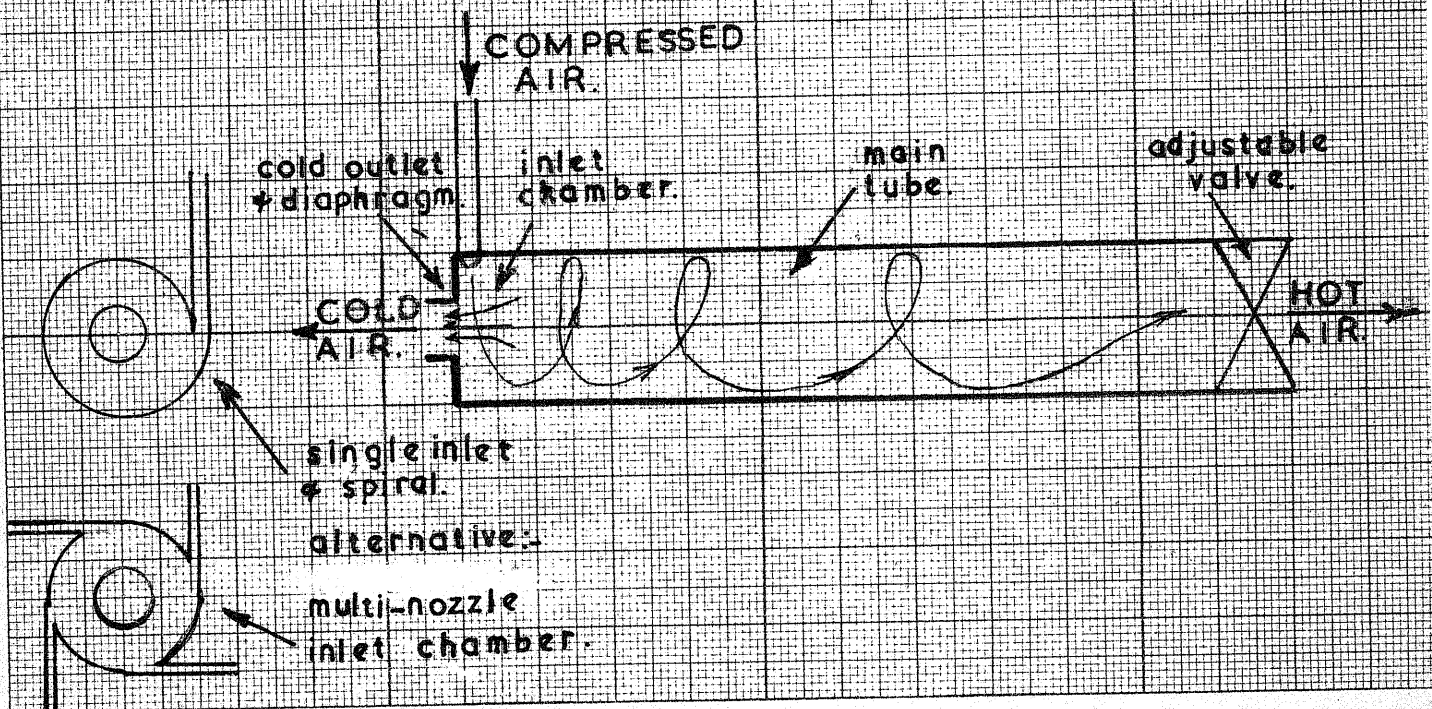# APPLICATION OF THE VORTEX TUBE TO

VENTILATED SUIT COOLING.

JET ENGINE

COMPRESSOR.

PRECOOLER.

VENTILATED SUIT.

VORTEX TUBE.

FIG 2.

SIMPLIFIED VORTEX TUBE.

COMPRESSED AIR.

cold outlet + diaphragm.   inlet chamber.   main tube.   adjustable valve.

COLD AIR.   HOT AIR

single inlet & spiral

alternative:-

multi-nozzle inlet chamber.

FIG. 3

TYPICAL HILSCH VORTEX TUBE.

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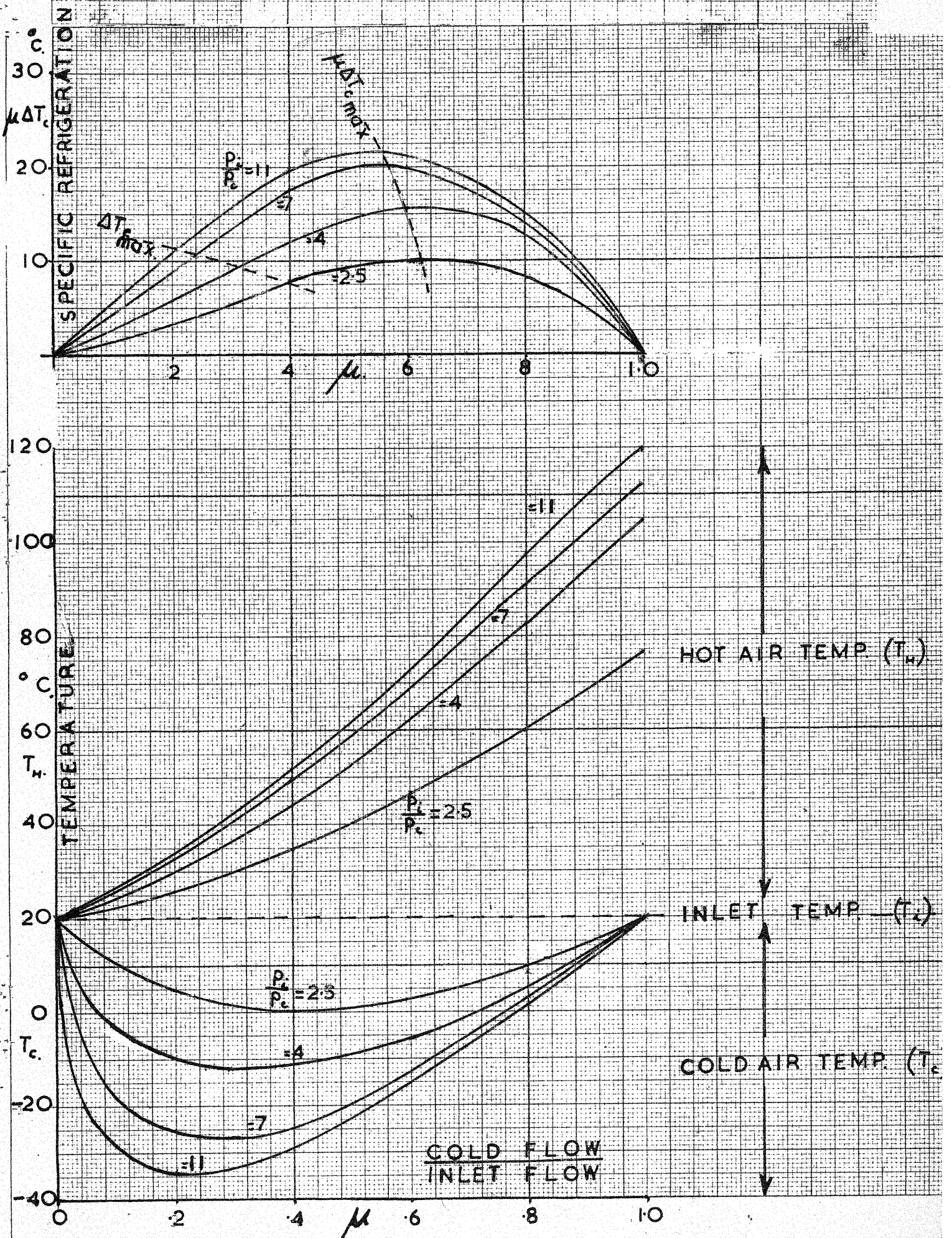
FIG. 4

PERFORMANCE OF HILSCH VORTEX TUBE AT
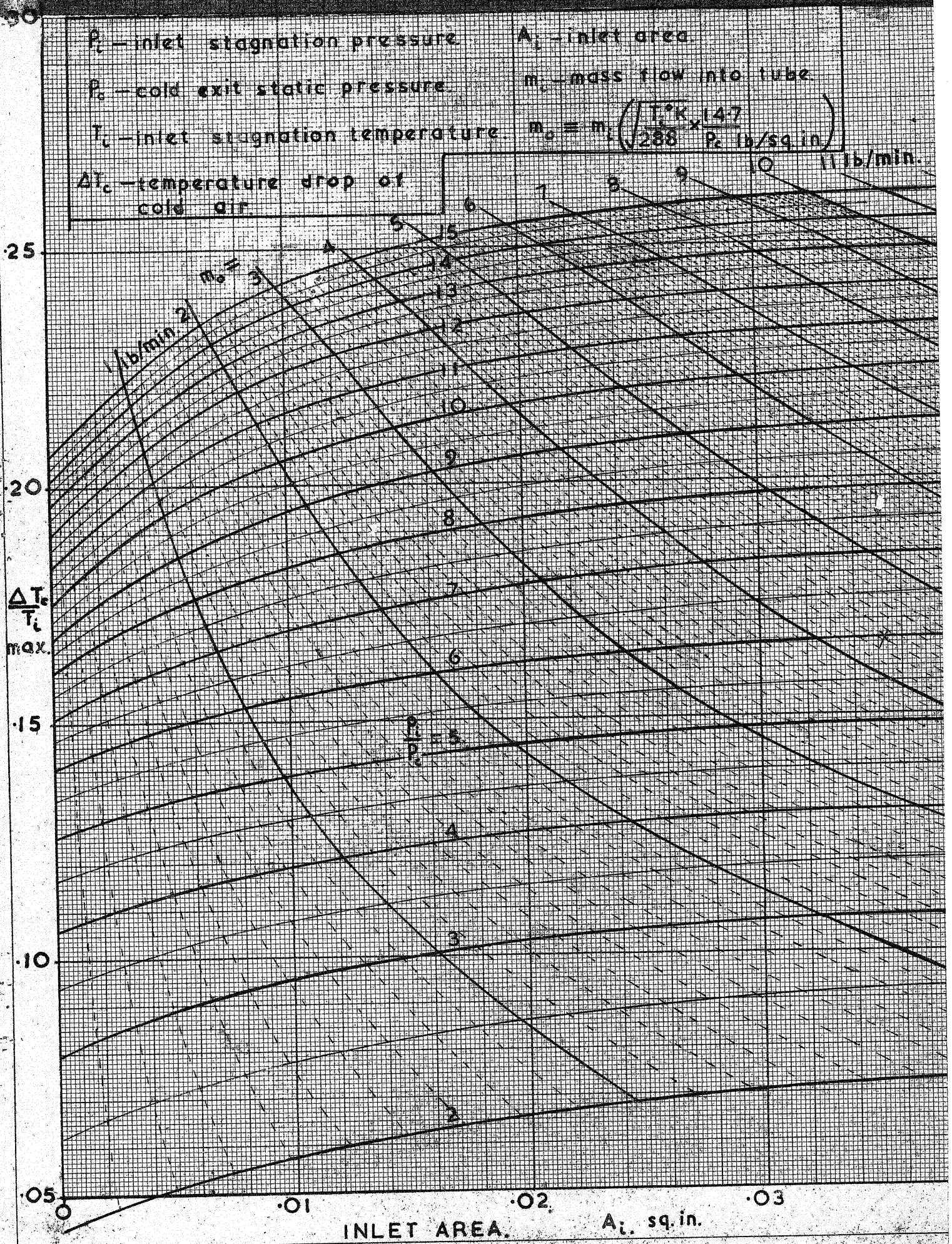## MAX. TEMPERATE DROP.

P_i — inlet stagnation pressure

P_o — cold exit static pressure

T_i — inlet stagnation temperature

ΔT_c — temperature drop of cold air

A_i — inlet area

m_i — mass flow into tube

$$m_o = m_i \left(\sqrt{\frac{T_i \, °K}{288}} \times \frac{14.7}{P_o \; \text{lb/sq.in}} \right)$$

$\dfrac{\Delta T_c}{T_i}$ max.

INLET AREA. A_i. sq. in.

FIG.5.

COLD FLOW RATIO FROM HILSCH VORTEX TUBE
AT MAX TEMPERATURE DROP.

μ

$\mu = \dfrac{\text{COLD FLOW}}{\text{INLET FLOW}}$

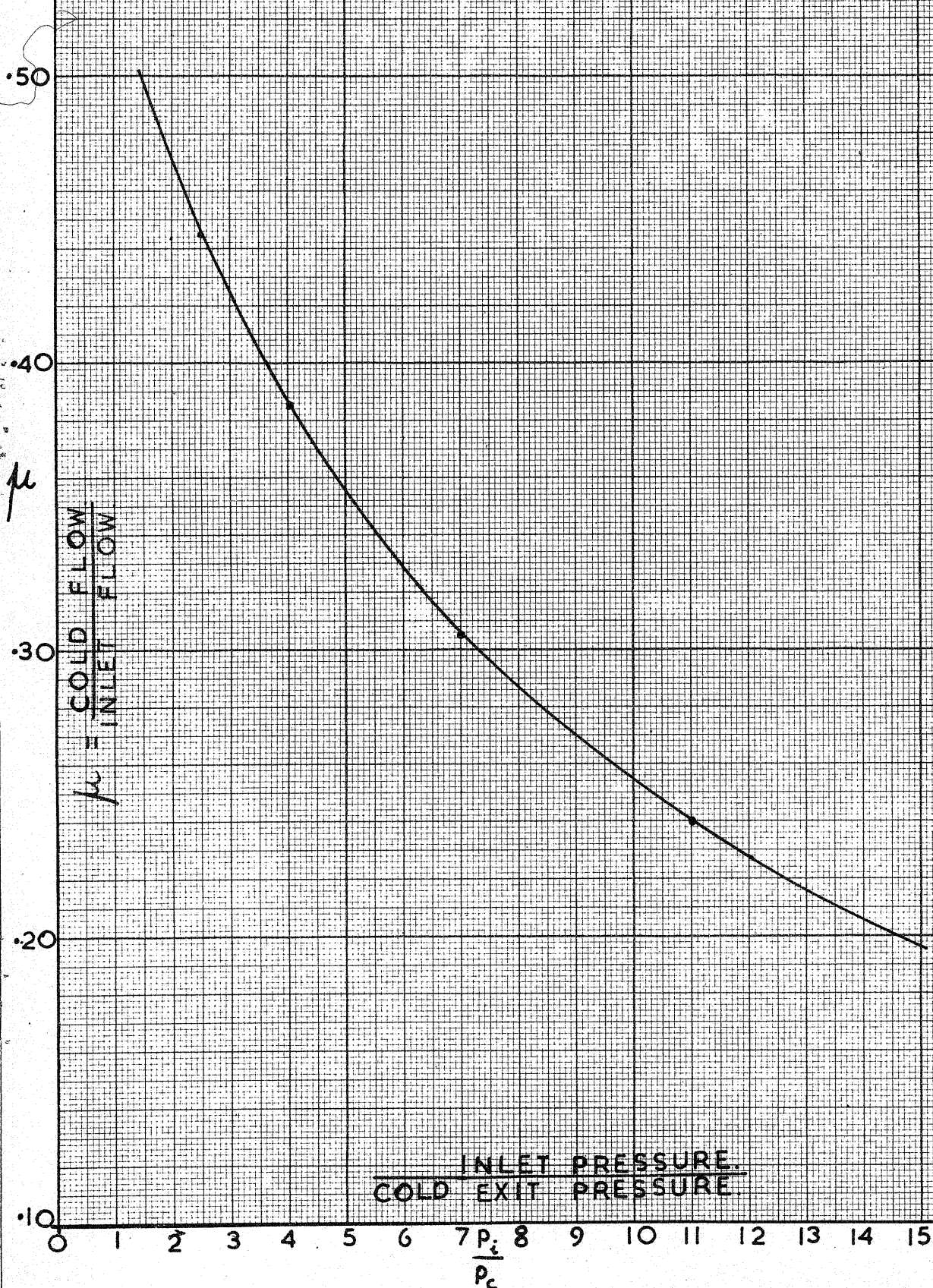$\dfrac{\text{INLET PRESSURE.}}{\text{COLD EXIT PRESSURE}}$

$\dfrac{P_i}{P_c}$

FIG 6

MAX. PERMISSIBLE MACH NO. v. COMPRESSION RATIO
FOR VENTILATED SUIT AIR SUPPLY $\geq$ 115° F

Conditions :-

Sea level max. tropical temp. = 45°C.
pressure = 14·7 lb/sq in

Engine intake efficiency = 93%
" Compression efficiency = 86%
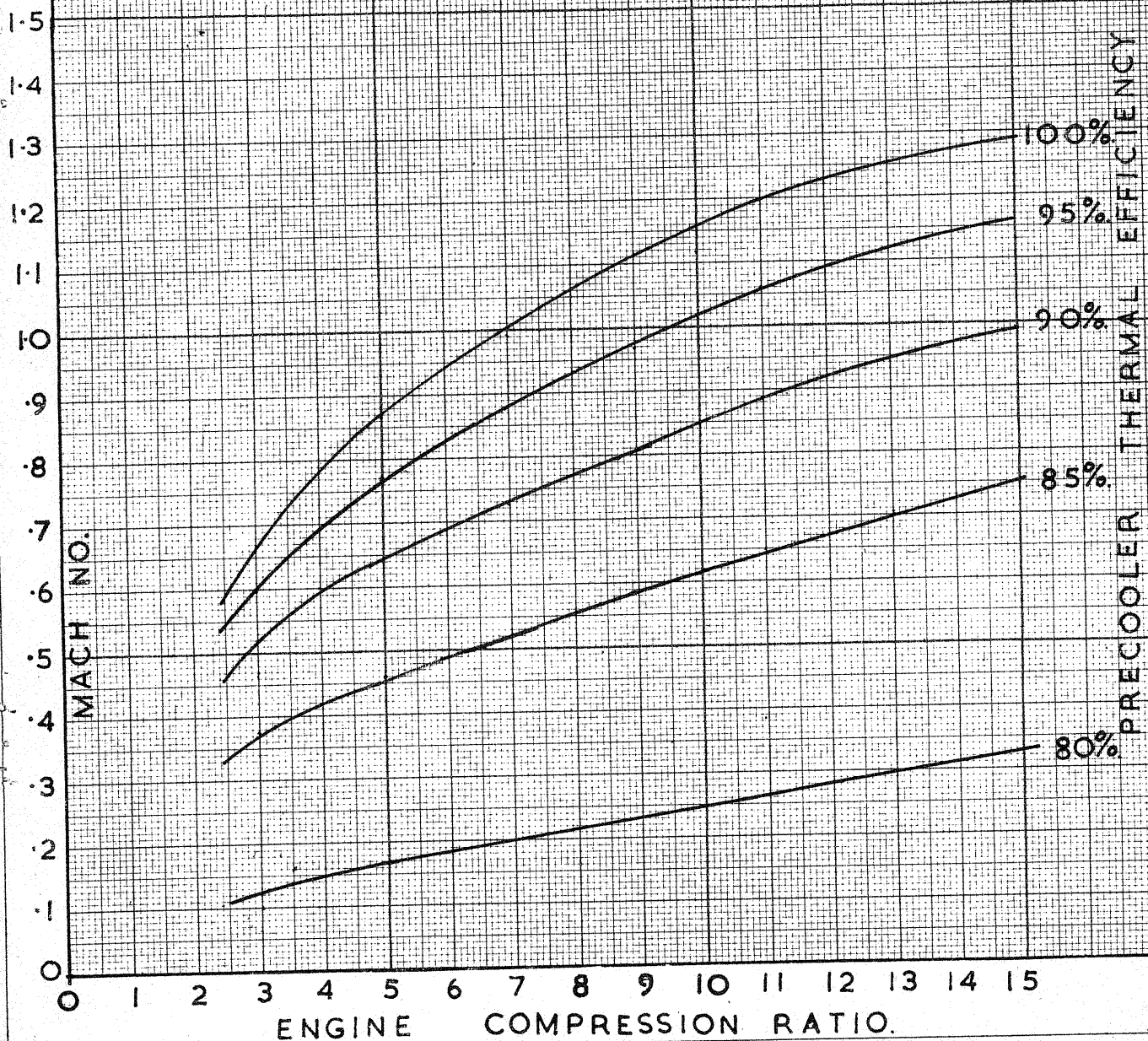
Precooler thermal efficiency = 80, 85, 90, 95, 100%

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

ENGINE COMPRESSION RATIO.

15·0
12·5
10·0
7·5
5·0
2·5

MACH NO.

PRECOOLER THERMAL EFFICIENCY.
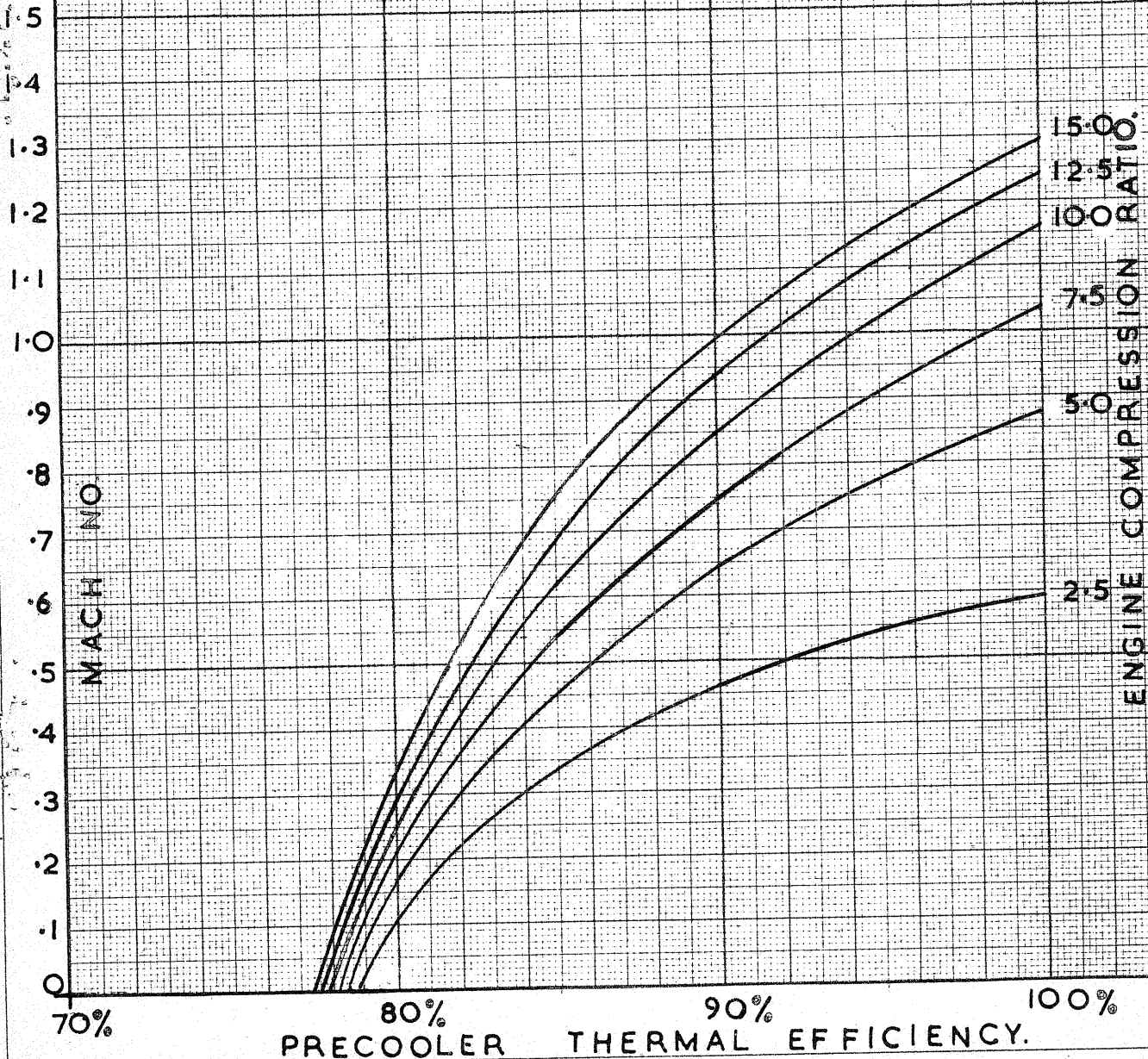
Improvements in the Performance
of a Vortex Tube

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 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

$$\left(\frac{T_i}{T_{c_{min}}}\right) = \left(\frac{p_i}{p_c}\right)^{const.}$$

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 preceeding 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 systems.

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