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CoA Note 9

The College of Aeronautics
Cranfield

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A Bibliography and Survey of The Vortex Tube

by

R. WESTLEY, B.Sc., D.C.Ae.

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NOTE NO. 9

MARCH, 1954.

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A Bibliography and Survey of

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of the

Department of Aerodynamics

SUMMARY

A comprehensive bibliography of vortex tube publications is given together with a brief survey of the development of the vortex tube between 1931 and 1953.

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CONTENTS

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1. SYMBOLS

In section 4 the references are classified by the letters which are found in the contents column. The capital letter indicates the general classification of the reference and the small letters indicate details of the contents.

Contents Letters

1.1. General Classification

No capital letter	:-	Vortex tube work
P	:-	Non-technical or popular publication on the vortex tube
Z	:-	Work not directly connected with the vortex tube.

1.2. Contents Details

a :- Applications
b :- Bibliography
d :- Discussion or Description
e :- Experimental
t :- Theoretical.

2. INTRODUCTION

The objects of this note are to provide a comprehensive bibliography of vortex tube publications, to give a brief summary of their contents and to survey developments between 1931 and 1953.

Although a large number of vortex tube investigations have been made since Ranque's discovery in 1931, many of the publications are not well known or readily available and some investigations have been duplicated.

A summary of the main publications and the development of the vortex tube is given in section 3. The section is subdivided under the headings of the various developments between 1931 and 1953.

/The Author ...

The Author Index of section 4 gives a list of the authors in alphabetical order.

Details of author, subject, source and date of just over a hundred references are listed in section 5. They are numbered in chronological order.

The locations of reported vortex tube investigations are given in section 6 under the three sub-headings of Universities and Colleges, industrial firms and Government Establishments.

The general nature of each publication and the classification of its contents are indicated by the contents letters. These are found in section 4 and the key to the notation is given in section 1. Eighty-six of the references are technical reports on the vortex tube, fifteen are non-technical papers and the remainder are only indirectly connected with the vortex tube.

3. DEVELOPMENT AND SUMMARY OF VORTEX TUBE INVESTIGATIONS

3.1. Ranque's Invention (1931)

The vortex tube was first mentioned in a French patent (ref. 1), applied for by G.J. Ranque on the 21st December 1931.[x] The invention was called "an apparatus for obtaining from a fluid under pressure two currents of fluids at different temperatures" and the patent was assigned to the company of "La Giration Des Fluides". Ranque was a metallurgist at a steel works in Montluçon, Central France and it is thought that he may have observed the vortex cooling effect in connection with cyclone separators. The patent indicates that considerable research must have been done on the vortex tube and it mentions both the helical inlet chamber and multi-nozzle inlets. A similar patent (ref. 4) was applied for in the United States on 6th December 1932 and was

/granted ...

x see C.D. Fulton, refs. 48 and 49).

granted in March, 1934.

In June 1933, Ranque, (ref. 2), read a paper to the Société Française de Physique. Few details were given in this paper and he offered an explanation of vortex tube cooling different from that given in his patent. This explanation was, however, of the kind that is usually accepted today.

During the discussion on Ranque's paper, E. Brun, (ref. 3), a not undistinguished member of the Society and an aerodynamicist, dismissed Ranque's discovery on the grounds that he had confused static temperature with total temperature. Oddly enough, Ranque published no reply to this criticism and it is possible that he deliberately fostered scepticism in order to gain time in the development of his invention. These developments may have brought the disappointing realisation that the vortex tube was inefficient as a refrigerator for no further reference was made to it by the inventor.

3.2. Hilsch's Investigations, (1944)

Dr. Hilsch, of the Physics Institute at the University of Erlangen, Germany, read Ranque's paper and began investigations in 1944 with a view to using the vortex tube to cool underground mines and shafts. Although this particular application was not successful Hilsch was able to use the vortex tube as a substitute for the ammonia pre-cooler in his laboratory's air liquifying plant.

3.3. The American Rediscovery, (1945)

In June 1945, at the end of German War, C.W. Hansell, an investigator for the United States and British Technical Industrial Intelligence Committee, visited Erlangen University and rediscovered the vortex tube. Reports of the investigation are given in refs. 15, 16 and 17. About the same time R.M. Milton of Johns Hopkins University also visited Erlangen and took a

/working model ...

working model and a thesis by Hilsch back to the United States. The thesis was translated by I. Estermann of the Physics Department, Carnegie Institute of Technology and the translation was circulated through Wright Field. The original paper was published in Germany in April 1946, (ref. 18), and gave performance data and optimum dimensions for the vortex tube.

Widespread American attention was drawn to the vortex tube when Milton published a short descriptive article (ref. 19), in Refrigerating Engineering, May 1946. The extreme simplicity of the device suggested that it might replace many of the more complicated refrigeration appliances. This possibility stimulated a large number of investigations to be initiated between 1946-1948. During these investigations it became clear that the power required to drive a vortex tube was many times that required by a conventional refrigerator and that, in spite of its simplicity, its general application would not be practicable. Besides its possible importance as a practical device, the vortex tube presented a new and intriguing phenomenon in fluid dynamics.

3.4. Object of Further Investigations

After the initial burst of enthusiasm, research workers have continued to make about a dozen contributions each year. The objects of the investigations may be classified under four main headings:-

(a) Explanation and theoretical prediction of the vortex tube performance.

(b) Experimental investigation of the internal flow in the vortex tube as well as the overall performance.

(c) Modifications of the vortex tube configuration to increase the performance.

(d) Investigation of practical applications of the vortex tube in which the tube's advantage of simplicity is not over-ruled by the disadvantage of its high power consumption.

/3.5. ...

3.5. Experimental Investigations at the Massachusetts Institute of Technology, (1947)

Following Hilsch's experimental paper, the vortex tube was discussed in various minor papers. The next contributions of importance were contained in the following six theses (mainly experimental) which were completed at the Massachusetts Institute of Technology, during 1947; (refs. 25, 26, 32, 33, 39 and 40).

B.H. Mayer and J.W. Hunter, (ref. 25) and R.L. Greene (ref. 26) gave overall performance data showing the effects of inlet air pressure, cold orifice diameter and nozzle diameter.

The first experimental results on the internal flow in a vortex tube were given by G.A. Reed (ref. 32). He also included overall performances and the effects of altering the tube configuration. Reed suggested that the vortex tube might be used to cool the cockpits of high speed jet propelled aircraft.

Further performance results were given by R. Haddox, J.W. Hunter and W.H. Plunkett (ref. 33) and an attempt was made to vary the inlet air temperature.

R.J. Corless and R.L. Solnick (ref. 39) also gave overall data and showed sediment flow pictures and the static pressure distribution over the cold outlet plate.

The last paper to be published by the Massachusetts Institute of Technology in 1947 is by M. Fattah and A.N. Sweeny, (ref. 40). These experimenters used a convergent-divergent inlet nozzle and their investigations included overall performance data, visual flow, pressure and temperature measurements on the internal surfaces of the tube.

3.6. Canada, (1947)

A.F. Johnson, at the Department of Physics of the University of Toronto, also initiated an experimental investigation of the vortex tube in 1946 and his results were published

/in September ...

in September 1947 (ref. 41). In general he confirmed Hilsch's work and gave brief results when CO_2 and H_2 were used as the working fluid in place of air.

3.7. Theoretical Analysis, (1947-48)

Until the middle of 1947 explanations of the vortex tube process had only been suggested in general terms and there was no universal agreement or confirmation. The first important theoretical work was given during November 1947 in "Friction Laws and Energy Transfer in Circular Flow" by R. Kassner and E. Knoernschild, (ref. 42), of Wright Patterson Air Force Base. The analysis assumed that a free vortex was initially formed inside the vortex chamber, at the inlet nozzle, and that it was converted into a forced vortex as the air spiralled along the tube to the hot outlet. By making various assumptions the velocity and temperature in the resultant vortex was calculated. An estimate was then made of the tube's performance and this was compared with Hilsch's results.

In Norway the attention of D. ter Haar and H. Wergeland was drawn to the vortex tube by Milton's article and they published a brief theoretical analysis, (ref. 44) in January 1948. The explanation was based on the assumption that the process was simply adiabatic cooling in passing through the pressure gradient caused by the centrifugal field. Their simplifications do not appear to be acceptable.

A simultaneous theoretical contribution by G. Burkhadt, (ref. 45), of Germany, attempted to predict the vortex tube performance without a detailed analysis of the internal flow. The theory was based on several plausible assumptions and on an empirical observation from Hilsch's work.

In May 1948, C.D. Fulton completed two theoretical theses at the Massachusetts Institute of Technology. One dealt with the energy migration in the vortex tube whilst the other

/discussed ...

discussed the overall thermodynamics. Fulton first learned of the device in December 1946 whilst at the Mechanical Investigation Division of the General Electric Company where he began experimental investigations which were later taken over and published by J.E. Corr, (ref. 55). Fulton used this experience as a background to his theoretical investigation.

In the first paper, (ref. 48), he endeavoured to solve the equations for a three dimensional compressible vortex which was subjected to viscous or turbulent shear. He suggested an approximate solution and gave an expression for the temperature drop across the vortex. Although Kassner and Knoernschild did not consider compressible flow, Fulton generously concluded his report by stating that the method of Kassner and Knoernschild involved fewer uncertainties and that it appeared to agree satisfactorily with experiments.

Fulton's second paper, (ref. 49), considered the overall thermodynamics of the vortex tube and pointed out that, if the hot air from the tube was wasted, then the power required to drive a vortex tube refrigerator would be of the order of 100 times that of a well designed competing machine of conventional type.

3.8. Application to the Cooling of Aircraft, (1948)

E.M. Knoernschild and O. Morgensen of the Equipment Laboratory, Wright Patterson, wrote a paper, (ref. 50), in June 1948 entitled "Application of Hilsch Tube to Aircraft and Missiles". This was the first report to be concerned solely with the application of the vortex tube. It discussed the cooling of high speed aircraft or missiles and compared the merits of the vortex tube with those of the expansion turbine. For an expansion turbine with very low "specific speed" it was shown that the vortex tube might have superior efficiency and it was therefore concluded that, for small requirements of

/cooling air, ...

cooling air, the vortex tube would be the most practical means of cooling. With higher mass flow requirements the vortex tube would have lower efficiency and performance and its only merit would lie in its simplicity.

Although this paper discussed cooling systems in which the ram intake was utilised to give a source of high pressure air, much of the work would be applicable to systems using a high pressure bleed from a jet engine as suggested by Reed, (ref. 32).

3.9. Experimental Investigations at General Electric Company, (1948).

An experimental paper, (ref. 55), by J.E. Corr gave a summary of tests carried out at the G.E.C., Research Division, Schenectody, New York, between December 1946 and July 1947. The report, published in July 1948, stated that the company did not contemplate any further work on the project. The work investigated the effect on performance of inlet pressure, tube configurations and it was the first to give experimental results on the multi-nozzle inlet chamber as suggested by Ranque in his patent. Static pressure measurements were taken at the hot tube outlet and cold outlet diaphragm and, when used as parameters for plotting tube performance, revealed several interesting features. Corr carried out brief tests on a supersonic inlet nozzle but the results indicated a decrease of the temperature drop. Attemps were also made to investigate the internal flow using pressure and thermocouple probes. Other aspects included the use of a glass hot tube to observe flow lines on the internal wall, and a spectrograph analysis of hot and cold air samples revealed no separation of the component gases. Humidity measurements indicated only negligible increase of water vapour in the hot air.

The report suggested that a regenerative type of vortex tube system, in which the cold air was fed back to

/precool ...

precool the inlet air, might be used where large temperature drops were required. The advantages of this system were explained but the sample calculations assumed that the temperature depression in a vortex tube was independent of the inlet temperature.

Research on the vortex tube was again resumed at G.E.C. in 1949, (refs. 63, 69, 71 and 72).

3.10. Theoretical Investigations at the Massachusetts Institute of Technology, (1948-49).

The vortex tube work at the Massachusetts Institute of Technology was continued in a theoretical thesis by W.P. Barnes, (ref. 57), written September 1948. He assumed that the vortex tube flow was that of a two-dimensional symmetric and compressible vortex with small radial flow, and considered the cases of both laminar and turbulent shear. Mathematical difficulties prevented the completion of the laminar flow analysis, and an additional assumption had to be made for the turbulent flow case.

In May 1949, J.R. Nickerson, (ref. 60) of Massachusetts Institute of Technology, attempted to complete Barnes' work by making several assumptions and by using a slightly different approach to the equations of two-dimensional compressible turbulent flow. An approximate solution was obtained for the temperature distribution in the vortex, which agreed fairly well with the experimental results of Fattah and Sweeny (ref. 40). Nickerson, however, expressed the opinion that, in view of the assumptions, the agreement might be "somewhat of a coincidence".

3.11. Other University Investigations, (1949)

G.W. Scheper completed a thesis, (ref. 59) at Union College, Schenectody in May 1949. His experiments covered the internal flow of the vortex tube and gave the temperature, speed and flow direction distributions. He also proposed a heat

/transfer ...

transfer theory by which heat transfer occurred radially outward from the vortex core due to the low static temperature at the periphery. The experimental results were the first to show velocity distributions in the vortex. The theory was original in that it was based on forced convection due to static temperature gradients whereas previous investigators used the principle of energy transfer due to shear stress.

Other University contributions were made by J.J. Sochor of Syracuse University, (ref. 61), May 1949 and by B.B. Levitt of Rensselaer Polytechnic Institute, (ref. 62), in June 1949.

3.12. The Vortex Tube Free Air Thermometer. (1949)

Work on the vortex tube was revived at the General Electric Company's Research Laboratory under "Project Cirrus". In a report, (ref. 63), dated September 1949, B. Vonnegut described a novel application in which the vortex tube was used to eliminate the aerodynamic heating errors of free air temperature thermometers on aircraft.

The vortex tube was placed in the airstream, perpendicular to the direction of flight, and ram air was fed into the inlet whilst the hot end of the tube was exposed to suction by cutting the hot tube diagonally to its axis on the down stream side. The overall pressure difference between inlet and hot exit was about twice the dynamic head and its magnitude was controlled by a valve at the inlet. A thermometer bulb, to measure true air temperature, was placed inside along the axis of the vortex tube and the inlet valve was experimentally adjusted so that the thermometer read the true air temperature for a given altitude and aircraft speed. It was then found that this valve setting was satisfactory over a large range of speeds and altitudes, i.e. the error in true air temperature measurements was less than 0.5°C for speeds up to 260 m.p.h. in the range of altitudes, 0-25,000 feet.

/The success ...

The success of this device suggested that it could be modified to indicate true air speed. The principle was based on the determination of the difference between the stagnation temperature and the free air temperature along the axis of the vortex. The true air speed of the aircraft was then proportional to the square root of this temperature difference.

Additional references to the General Electric Company free air thermometer may be found in refs. 69, 71 and 72, and parallel work at the Cornell Aeronautical Laboratory was reported in April 1950 by S. Chapman (ref. 73).

3.13. Refrigerating Engineering (1950)

D.S. Webster carried out a limited investigation of vortex tubes at the Engineering Research Laboratory of E.I du Pont de Nemours and Co. Inc., and presented a paper to the 45th Annual Meeting of the American Society of Refrigerating Engineers, which was published in Refrigerating Engineering, February 1950, (ref. 70). His explanation of the vortex cooling aroused some controversy and it appeared that many previous publications on the vortex tube were not generally known.

In Refrigerating Engineering of May 1950, (ref. 74), C.D. Fulton re-asserted some of the explanations given in the less well known theses of May 1948, (refs. 47 and 48).

3.14. American University Research (1950-51)

A thesis by L. Lustick, (ref. 75), June 1950, of Syracuse University reviewed previous developments on the vortex tube and gave the theory for the overall thermodynamics. It was pointed out that the efficiency of the vortex tube would be considerably increased if the availability of the energy of high pressure hot gas could be realised instead of being rejected through the throttle valve. Unfortunately the added complication would undoubtedly cause the vortex tube to lose its most important advantage, i.e. simplicity.

/R. MacGee ...

R. MacGee submitted a thesis at Boston University Graduate School in 1950, (ref. 80). Past work on the vortex was discussed, and his experimental contribution investigated the pitch of the vortex along the hot tube by flow visualisation on the wall of a glass vortex tube. A comprehensive list of references was quoted and these were included in a bibliography by W. Curley and R. MacGee, (ref. 90) which was published by Refrigerating Engineering in February 1951.

3.15. Vortex Investigations and Applications, (1950)

In June 1950, H. Dornbrand wrote a very complete report (ref. 78), of the work done at the Republic Aviation Corporation under a U.S. Government contract. The report included experimental data on the effects of most parameters including those of inlet temperature and the pressure ratio across the vortex inlet and the cold outlet. Internal flow investigations included pressure, velocity and temperature traverses as well as visual flow patterns on the internal walls. A theory was developed for the flow in the laminar two-dimensional compressible vortex which was formed between two rotating cylinders. Attempts to improve the tube's performance included the testing of an internal guide vane.

Also in June 1950, (ref. 77), M.P. Blaber of the Research Laboratory of Kodak Ltd., Wealdstone, briefly described the construction of a simple vortex tube which he had made from perspex.

One of the first attempts to use the vortex for a practical application in Great Britain was given in a report by the De Havilland Aircraft Co. Ltd., Hatfield, (ref. 84), August 1950. This report investigated the applicability of the vortex tube for the cooling of a Vampire cockpit when the aircraft was flying at low altitudes in tropical conditions. Air, under pressure, was to be supplied from the jet engine to

/the vortex ...

the vortex tube. The report gave experimental data for tubes fitted with various inlet nozzles, hot tubes and cold outlets and a tube was developed which would satisfy the initial cooling requirements. It was considered inadequate however to meet revised specifications calling for an increased amount of cooling air.

3.16. European Developments, (1951)

After the publication of Hilsch's paper, most of the vortex tube investigations were carried out in America, but in 1951 the main contributions came from Europe.

In January 1951, K. Elser and M. Hoch, (ref. 88), described experiments in which various gases and gas mixtures were used as the working fluid in the vortex tube. They recorded the temperature drop and also analysed samples of gases leaving the hot and cold outlets. Unlike refs. 55 and 91 it was found that separation differences of about one per cent could occur between the hot and cold mixtures and the authors concluded that it was possible that the vortex tube was superior, or at least equal, to other separation devices. Elser and Hoch tried to ascertain if a centrifugal field was necessary for the Ranque cooling effect. A somewhat similar but smaller cooling effect was observed in the temperature distribution across four parallel air jets when placed in echelon.

U.A.F. Williamson and Miss J.A. Tompkins of the Mechanical Engineering Department, R.A.E. published some practical notes on the design of a vortex tube in March 1951, (ref. 92). It was stated that an inlet chamber with multi-inlet nozzles and with a diameter larger than the hot tube diameter would give improved performance. Their experimental results are difficult to compare with those of other investigators because the usual hot valve had been replaced by a fixed orifice which had the same diameter as that of the cold outlet.

The next paper, by H. Sprenger, (ref. 98), was published

/in July ...

in July 1951 and gave an account of several mainly qualitative but new experiments which were carried out at the E.T.H., Zurich, between 1949 and 1951. Hilsch and others had commented on the loud noise which was produced in the vortex. In order to investigate this effect Sprenger attached a tube, containing lycopodium powder, to the hot tube and detected an ultrasonic standing wave. The tests included the verification of Hilsch's results and the measurement of the temperature distribution along a simple vortex tube which had no hot flow and was without a cold diaphragm. Other novel features included the use of temperature indicating paints, vortex tubes constructed from celluloid or paraffin blocks, comparison of the internal flow pattern when the working fluid was air or water and the effect of rotating the vortex hot tube whilst the inlet nozzle remained at rest. The report observed that previous explanations of the vortex tube did not appear to be completely satisfactory and in a short article, published in August 1952, (ref. 110), Sprenger suggested that the vortex tube cooling and heating phenomena was due to an ultrasonic effect which was not solely restricted to circular flow. The heating and cooling effects experienced in a modified Hartmann type generator were cited as an example.

An American contribution on the vortex tube was made by S. Comassar, February 1951, (ref. 91). Previous work on the vortex tube was reviewed and details were given of experiments to investigate the application of the vortex tube to the reheat of gas turbines. In this case the vortex was used as a source of hot air. The application was not successful. The author states that an analysis of the exit gas streams from the vortex, indicated no separation of the constituents.

3.17. Applications of the Vortex Tube, (1952-53)

During 1952-53, emphasis was made on practical applications and four reports discussed devices which could be used in high speed aircraft.

/B. Vonnegut ...

B. Vonnegut of G.E.C. had developed a vortex tube which would measure free air temperatures for aircraft speeds up to 250 m.p.h. At the Naval Research Laboratory, Washington, this speed was increased to 500 m.p.h. by the more elaborate developments of Ruskin, Scheter, Merrill and Dinger, January 1952, (ref. 104).

In February 1952, (ref. 106), L.S. Packer, of the Physics Department, Cornell Aeronautical Laboratory, Inc., Buffalo, N.Y., issued a progress report of work which was being carried out for the United States Navy Department under "Project Vortex". The object was to develop the vortex free air thermometer for use on aircraft over the range of Mach numbers 0.3 to 0.95. Packer's report gave details of the experimental apparatus which he had designed to investigate vortex tube performances and, in particular, the internal flow characteristics. A list of references was also appended. (Reports of previous work on the vortex tube at Cornell Aeronautical Laboratory had been given by O.B. Finnamore, August 1948, (ref. 56) and S. Chapman, April 1950, (ref. 73).)

A further application of the vortex tube was given at the Proceedings of the Conference on Cooling of Airborne Electronic Equipment, March 1952, (ref. 108). A paper by M. Applegate of AiResearch Manufacturing Co., Los Angeles, California, described the use of a vortex tube for cooling and pressurising an airborne, 400 amps - 70 volt, generator. The vortex tube unit consisted of a bank of 20 tubes which was located between an air to air heat exchanger. Pressurised air was bled from the engine and precooled by ram air passing through the heat exchanger. The precooled air was then passed through the bank of vortex tubes to the generator. The unit supplied 6lb./min. of air at 160°F at sea level, 100°F at 50,000ft. and in the latter case the generator was pressurised to simulate 30,000ft. During preliminary experiments it was found that

/increased ...

increased efficiency was obtained by cooling the outsides of the hot tubes and they were therefore incorporated inside the air to air heat exchanger.

The application of the vortex tube to ventilated suit cooling in aircraft was discussed in a College of Aeronautics Tech. Note, April 1953, (ref. 114) by R. Westley. The report described part of the investigations which were being made at the College of Aeronautics, Cranfield. Under certain conditions the vortex tube presented a very simple method for cooling ventilated suits. The disadvantages of the device were that it was not as efficient as the more complicated refrigeration turbine and the latter had usually a larger available temperature drop.

3.18. Vortex Tube Theory, (1952)

One of the best theoretical contributions on the vortex tube was given by J.J. Van Deemter of the Royal Dutch Shell Laboratory, Amsterdam in Applied Scientific Research, 1952, (ref. 109). The paper combined the conceptions of Hilsch and Prins. Van Deemter pursued an approach similar to that used by Fulton, in which the temperature distribution in the vortex was determined by the ratio of work flux to heat flux, but he pointed out that the heat flux in turbulent circular flow was not solely proportional to the temperature gradient but included a term which was proportional to the radial acceleration.

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Scheper, G.W. Jr.	101	e,t
Schmidt, K.	111	e
Schneider, F.B.	64	Z.
Schultz-Grunow, F.	87	d

Author	Reference Number	Contents
Schultz-Grunow, F.	94	t
Schultz-Grunow, F.	100	t
"Science News Letter"	28	P. d
"Scientific American"	34	P. d
Shepherd, C.B., and Lapple, C.E.	7	Z.
Shepherd, C.B., and Lapple, C.E.	8	Z.
"Sira Technical News"	115	e
Sochor, J.J.	61	-
Solnick, R.L., (see Corless, R.J.)	39	e
Sprenger, H.	98	e
Sprenger, H.	103	e
Sprenger, H.	110	e,d
Stene, J.	81	-
Still, E.W.	113	Z. a
Sweeny, A.N. (see Fattah, M.N.)	40	e
Taylor, W.J., (see R.L.K.)	22	d
Teichmann, O.E., (see Kafader, A.D.)	107	P. d
Tompkins, J.A. Miss, (see Williamson, U.A.F.)	92	e
Van Deemter, J.J.	109	t
Vonnegut, B.	63	a,e
Vonnegut, B.	69	a,e
Vonnegut, B.	71	d,a
Webster, D.S. and discussion by Bailey, V.P., Goetz, A., Fulton, C.D. Hall, N., Bolstad, M.M. and Ashley,C.M.	70	d,t
Weise, W. (see Eckert, E.)	12	Z.
Weise, W. (see Eckert, E.)	13	Z.
Wergeland, H. (see Haar, D. ter.)	44	t
"Westinghouse Engineer"	35	P. d
Westley, R.	114	a
Williamson,U.A.F., and Tompkins,J.A.Miss	92	e
Wood, H.J.	21	Z.

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6. LOCATION OF VORTEX TUBE INVESTIGATIONS

6.1. Universities and Colleges

Boston University Graduate School, (Physics Department), Boston, U.S.A.

California Institute of Technology, California, U.S.A.

Cranfield, College of Aeronautics, (Aerodynamics Department), Bedfordshire, ENGLAND.

E.T.H., Institute für Aerodynamik, Zurich, SWITZERLAND.

Erlangen, Physikalishen Institut, GERMANY.

Illinois Institute of Technology, Research Foundation, U.S.A.

Johns Hopkins University, (Department of Chemistry), Silver Springs, Md. Buonaginurio, G.C., U.S.A.

Maryland, University of Maryland, (Mechanical Engineering Dept.) U.S.A.

Massachusetts Institute of Technology, (Departments of Chemical Engineering, Mechanical Engineering and Aeronautical Engineering). Cambridge 39, Massachusetts, U.S.A.

Minnesota, University of Minnesota, U.S.A.

Missouri, University of Missouri, U.S.A.

New Hampshire, University of New Hampshire, U.S.A.

Northeastern University, U.S.A.

Purdue University, (Mechanical Engineering Department) U.S.A.

Rensselaer Polytechnic Institute, Troy, New York, U.S.A.

Syracuse University, (Departments of Mechanical Engineering and Chemical Engineering), U.S.A.

Toronto, University of Toronto, (Department of Physics), Ontario, CANADA.

Union College, Schenectady, New York, U.S.A.

6.2. <u>Industrial Firms</u>

AiResearch Manufacturing Co., Los Angeles, California, U.S.A.

British Scientific Instrument Research Association Laboratories, ENGLAND.

Carrier Corporation, U.S.A.

Cornell Aeronautical Laboratory, Inc., Buffalo, New York, U.S.A.

De Havilland Aircraft Co. Ltd., (Structural Test House, "E" Block), Hatfield, Herts. ENGLAND.

E.I. du Pont de Nemours and Co. Inc., Engineering Research Laboratory, U.S.A.

General Electric Company, Research Division, Schnectady, New York, U.S.A.

General Motors Company, Research Laboratories, Detroit, U.S.A.

Godfrey, Sir George Godfrey and Partners Limited, Hanworth, Middlesex. ENGLAND.

Kodak Ltd., Research Laboratories, Wealdstone, Middlesex. ENGLAND.

Montlucon, "La Giration Des Fluides, Societe a Responsabilite Limitee", Montlucon. FRANCE.

Radio Corporation of America, Camden, New Jersey, U.S.A.

Republic Aviation Corporation, Farmingdale, L.I., New York. U.S.A.

Royal Dutch Shell Laboratory, Amsterdam. NETHERLANDS.

Teddington Controls Ltd., Cefn Coed, Merthr Tydfil, WALES.

Westinghouse Electric Corporation, Baltimore, Md., U.S.A.

6.3. Government Establishments

National Bureau of Standards, Washington, D.C. U.S.A.

National Physical Laboratory, Teddington, Middlesex, ENGLAND.

Naval Research Laboratory, Washington, D.C. U.S.A.

Office of Naval Research, Washington, D.C. U.S.A.

Royal Aircraft Establishment, (Mechanical Engineering Department), Farnborough, Hants. ENGLAND.

Wright-Patterson Air Force Base, (Propulsion Section and Equipment Laboratory, Engineering Division), Air Material Command, Dayton, Ohio. U.S.A.
