INVESTIGATION OF THE ENERGY DISTRIBUTION IN A HIGH VELOCITY VORTEX TYPE FLOW[1]

by

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INTRODUCTION

The vortex tube has been the subject of considerable interest since it was first patented by George Ranque of France in 1931. This device essentially consists of a simple tube such as shown in Figure 1, into which compressed air is introduced tangentially to the tube surface resulting in a separation of the compressed air into a low energy central region and a high energy outer region. In this country, the vortex tube principle was introduced immediately after the war, when a group of United States scientists discovered a working model in the laboratory of Rudolph Hilsch in Germany. The initial interest in the vortex tube was its possible application in the field of refrigeration. Extensive testing of the overall performance of this device indicated that it was quite inefficient and could not compete with the existing commercial refrigeration machines. During this period many different theories were advanced to explain the observed performance of the vortex tube, among these were the work of Kassner and Knoernschild (4), Fulton (2), Webster (9), Scheper (5), Schultz-Grunow (6), Ackeret (1), Wenig (10) and Van Deemter(7). The early experimental work consisted of measurements of total flow, cold end flow and hot end flow for various combination of nozzle sizes, orifice sizes and valve openings. The results of these investigations contributed little to a basic understanding of the energy transfers within a vortex type flow and could cast no light as to

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which, if any, of the analyses are basically correct.

In more recent years several new applications of the vortex type have been suggested. Among these are its use as a dehumidifier or mass separator and also its use as a dew point indicator. Perhaps the application now receiving the greatest attention is its use as a free stream static temperature indicator for aircraft at high flight speeds as first suggested by Vonnegut (8). In this last mentioned application, it is the hope that the cooling effect associated with the vortex type flow can be made to exactly compensate over a wide range of altitudes and speeds for the increase in temperature above free stream static condition caused by the aerodynamic heating effect.

Realizing that developmental work on applications of the vortex tube was continuing even though the energy transfers occurring within such a vortex type flow were not understood, the Heat Transfer Laboratory of the University of Minnesota submitted to the Office of Ordnance Research a proposal to undertake an experimental investigation. This proposal called for the measurement of pressures and temperatures within the vortex type flow and the interpretation of such measurements. The Office of Ordnance Research agreed to support the program which was activated in February 1954 and has continued under their support to the present time.

EQUIPMENT

Three Inch Diameter Vortex Tube

The primary consideration in the design of the vortex type was the establishing of a well-defined vortex in a tube of sufficient diameter to allow the insertion of measurement probes without causing a major disturbance of the entire flow. In addition, it was felt that the tube should be transparent to allow flow visualization studies. As a consequence, a three inch diameter Plexiglass tube of 30 inches in length was selected and is shown in Figure 1. The manifold section was fabricated of transparent plastic. Eight nozzles, equally spaced around the circumference of the tube directed the compressed air tangentially into the main vortex tube. At a distance of 1 inch from this nozzle cross section, the so-called "cold end" orifice section was located and was so constructed that various size orifices could be inserted from 0 inches (completely closed) up to 1 inch in diameter. At the other end of the 30 inch long tube a cone-shaped valve was located. This geometry was chosen to preserve flow symmetry, and with a single noted exception this was the valve used throughout the test program reported herein. Opening ports for inserting instrumentation were located at 6 axial positions along the tube. The completed unit was installed at the Rosemount Aeronautical Laboratories of the University of Minnesota where large quantities of clean dry compressed air were available. A venturi meter installed prior to the vortex tube measured the flow rates of the air.

The instrumentation necessary for the measurement of pressure and temperature had to meet several criteria. The probes have to be made as small as possible in order to minimize the flow disturbance, but still they must be stiff enough to withstand the forces within the flow field. The probes should also be relatively insensitive to variations in yaw and pitch, since it is practicable to rotate the probe only in one plane which may result in the probe not being completely aligned with the velocity vector. Fortunately, the National Advisory Committee had conducted many tests on total pressure probes and reference to this work (3) indicated total pressure probe geometries which appeared promising for the type of measurements anticipated. The resulting total pressure probes are scaled-down versions of probes tested by the NACA and are shown in Figure 2. The NACA measurements indicated that the Kiel type total pressure probe is insensitive to within 1 per cent of the impact pressure (i.e., total pressure-static pressure) over an angle of attack range of $\pm$ 41.5°. The other total pressure probe shown is insensitive to changes in angle of $\pm$ 37° with the same accuracy, 1 per cent of the impact pressure. These figures on insensitivity were obtained in a straight flow, and when the probes were used in the vortex tube some differences were found. In this case of rotating flow, the probes were insensitive to change in angle of approximately $\pm$ 10°.

The static pressure probes are shown in Figure 3. Two different models of the Prandtl probe are used, one with 4 holes around the circumference and the oth with only 2 openings. The 4 hole Prandtl probe was constructed first and when measurements indicated large radial pressure gradients in the vortex tube, it was decided to construct another probe with openings only on the sides, thereby havi openings only at the same radius. The third probe shown is a commercially avail probe constructed by the Flow Corporation of Cambridge, Massachusetts, and has excellent characteristics with respect to insensitivity to yaw and pitch angles. The pressure probes are from 1/16 to 1/8 inch in diameter and are of the hook ty thereby ensuring that all measurements are made in the plane of the probe stem.

The total temperature probes shown in Figure 4 were constructed in the laboratory and were designed to give high recovery factors, thereby allowing the measured temperatures to be interpreted directly as total temperatures. The temperature measurements with these two probes demonstrated excellent agreement outside of the central core.

A probe holder was designed to retain the probes and a Vernier micrometer mounted on the holder indicated the radial position of the probe inside the vortex tube. In addition, the orientation of the probe could be read from a mounted protractor.

Five Inch Diameter Vortex Tube

Recently a five inch diameter Plexiglas vortex tube has been constructed wi more control of the inlet air velocity orientation. This is accomplished by the use of a grid of 12 inlet guide vanes, which are so installed that one central control moves all 12 vanes simultaneously. This essentially allows control of the ratio of axial to circumferential velocity. The entrance to the guide vanes is carefully contorted to prevent flow separation. The resulting vortex tube is shown in Figure 21. Its 4 foot transparent section is connected by eight feet of sheet metal piping to a blower. The blower draws the air through the guide vanes, through the test section, the sheet metal piping and discharges it to the surroundings. An egg-crate type straightener is placed in the sheet metal piping before the blower.

TEST PROGRAM

Three Inch Diameter Vortex Tube

The main objective of the research program is to attain an understanding of the energy transfers within a vortex type flow. Consequently, it was decided to initially concentrate in the case where a well defined vortex is generated at the nozzle cross section and proceeds in one main direction down the tube to be discharged through the cone shaped valve. The "cold-end" orifice is completely closed during these studies.

Attempts were made at flow visualization, first by introducing smoke and later by use of a single wool tuft stretched across the tube on a fine diameter wire. The smoke technique was unsuccessful at the high velocities occurring within the 3 inch diameter tube as it immediately diffused, giving no information about the flow pattern. The second technique of introducing the wool tuft was more successful. At the outer edge of the flow near the wall the tuft indicated a velocity with negligible radial component and having a large circumferential component and also an axial component in the direction of the cone discharge valve. As the tuft was moved toward the central region of the flow the axial component decreased and the velocity was directed mainly in the circumferential direction. In the region near the very center, the tuft behaved in a very erratic manner and gave evidence of a turbulent core.

The next step involved the actual measurement of static and total pressures and total temperatures at several cross sections along the tube length. The initial tests were made with an inlet pressure of 10 psig, which was maintained by a pressure regulating valve. The total pressure was first measured by rotating the probe the position where the highest pressure was indicated and the angle recorded. static pressure and total temperature probes were subsequently set at this angl their respective measurements. To determine reproducibility of results, these and temperature measurements were repeated many times over a period of several retaining the same discharge valve opening and the same inlet pressure. On co of this test sequence the inlet pressure was increased, in turn, to 15 psig an psig and the required pressure and temperature measurements accomplished. All these runs were for the same opening of the cone-shaped discharge valve, with "cold end" orifice completely closed.

It was realized that the introduction of the probes into the flow causes disturbances. This is especially difficult to avoid when the flow is purely r tional, since the probe is then, so to speak, arranged in its own wake. This accomplished by introducing the pressure probe into the flow and then arrangi another probe of the same diameter near the first one and noting the change i reading of the first probe caused by the introduction of the second. The res of this study are presented in the section entitled "Results".

Throughout the entire sequence, the cone type valve had been used to ins symmetry of the flow. Another type of effective symmetrical valve is an orif Accordingly, it was felt desirable to obtain data with such a geometry and th valve was replaced with an orifice of the same area opening and data were ob at 10 psig inlet pressure.

Five Inch Diameter Vortex Tube

Up to the present time, the major program using the five inch diameter has been a flow visualization study wherein smoke is introduced into the tub through a small probe and the resulting flow field observed. The effects of the guide vane angle setting and of varying the conditions at the end of the long transparent section have also been studied.

RESULTS

Three Inch Diameter Vortex Tube

The local measurements of total and static pressure and total temperature are shown in Figure 5, 7 and 9 at three cross sections, identified as Sections A, C and E, for an inlet pressure of 10 psig. Section A is located 1 inch from the nozzle cross section; Section C, 6 inches from the nozzle cross section and Section E, 18 inches from the nozzle cross section and 12 inches from the exit. The plotted results are the measured values obtained in several runs taken at different times over a period of several weeks and using different probes. In the outer regions of the flow beyond a radius of 0.5 inches, the measured results show good repeatability for all 10 psig runs, while inside the 0.5 inch radius the results are much more erratic reflecting the difficulty of making measurements in this region. As anticipated, the total and static pressures decrease from a high value at the wall to a minimum at the center. The total temperature also decreases to a minimum at the center, or expressed in other words the temperature depression below the inlet temperature increases to a maximum at the center. Since the manifold temperature, T_m, varied somewhat from one run to the next, the total temperature results are shown as $T_m - T_t$ to take into account the change in inlet temperature.

It may be noted that the pressure and temperature measurements demonstrate a lack of symmetry about the center of the tube. This behavior is apparently due to the probe itself, for if the probe is inserted at the same cross section through an opening at 180° around the tube, the resulting measurements are a mirror image of the original measurements crossing them at the center of the tube. Again the results in the outer regions of the flow appear more reliable than those in the central region.

The velocity and the static temperature may be calculated from the measured results and these are shown in Figures 6, 8 and 10. In the outer regions of the flow beyond a radius of 0.5 inches the velocity and static temperature results are quite well defined, but in the central region the results scatter and any curve drawn in this region is completely arbitrary. The static temperature variation across the tube is seen to be quite small, being of the order of 10 degrees Fahrenheit. This small static temperature difference offers evidence that the observed separation of total energy (i.e., high total temperature in th outer flow regions and lower total temperatures in the central region) is not du to conduction heat flow.

Similar data on pressure and temperatures were obtained at inlet pressure levels of 15 psig and 20 psig and these results lead to the same conclusions as presented for the 10 psig inlet pressure. In the interest of space economy, th results for the higher inlet pressures will not be giv[illegible].

The measured pressures and temperatures were obtained by the insertion of a probe into the vortex flow and consequently the question arises as to what effect the probe produces on the flow field. There is little doubt that some disturbance is caused, even though the probe sizes were held to a minimum (from 1/16" to 1/8" diameter). In addition, at certain positions the rotating flow passes by the probe on its way to the probe entrance, thereby complicating the measurements. This effect certainly contributes to measuring difficulties found in the central region of the flow where the flow travels only a very shor distance after leaving the back surface of the probe until it reaches the probe entrance. Some indication of the effect of introducing an obstruction into the flow was obtained by inserting the probe to a given location and measuring the pressure at that point and then introducing a second obstacle the same diameter as the probe within the flow field and then reading again the indication of the first probe. The results of this study indicate an appreciable change in pres when the second probe is introduced into the tube when the measuring probe is the central flow region. When the measuring probe is located outside a radius 0.5 inches, the effects of the second obstacle are not strongly felt, generall in a change of less than 0.2 inches mercury at a total pressure of 7 inches of

The velocity as shown in Figures 6, 8 and 10 represents the total magnitude of the velocity vector. The orientation of this vector was approximately indicated by the position of the total pressure probe where a maximum reading was found. With this information, it was possible to resolve the velocity into axial and circumferential components. Typical values are shown in Figures 11 and 12. The radial component of the velocity is assumed to be negligible as indicated by the visual observation of the wool tuft. The axial velocity distribution indicates that large axial flow exists only in an annulus approximately 0.3 inches thick adjacent to the tube wall. It also shows an annular region at a radius of 0.5 inches in which the flow moves in a direction opposite to the main flow, i.e., a region of back flow. The calculation circumferential velocity V_θ should be consistent with the observed static pressure distribution since a force balance yields the relation $dPs/dr = \rho V_\theta^2/r$. This relationship is fulfilled except in the central flow region where the results are unreliable.

The variation of the static pressure, total pressure, total temperature and static temperature along the tube at constant radii is given in Figures 13, 14, 15 and 16 for the inlet pressure of 10 psig. It might be mentioned that the results for 15 and 20 psig have the same appearance which hints that a dimensionless representation should be possible. Such a representation has not been accomplished at the present time. The static pressure at any given radius changes very little in the axial direction, showing a slight decrease in the flow direction near the tube wall and near the central region of the vortex. At radii of 1/2 and 3/4 inches the static pressure increases in the flow direction, which may reflect the reverse flow found in this section of the tube. The total pressure distribution along the tube demonstrates this same reverse trend at the same radial positions. At any given radius, the total and static temperature increase along the tube length. This indicates a minimum temperature in the vicinity of the nozzle cross section.

The effect of increasing the inlet pressure on the local measured temperatures and pressures within the tube is shown in Figures 16, 17 and 18, where representative data for the cone-shaped discharge valve are shown for one axial position. At the outer region of the flow the pressure increases with increasing manifold pressure, while in the central regions of the flow the pressure is diminished with increasing inlet pressure. The decrease of static pressure in the core with increasing pressure is anticipated, since an increase in inlet pressure should increase the strength of the vortex, thereby causing the lower pressure values.

The influence of varying the valve geometry is appreciable as may be seen in Figure 20, where the measured pressures and temperatures are shown for the case where an orifice of 1-1/2 inch diameter was used to replace the cone valve. Although the same area opening is used for the orifice valve as for the cone valve the flow rate has changed from 142 scfm to 115 scfm and the measured pressures are higher in the flow region near the wall and lower in the center region. The temperature depression is much smaller in the case where the orifice valve is used. It is apparent that the boundary conditions at the exit of the vortex tube play a primary role in determining the pressures and temperatures throughout the entire length of the tube.

Five Inch Diameter Vortex Tube

At this stage in the experimental program it was decided to construct a larger tube with the more flexible inlet conditions and to attempt to visualize the flow field by the injection of smoke. Consequently, the previously described 5 inch diameter tube was constructed and the flow visualization study started. The smoke technique was successful at the lower velocities encountered in this study and gave support to the measurements found with the 3 inch diameter tube. Definite indications of an annular ring of reverse flow with a flow pattern as shown in Figure 22 were found when the guide vanes were set to give large circumferential velocity to the incoming air stream. This backward flow region may play a vital role in the energy transfer process since the air in this backward flow region has already traveled a considerable distance in the main flow direction. This means that some of the air at the nozzle cross section has spent a considerable time within the vortex and this may well account for the fact that the lowest temperatures are found at the nozzle cross-section.

In conclusion, it should be pointed out that the foregoing results deal only with one geometry and that much additional study is required before a complete understanding of the vortex flow is obtained.

REFERENCES

1. Ackeret, J., Personal communication.

2. Fulton, C. D., "Ranque's Tube", Refrigerating Engineering, 58:5, May, 1950, pp. 473-479.

3. Gracey, W., Letko, W., and Russell, W. R., "Wind Tunnel Investigation of a Number of Total-Pressure Tubes at High Angles of Attack - Subsonic Speeds", National Advisory Committee for Aeronautics, Technical Note 2331, April, 1951.

4. Kassner, R., and Knoernschild, E., "Friction Laws and Energy Transfer in Circular Flow", Technical Report No. F-TR2198-ND, Project No. LP-259, U. S. Air Force, Air Material Command, Wright Patterson Air Force Base, Ohio, March 1948.

5. Scheper, George W., Jr., "Vortex Tube - Internal Flow Data and Heat Transfer Theory", Refrigerating Engineering, 59:10, October 1951, p. 985 (see also comments by C. D. Fulton, p. 984).

6. Schultz-Grunow, F., "Die Wirkungsweise des Ranque-Wirbelrohres" (The Operation of the Ranque Vortex Tube), Kaltetechnik, Band 2, No. 11, 1950, pp. 273-274.

7. Van Deemter, J. J., "On the Theory of the Ranque-Hilsch Cooling Effect", Applied Scientific Research, (Netherlands), Section A, 3:3, 1952.

8. Vonnegut, B., "Vortex Thermometer for Measuring True Air Temperatures and True Air Speeds in Flight", Review Scientific Instruments, 21:2, February, 1950, p. 136.

9. Webster, D. S., "Analysis of Hilsch Vortex Tube", Refrigerating Engineering, 58:2, February, 1950, p. 163.

10. Wenig, Harold G., "The Ranque-Hilsch Effect in a Vortex Tube", Doctoral Dissertation, New York University, May 1952.

LIST OF FIGURES

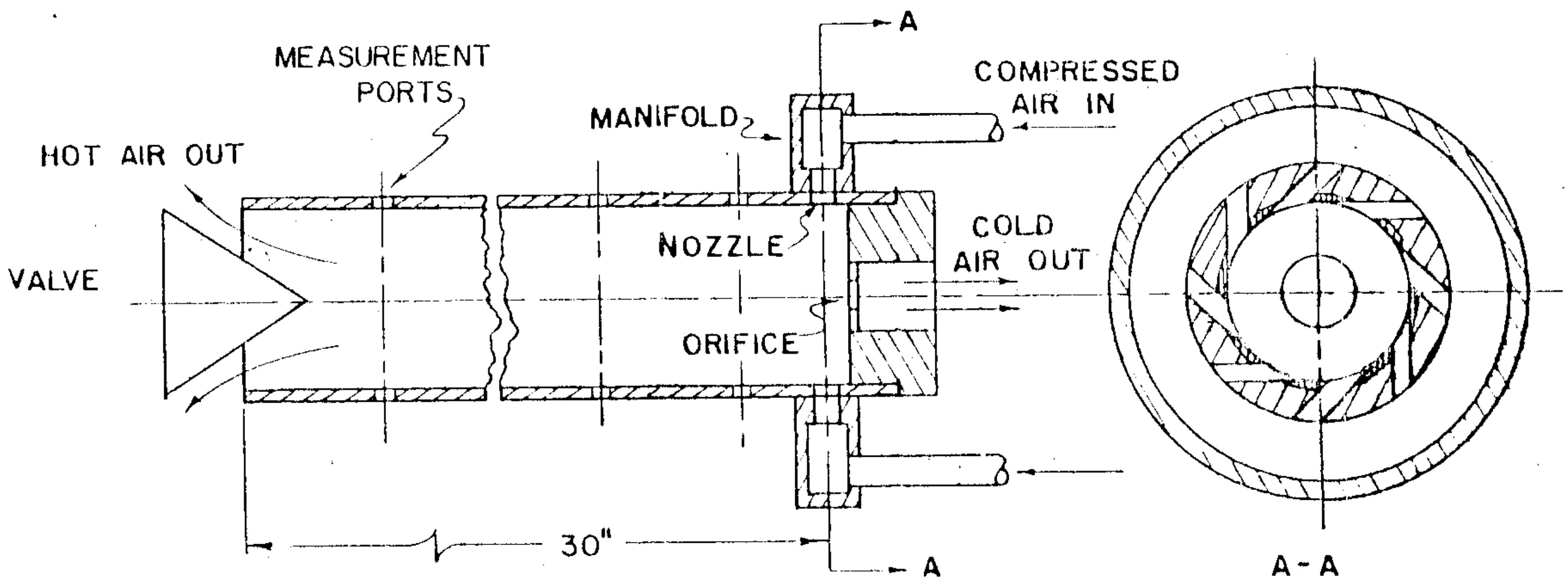

FIG. I VORTEX TUBE

CALCULATED VELOCITY AND STATIC TEMPERATURE IN A 3 INCH DIAMETER VORTEX TUBE

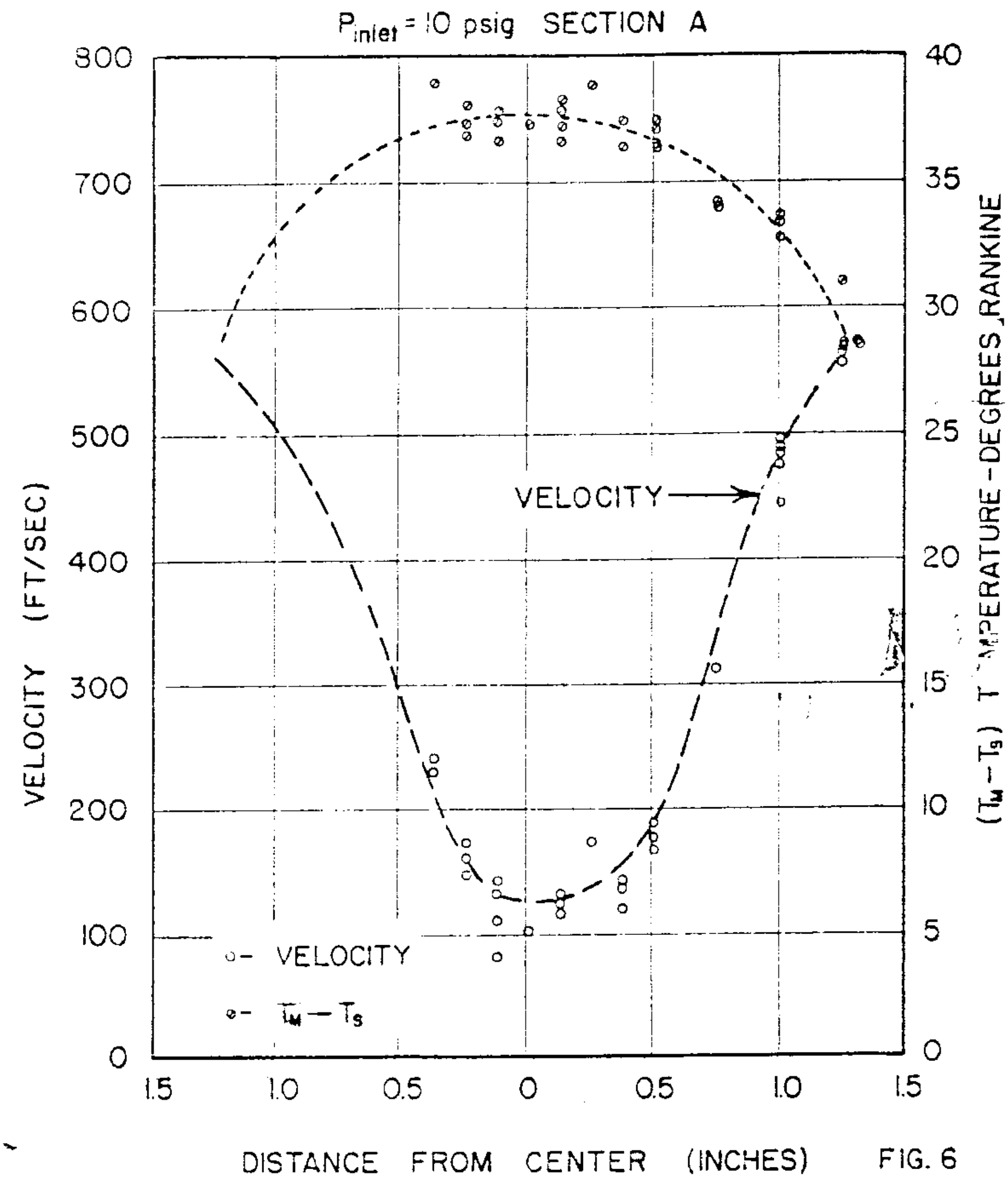

FIG. 6

PRESSURES AND TEMPERATURES IN A 3 INCH DIAMETER VORTEX TUBE

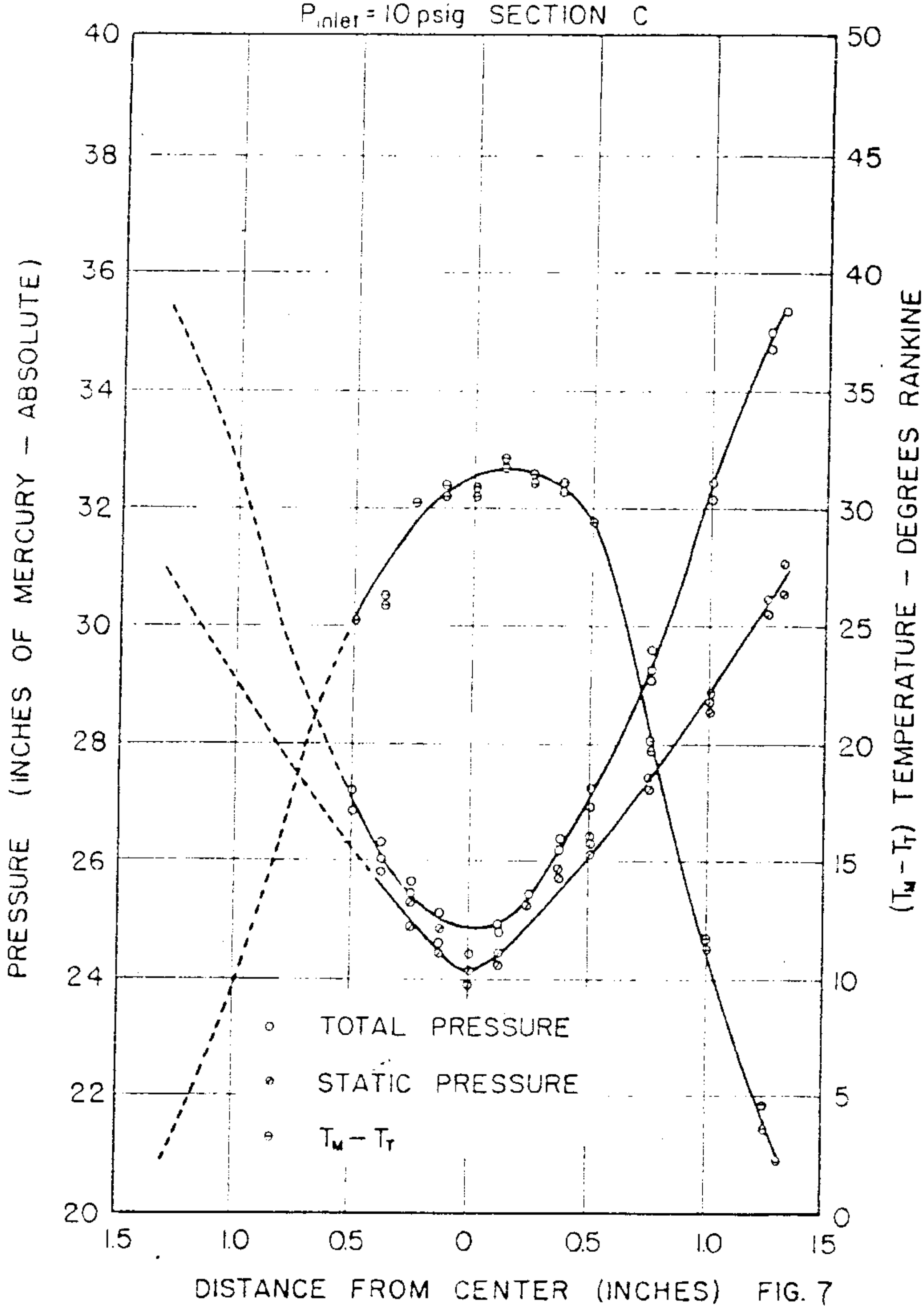

FIG. 7

SYMPOSIUM

THE VORTEX TUBE AS A TRUE FREE AIR THERMOMETER

This volume contains reprints of papers presented at a symposium on the subject "The Vortex Tube as a True Free Air Thermometer", held at the Armour Research Foundation, Chicago, Illinois on May 24, 1955.

The symposium was organized at the request of the Air Research and Development Command, Wright Air Development Center, Dayton, Ohio, for the purpose of exchanging information among the various organizations engaged in research programs on this subject.

Papers were presented by seven organizations with subjects ranging from the theoretical aspects of flow in vortex tubes to a description of the actual use of vortex thermometers for free air temperature measurement from aircraft.

The sponsors of the symposium wish to thank the authors and other participants who helped to make the meeting a success. Special acknowledgement is due Mr. K. W. Miller of the Armour Research Foundation and Mr. R. L. Fine of the Wright Air Development Center, who served as chairmen of the sessions.

H. A. Leedy
Director

HELD MAY 24, 1955 AT

ARMOUR RESEARCH FOUNDATION