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EFFECT OF INLET GEOMETRY ON FLOW-ANGLE CHARACTERISTICS OF MINIATURE TOTAL-PRESSURE TUBES

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16. Abstract

The effect of flow angle on the indication of miniature (0.02 to 0.32 cm o.d.) total-pressure tubes of simple geometry was experimentally determined for subsonic flow. The effects of flow angle are conveniently expressed in terms of the angle α_1 at which the error in indicated total pressure becomes 1 percent of the stream impact pressure. Generally, internally beveled tubes have the greatest value of α_1 (up to 27°), while flattened oval tubes have the smallest (down to 12°). Effects of variations in Reynolds number on α_1 were negligible. However, increasing the intensity of stream turbulence by 20 percent decreased the value of α_1 by 5°.

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EFFECT OF INLET GEOMETRY ON FLOW-ANGLE CHARACTERISTICS OF MINIATURE TOTAL-PRESSURE TUBES

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SUMMARY

The effect of flow angle on the indication of miniature total-pressure tubes of simple geometry has been experimentally determined. Various tip shapes were investigated: square-ended tubes with circular and flattened oval openings, and circular tubes with internal bevels. Tube outside diameters ranged from 0.02 to 0.32 centimeter. The tubes were tested in air at room temperature over a Mach number range of 0.3 to 0.9 and a Reynolds number range from 500 to 80 000. The effects of flow angle are conveniently expressed in terms of the angle α_1 at which the error in indicated total pressure becomes 1 percent of the stream impact pressure.

Generally, the beveled tubes have the greatest value of α_1 (up to 27°), while the flattened oval tubes have the smallest (down to 12°). The effect of variation in Reynolds number is negligible; increasing Mach number from 0.3 to 0.9 increased α_1 by about 2°. Increasing the intensity of stream turbulence by 20 percent decreased α_1 by about 5°. The effect of proximity of a transverse cylindrical supporting strut is negligible if the strut is two or more strut diameters downstream from the tube tip.

INTRODUCTION

One of the simpler measurements in the field of fluid mechanics is that of total pressure. For this measurement, it is frequently important to use total-pressure tubes which are insensitive to flow direction. The flow-direction characteristics of some common types of tubes are shown in figure 1. It is seen from the figure that the use of an internal bevel increases the range of insensitivity over that of a simple tube. Placing a shield around the tube increases the insensitivity range still further. The curves of figure 1 are from the work of Gracy, Letko, and Russell (ref. 1) which has been used

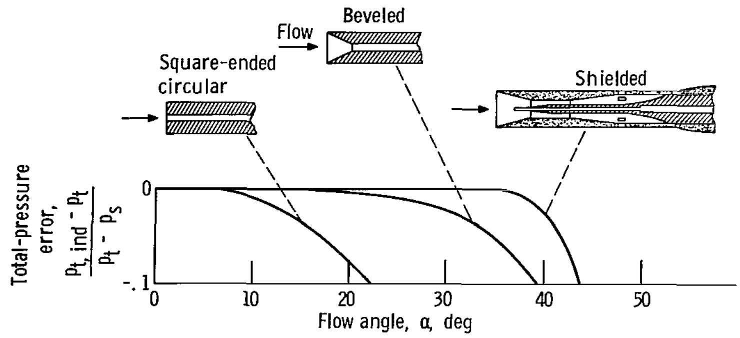


Figure 1. - Variation in total-pressure error with flow angle for three types of total-pressure tubes. ($p_{t,ind} - p_t$) is the total-pressure defect, and ($p_t - p_s$) is the impact pressure.

as a standard reference since 1951 for the flow-angle characteristics of total-pressure tubes. A review of the total-pressure tube, published in 1956, is given in reference 2. Reference 2 contains an extensive bibliography.

Reference 1 was concerned primarily with large tubes (o.d. about 2.5 cm) of the type suitable for airplane and wind tunnel use. In many applications in fluid mechanics, such as traverses in small turbomachinery or boundary-layer-profile studies, much smaller probes are required. The outside diameters of circular probes used in small turbomachines may be as small as 0.05 centimeter; boundary-layer-probe tips can have flattened oval openings as small as 0.01 centimeter. Due to space limitations and flow blockage, shields cannot be placed around these tubes.

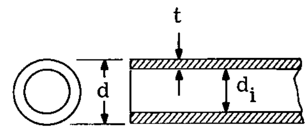
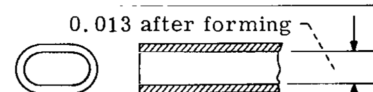
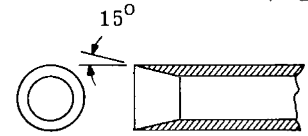
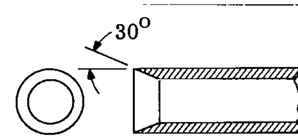
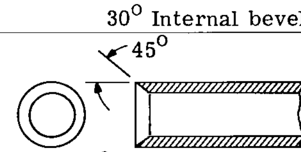
This report presents the flow-angle characteristics of miniature total-pressure tubes of simple geometry; that is, square-ended tubes with circular and flattened oval openings, and circular tubes with openings having internal bevels. Tube sizes ranged from 0.025 to 0.32 centimeter outside diameter. The tubes were tested in air at room temperature over a Mach number range of 0.3 to 0.9 and a Reynolds number range, based on tube outside diameter, of 500 to 80 000 (this involved a static-pressure range of 1.6×10^4 to 2.3×10^5 N/m^2).

TOTAL-PRESSURE TUBES AND TEST APPARATUS

Total-Pressure Tubes

The flow-angle characteristics were experimentally determined for square-ended tubes of five inlet geometries. Table I lists the tube sizes tested, according to inlet geometry, size, and diameter ratio. These are tubes with circular openings, tubes with flattened oval openings, and circular tubes with 15°, 30°, and 45° internal bevels.

TABLE I. - TOTAL-PRESSURE TUBES TESTED

Tube	Outside diameter d and wall thickness t				Ratio of inside-to-outside diameter, d_i/d	Inlet geometry
	cm		in.			
	d	t	d	t		
A-1	0.317	0.063	0.125	0.025	0.60	 Circular
A-2	.081	.015	.032	.006	.63	
A-3	.051	.010	.020	.004	.61	
A-4	.025	.005	.010	.002	.60	
A-5	.317	.046	.125	.018	.71	
A-6	.081	.013	.032	.005	.68	
A-7	.317	.030	.125	.012	.81	
A-8	.163	.015	.064	.006	.81	
A-9	.081	.008	.032	.003	.80	
A-10	.051	.005	.020	.002	.80	
[a]B-1	0.051	0.010	0.020	0.004	0.61	 Flattened oval
[a]B-2	.025	.005	.010	.002	.60	
[a]B-3	.051	.005	.020	.002	.80	
C-1	0.317	0.063	0.125	0.025	0.60	 15° Internal bevel
C-2a	.081	.015	.032	.006	.63	
C-2b	.081	.015	.032	.006	.63	
C-3	.317	.030	.125	.012	.81	
C-4	.081	.008	.032	.003	.80	
D-1	0.317	0.063	0.125	0.025	0.60	 30° Internal bevel
D-2a	.081	.015	.032	.006	.63	
D-2b	.081	.015	.032	.006	.63	
D-3	.317	.030	.125	.012	.81	
D-4	.081	.008	.032	.003	.80	
E-1	0.317	0.063	0.125	0.025	0.60	 45° Internal bevel
E-2	.081	.015	.032	.006	.63	
E-3	.317	.030	.125	.012	.81	
E-4	.081	.008	.032	.003	.80	

[a]Dimensions are of original tube, prior to forming.

For each geometry, tubes of various sizes and inside-to-outside diameter ratios d_i/d were examined. The outside diameters of the tubes ranged from 0.025 to 0.32 centimeter and the diameter ratios ranged from 0.6 to 0.8, which is typical of commercially available tubing. The overall dimensions of the tubes are given in table II. All tubes were machined to ensure square ends, free from burrs. The tips of tubes B-1, B-2, and B-3 were flattened for a distance of 0.2 centimeter. At least two tubes of each designation were tested, to allow for machining imperfections.

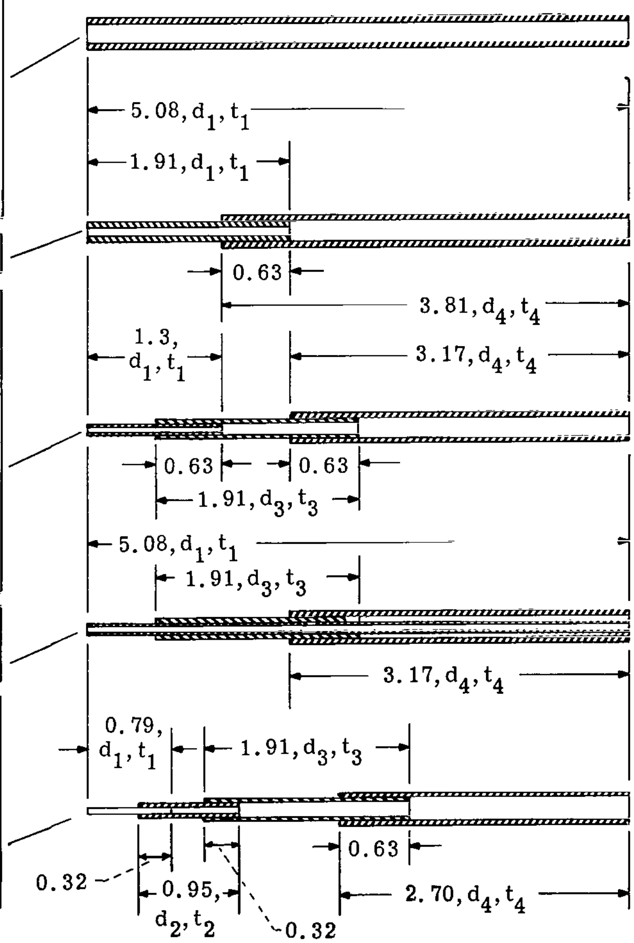
In addition, two square-ended circular tubes 0.16 centimeter in outside diameter with 0.030 centimeter thick walls were tested to determine the effect of a support on

TABLE II. - DIMENSIONS OF TUBES (IN CENTIMETERS)

[Tube geometries expressed as length, outside diameter, wall thickness.]

Tube	d_1	t_1
A-1	0.317	0.063
A-5		.046
A-7		.030
C-1		.063
C-3		.030
D-1		.063
D-3		.030
E-1		.063
E-3		.030
A-8	0.163	0.015
A-2	0.081	0.015
A-6		.013
A-9		.008
C-2a		.015
C-4		.008
D-2a		.015
D-4		.008
E-2		.015
E-4		.008
C-2b	0.081	0.015
D-2b	.081	.015
A-3	0.051	0.010
A-4	.025	.005
A-10	.051	.005
B-1	.051	.010
B-2	.025	.005
B-3	.051	.005

d_2	t_2	d_3	t_3	d_4	t_4
0.076	0.010	0.157	0.032	0.317	0.071



the flow-angle characteristics. These tubes are identical except for their support. The support of one extends entirely across the test nozzle, whereas the other is cantilevered. Initially, the tips of the total-pressure tubes were located four support diameters upstream of the support. The lengths of the tubes were then progressively decreased and the flow-angle characteristics determined down to zero support diameters.

Test Apparatus

A circular-cross-section support, 0.63 centimeter in diameter, was used for all total-pressure tubes. Figure 2 shows a tube mounted in the support at the test nozzle

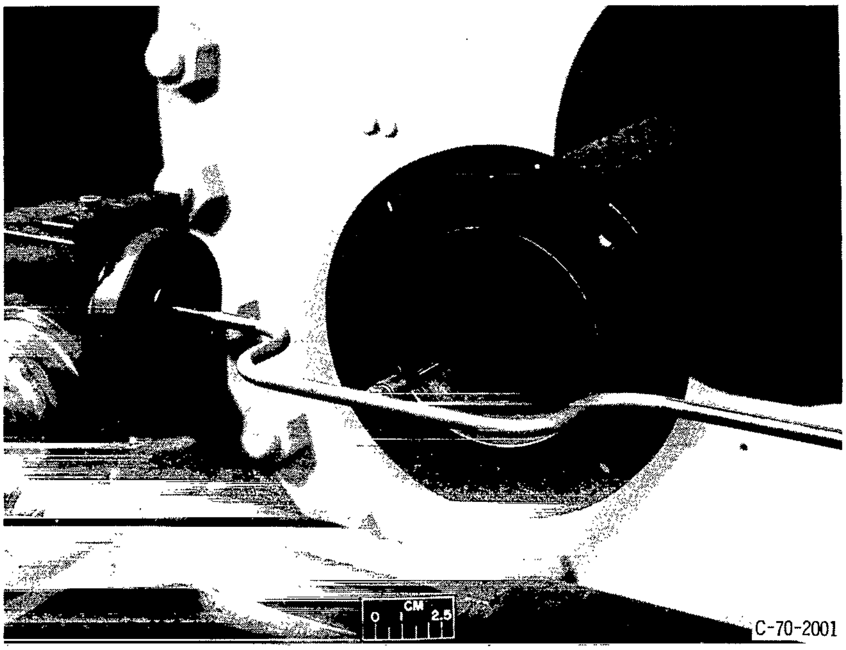


Figure 2. - Total-pressure tube mounted at exit of 9-centimeter free jet.

exit. The support extended entirely across the test nozzle exit. Each tube was inserted into a modified tube fitting soldered to the support. The axis of rotation of the support passed through the tube tip so that the tip remained at the same location for all angle-of-attack settings.

The characteristics of the total-pressure tubes were determined in the small tunnel facility shown in figure 3. This facility uses a free jet and a variable density jet with test nozzles having throat sections about 8 centimeters in diameter. The flow in the nozzles and test sections is isentropic within the accuracy of the pressure and tempera-

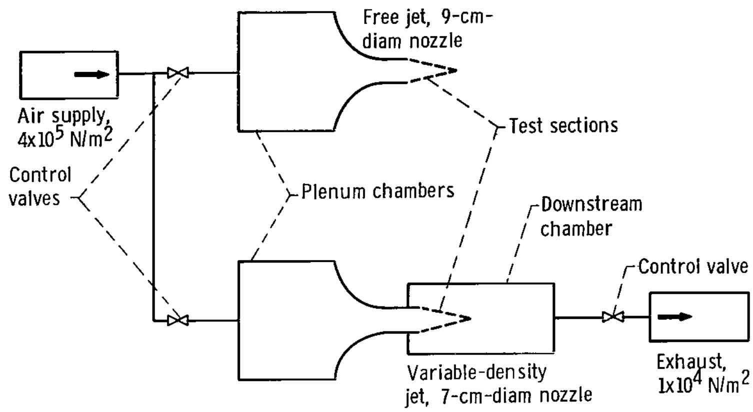


Figure 3. - Schematic diagram of the small tunnel facility.

ture measurement (0.05 percent or better) over 95 percent of the nozzle exit cross section. Tests were made at near ambient temperature. The range of conditions investigated were $500 \leq Re \leq 80\,000$, $0.3 \leq M \leq 0.9$, and $-45^o \leq$ flow angle $\alpha \leq 45^o$.

RESULTS AND DISCUSSION

The angle characteristics of a typical total-pressure tube are shown in figure 4. The figure is an actual trace of the electrical output of the pressure transducer used to measure the total pressure. The difference between the probe indication and true total pressure $(p_{t,ind} - p_t)$ is expressed as a fractional part of the impact pressure $(p_t - p_s)$, and is plotted against flow angle α. At zero flow angle, the tube is reading exactly total pressure; this is true for all the tubes reported herein. As shown in figure 4, pressure fluctuations are normally encountered when total-pressure tubes are at high angles of attack.

It would be awkward to present all results in the form of figure 4 because of the large number of tubes tested. For more convenient presentation, the flow angle at which $(p_{t,ind} - p_t)/(p_t - p_s) = -0.01$ has been determined, and then used as a figure of merit. This angle is termed α_1. It is obtained from physical measurements of traces such as figure 4. The accuracy of determination of α_1 in these experiments is about $\pm 0.5^o$.

The major portion of the results is for the case where the strut supporting the total-pressure tube is far enough downstream that its influence on α_1 is negligible. Later in the report, the effect of support proximity is shown.

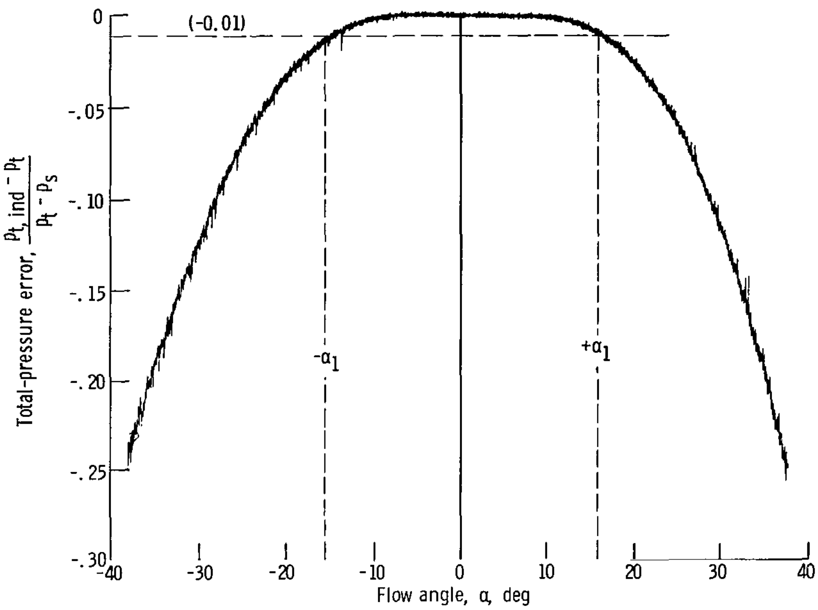


Figure 4. - Variation of total-pressure error with flow angle for tube A-1. Mach number, 0.6.

Overall Results

The overall results are presented in figure 5, which is a bar graph of α_1 for the probes tested. The figure shows the effect of tube type (i.e., circular with a square end, flattened oval with a square end, or circular with an internal bevel), tube size, ratio of inside to outside diameter, bevel angle, and Mach number. The results are for a static pressure of 1 atmosphere. Each bar represents the average value for two tubes. The average deviation between like tubes was 0.2° (1° maximum deviation). For tubes with flattened oval openings, a value of α_1 was determined for flow about the x axis. The tubes were then rotated 90° to obtain a value of α_1 about the y axis. Generally speaking, the beveled tubes have the highest value of α_1 (up to 27°), while the flattened oval tubes have the smallest (down to 12°). In all cases, α_1 increases slightly with increasing Mach number. Increasing the Mach number from 0.3 to 0.9 increases α_1 by 1 or 2 degrees. It is interesting to note that this is opposite to the trend found in reference 3 for the case of shielded total-pressure tubes with large values of α_1.

There is no significant trend in α_1 with tube size over the range tested. This is shown in figure 5 for the series A tubes with a constant ratio of d_i/d of 0.6, where the tube size ranged from 0.025 to 0.317 centimeter in outside diameter. However, it should be noted that the higher time response of the smaller tubes, if they are fed into a

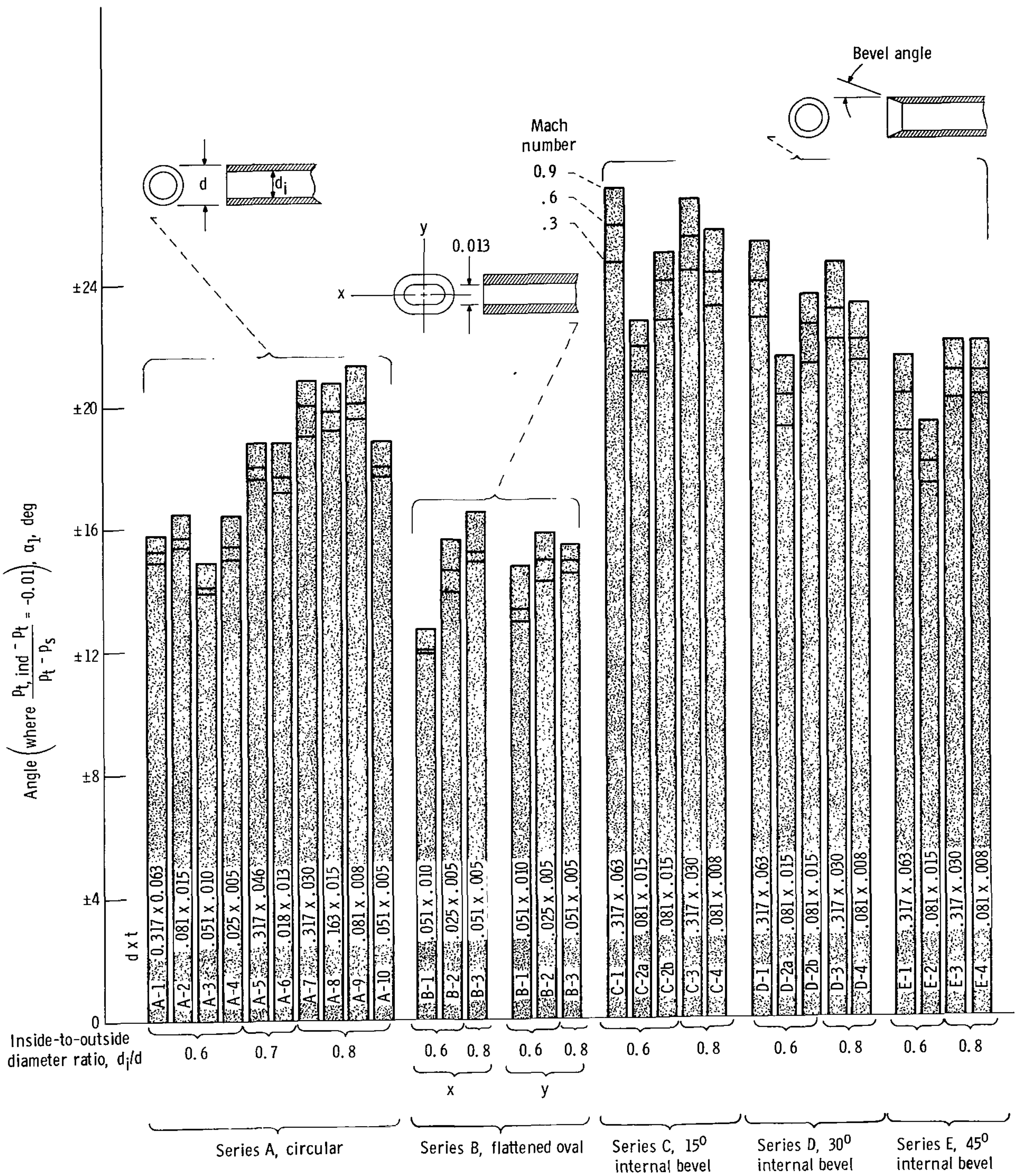


Figure 5. - Summary of test results.

system of appreciable volume, may make them unsuitable for a fast traverse through a large pressure gradient.

The effect of inside-to-outside diameter ratio d_i/d is shown more clearly in figure 6. Figure 6 is a plot of α_1 against diameter ratio for circular tubes with square ends. The figure also includes data from reference 1. The present work covers a ratio range of 0.6 to 0.8, which is typical of commercial tubing. Angle α_1 increases by about 4^o as the diameter ratio increases from 0.6 to 0.8. Also, the insignificant effect of tube size is again demonstrated here because a 100-to-1 range of tube size is repre-

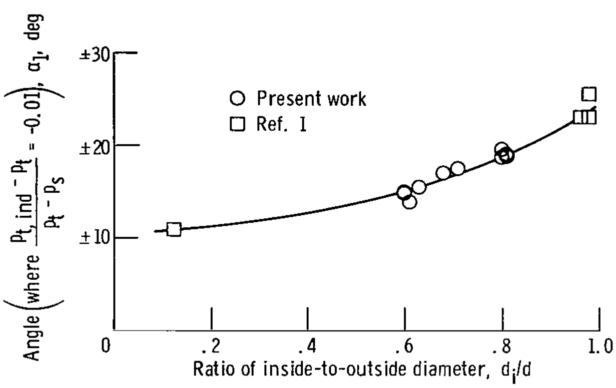


Figure 6. - Variation of angle α_1 with ratio of inside-to-outside diameter for circular entrance tubes. Mach number, 0.3.

sented in figure 6 by inclusion of the data of reference 1. It is evident that thin-walled tubing is to be preferred when one is concerned with angle effects.

Figure 7 is a plot of α_1 against bevel angle. Again, data from reference 1 are included. It is seen that α_1 increases as the bevel angle decreases.

From figure 5 it can be seen that some of the tubes (e.g., A-3, B-1, C-2a, D-2a, and E-2) have values of α_1 slightly below what might be expected. From physical inspection, the quality of the tube inlets appeared to be satisfactory. Also, the agreement between the values of α_1 obtained from the two samples of each of these tubes was normal (within 1^o). However, it was discovered that α_1 could be changed slightly by altering the internal geometry of the tubing downstream of the inlet. For example, the C-2a configuration had internal geometries which consisted of 1.3 centimeters of 0.05-centimeter-inside-diameter tubing followed by 1.3 centimeters of 0.1-centimeter-inside-diameter tubing; its α_1 was 21^o at $M = 0.3$. The C-2b configuration had 5.1 centimeters of 0.05-centimeter-inside-diameter tubing; its α_1 was 23^o at $M = 0.3$. A similar effect was obtained with tubes D-2a and D-2b. It can be speculated that the "effective" geometry at the tube lip is changed (consequently changing α_1) by either the

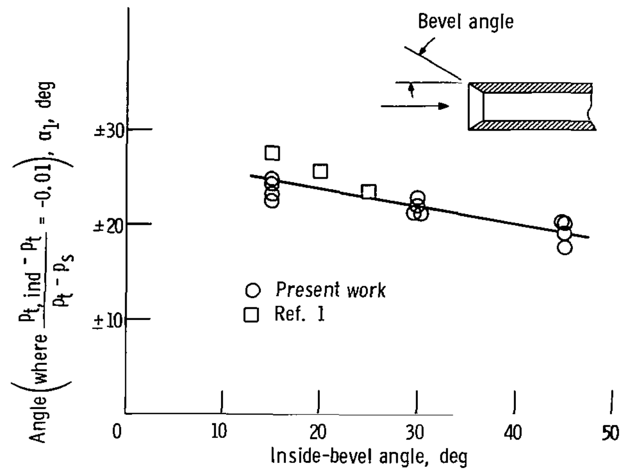


Figure 7. - Variation of angle α_1 with inside-bevel angle. Mach number, 0.3.

change in internal resistance (which would affect averaging of minute flow fluctuations within the tube), or by standing waves which may be present inside the tube under certain conditions.

Reynolds Number Effects

No significant variation of α_1 with Reynolds number was noted. This is shown in figure 8 for a Reynolds number range (based on tube o.d.) from 500 to 5000. The results are for A-10 configurations and Mach number 0.3; however, figure 8 is representative of all tubes tested. If the Reynolds number had been based on wall thickness, the lower value would be about 50. This would be low enough for viscous effects to be present in the lip region of the tube, but apparently there is negligible effect on α_1.

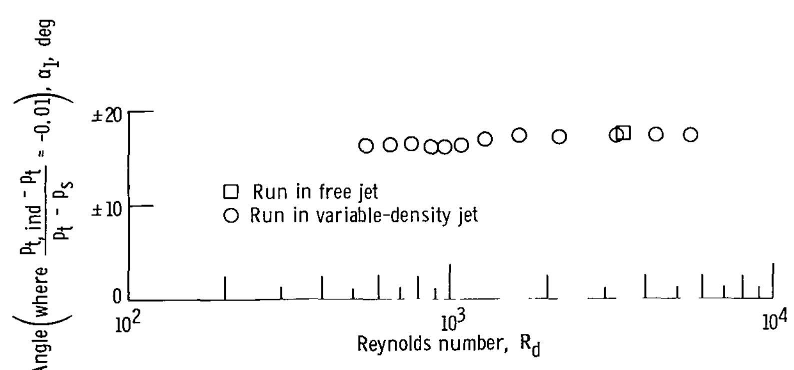


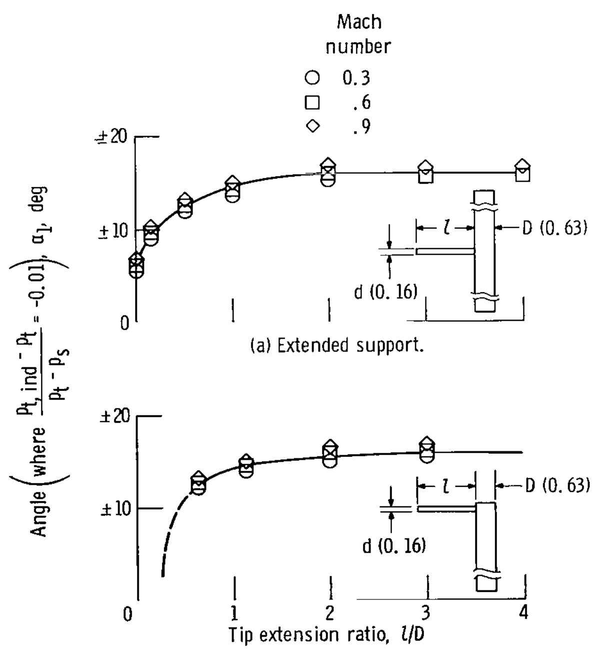
Figure 8. - Variation of angle α_1 with Reynolds number for tube A-10. Mach number, 0.3.

Support Effect

Results presented thus far have been for the case where the supporting strut is far removed from the total-pressure sensing tip. However, in many applications utilizing measuring probes or rakes (i.e., many sensing elements on a single support), it is sometimes necessary to have a total-pressure sensing tip located near its supporting strut. So, it is of interest to know how small the tip-to-support distance can be without influencing α_1. Figure 9 presents this information. The figure shows the variation of α_1 with tip extension ratio l/D for both the extended and cantilevered supports. The extended support is normally associated with rakes, while individual probes normally use cantilevered supports. For both cases, there is negligible effect on α_1 if the sensing tip is two or more support diameters upstream from the support.

The two-or-more-support-diameters criterion is close to that required when considering total-pressure-gradient effects. That is, when measuring a total-pressure gradient, the sensing tip should be three or more support diameters upstream of the support to keep the support from influencing the measurement (ref. 4). So, if a particular probe or rake is designed properly for measurements in a gradient, the support will be far enough removed so that there will be no influence on α_1.

In figure 9(b), it can be seen that α_1 approaches zero for small values of the ratio



(b) Cantilevered support.

Figure 9. - Variation of angle α_1 with tip extension ratio.

l/D. Actually, with l/D equal to 0.25, the total-pressure error with the probe alined with the flow is greater than 1 percent. This effect is due to the crossflow near the end of the support, which produces a local flow angle at the sensing tip. This effect does not occur for the case of the extended support, as shown in figure 9(a).

Normalized Angle Characteristics

In some cases, knowledge of α_1 alone is insufficient when using fixed total-pressure tubes. It is then of interest to know the shape of the curve of total-pressure error against flow angle. Figure 10 presents this information in a normalized manner so that only a single curve is required for each type of tube. In the figure, the abscissa is expressed as a fraction of α_1. That is, a value of 1 on the abscissa represents α_1, and also corresponds to a value of -0.01 on the ordinate. In order to convert the ab-

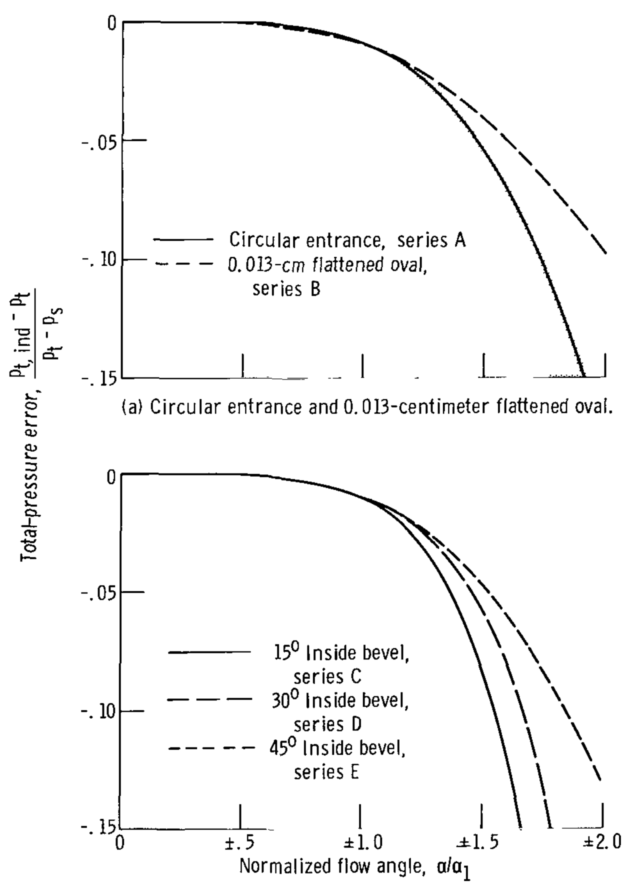


Figure 10. - Variation of total-pressure error with normalized flow angle for all tubes.

scissa of figure 10 into degrees for a particular total-pressure tube, α_1 for that tube must be obtained from figure 5 and used as an abscissa multiplier. From figures 10 and 5, the error in total-pressure measurement can be determined for flow angles up to about a value of $2\alpha_1$. All tubes indicate true total pressure for flow angles up to a value of $\alpha_1/2$.

Since all curves of figure 10 have the same values at normalized angles of 0 and 1, all curves are nearly identical between these points. However, for normalized angles greater than 1, each type of tube is represented by a different curve. These curves represent averages for several tubes and several Mach numbers. The scatter in the data associated with such a curve is typified by the shaded band in figure 10(a), which applies to the square-ended tube. The shaded band would be narrower for the other types of tubes.

A general result that appears from figure 10 is that the greater the value of α_1, the more steep is the dropoff for normalized angles greater than 1.

Turbulence Effects

The information presented thus far has been for low values of intensity of stream turbulence (less than 1 percent). Since total-pressure tubes are sometimes used under conditions where turbulence is appreciable, it is of interest to know the effect of turbulence on α_1. Figure 11 shows the variation of α_1 with intensity of turbulence for a square-ended tube (A-1) and for an internally-beveled tube (C-1). The range of turbulence intensities was obtained by positioning the total-pressure tubes at particular positions in the mixing region of the jet issuing from the 9-centimeter-diameter nozzle (fig. 2). A

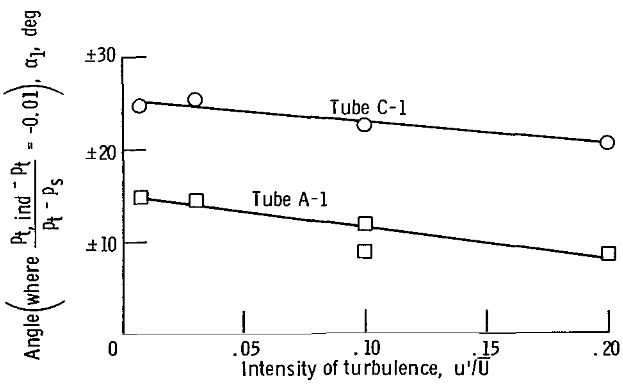


Figure 11. - Variation of angle α_1 with intensity of turbulence. Mach number ≤ 0.3. (u' is root-mean-square average of the fluctuating velocity; $\bar{U}$ is mean velocity.)

hot-wire anemometer had previously been used to measure the intensity of turbulence at these particular positions. It can be seen from figure 11 that α_1 decreases with increasing turbulence; the decrease is about 5° for a 20 percent increase in turbulence.

The scale (size) of turbulence for the data of figure 11 was between 0.8 and 2.5 centimeters.

SUMMARY OF RESULTS

This report presents the experimentally obtained flow-angle characteristics of miniature total-pressure tubes of simple geometry; that is, square-ended tubes with circular and oval openings, and also tubes with openings having internal bevels. Tube diameters ranged from 0.02 to 0.32 centimeter. The tubes were tested in air at room temperature over a Mach number range of 0.3 to 0.9 and a Reynolds number range of 500 to 80 000. The flow-angle characteristics are expressed in terms of α_1, the angle at which the total-pressure error becomes 1 percent of the impact pressure. The following significant results were obtained from the experiments:

1. Generally, the internally-beveled circular tubes have the greatest value of α_1 (up to 27°). Also, the value of α_1 decreases as the bevel angle increases. The flattened oval tubes have the smallest value of α_1 (down to 12°). (It would be expected that the value of α_1 for flattened oval tubes may be appreciably increased if an internal bevel is machined before flattening.)
2. Thin-walled tubes give a higher value of α_1. Increasing the ratio of inside-to-outside diameter from 0.6 to 0.8 for the square-ended tubes with circular openings, increases α_1 by about 4°.
3. In all cases α_1 increased slightly with increasing Mach number. Increasing the Mach number from 0.3 to 0.9 increased α_1 by 1 or 2 degrees.
4. No significant variation of angle characteristics with Reynolds number or tube size was noted over the ranges tested.
5. The effect on α_1 of placing a supporting strut downstream of the total-pressure tube is negligible if the strut is two or more strut diameters downstream from the tip.
6. Increasing the stream turbulence decreases α_1. A 20 percent increase in intensity of turbulence, at a Mach number of 0.3, decreased the angle by 5°.
7. All tubes indicate true total pressure for flow angles up to $\alpha_1/2$.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 26, 1971,
720-03.

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