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EXPERIENCES WITH FLOW-DIRECTION INSTRUMENTS

By B. Eckert

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SUMMARY

The method of recording the direction of flows on the basis of the hydrodynamic zero-point measurement has now reached a certain limit, in spite of the good results achieved. While the available flow-direction devices are accurate enough for many purposes, they are all insufficient for perfectly exact prediction of the flow direction. The next problem will be to achieve a point-by-point flow-direction record, whereby the test procedure must be simplified, accelerated, and the degree of accuracy of the test data, improved.

INTRODUCTION

I. METHODS OF FLOW-DIRECTION RECORDING

Theoretically, there are two ways of measuring the direction of flow: direct and indirect.

1. Direct Measurement

By this method the angle of the flow and the pressure of the flowing medium are directly recorded and read on protractors or pressure indicators. The angle of yaw of the instrument with respect to a fixed reference plane, affords an indication of the flow direction. The process is therefore very simple; but because of space requirements, such an instrument can only be employed in the free stream or in spatially very extensive flows. If a Prandtl tube is used, the static pressure and the total head are obtained immediately without pressure conversion factor, while most of the other instruments require a correction factor for the pressure.

*"Erfahrungen mit Messgeräten zur Bestimmung der Strömungsrichtung." Jahrbuch 1938 der Deutschen Luftfahrtforschung, pp. II 381-386.

2. Indirect Measurement

In principle, a surface contains a number of orifices at certain angles (for instance, the spherical pitot) on which the pressure is recorded. These pressures afford coefficients which are represented in calibration curves for the particular instrument. From the recorded pressure and the calibration curve, a definite angle of flow, also the static pressure and the total head are obtained. To plot the calibration curves, the instrument is mounted on a yawing device and the pressure at the different orifices of the instrument recorded at different angular settings. The obtained and computed coefficients are then plotted against the angular setting. This method is simple and much preferred for experimental use. It has the added advantage of requiring a minimum of space.

II. INSTRUMENTS FOR FLOW-DIRECTION MEASUREMENTS

I. Generalities

The simplest method of flow-direction measurement is to render the flow paths visible and to record the streamlines by camera or motion-picture machine. The streamlines in the water can be made visible by air bubbles, dyes, or lycopodium powder. A simple direction reading of an air stream is possible with the aid of wool tufts or streamers. This method is preferred in small tunnels, for instance, between the fins of cylinders, or for viewing flow around models where, for reasons of space, pitot tubes are unsatisfactory. Smoke mixed with air affords a better insight into the flow conditions.

Where space permits, the hydrodynamic zero-point measurement is widely used. This method employs a symmetrically designed pitot-static head, with the same pressure distribution on both sides, so that the orifices provided at the same angles to the stagnation point indicate the same pressure. The advantage of this type is its satisfactory use in both water and air. The turbulence effect is small, especially since the errors accruing from defects in symmetry are usually much greater. For accurate reading, stagnation-point instruments are unsatisfactory by nonstationary flow with respect to time since, by periodic flow, only a time average of the flow velocity

$$v' = \sqrt{\frac{1}{\rho/2}\int_0^t (p_{tot} - p_{stat})\, dt}$$

instead of the actual average value

$$v = \int_0^t \sqrt{\frac{1}{\rho/2}(p_{tot} - p_{stat})}\, dt$$

can be measured. Flows embodying strong vortex zones, such as downstream from bodies of resistance, are also difficult to measure.

In restricted flow spaces, measurement with pitot-static heads is no longer possible, since the spatial extent of the instrument disturbs the flow at the test point. The test instrument itself must be suspended in the flow so as to be bend-resistant and free from vibrations. Its size depends upon the mechanical practicability and the possibility of housing the little pressure tubes on the inside. The spindle or shaft diameter also depends on the size of these little pressure tubes. If they are too narrow or too long, especially in water, the terminal pressure state can only be accurately defined after several minutes. For this very reason, the pressure tubes are given a greater diameter downstream from the experimental head.

2. Design Types

The design of the head is largely dependent on whether the flow is two- or three-dimensional:

a) Two-dimensional flow direction - pitot tube.- Figure 1 shows the pitot tube and the relationship between total head and angle of yaw as obtained by calibration - the tube being yawed until zero total head is achieved by a positive or a negative angle of yaw. This brings the direction of flow in the exact center of the two pressure-reversal points. The total head is measured very simply by setting the pitot in the median position. Up to $\psi \pm 15^\circ$ yaw, the pitot tube is not directionally susceptible to oblique flow, and therefore, very practical for total-pressure measurement (fig. 1). But, after determination of the pressure-reversal points, it is also useful for flow-direction measurement. The yawing of the instrument must be made about the pressure test station. The static pressure is then best determined by another instrument - say, by Prandtl tube, as comparative instrument. By strong turbulence, however, the pitot tube fails as direction instrument because the errors become excessive. The principal advantage of the pitot tube consists in its point-by-point measurement, since only a very restricted zone of flow is involved.

Prandtl Pitot Tube

Figure 2 shows this well-known instrument and the pressure variation in relation to the angle of yaw. The pressure-reversal point of the instrument employed in the Institute is located at $\pm 48^{\circ}$. The permissible angle of yaw is $\psi = \pm 5^{\circ}$. Theoretically, this instrument is also suitable for flow-direction measurements, provided the reversal points, as in figure 2, are known. These reversal points must be defined for every instrument, since the head shape has a far-reaching effect on the direction susceptibility.

Since the Prandtl tube, like the pitot tube, must be bent for point-by-point measurements, where the spindle must be yawed around the total head station, these instruments are unsuitable in measurements adjacent to flow boundaries (i.e., walls).

Figure 3 shows a Prandtl tube arranged for a three-dimensional-flow measurement, which is also suitable for direction determination in the open jet.

Sers Plate (reference 1)

This instrument is illustrated in figure 4. It consists of a round plate with a 0.4-millimeter pressure orifice in the center soldered to a tube. The pressure reversal point is determined by yawing and, through it, a certain angular deflection from the zero position is ascertained. The pressure variations obtained with different plates are shown in figure 5. The normal setting - i.e., parallel flow around the plate, gives the static pressure, to be corrected with a correction factor; a 90° setting of the plate to the flow direction enables the total-head measurement. On slightly curved flow, the instrument is quite practical for flow-direction measurements; but on greatly curved flow paths, the necessary disk dimensions involved prove its use as unsatisfactory.

Two Pitot Tubes Set at Specific Angle (fig. 6)

In the tests the pitot tubes sloped at about 126° toward one another. The zero point was determined by adjustment for equal pressures on both pitot tubes, or zero setting on the differential pressure gage. The bisector of both pitot-tube axes is then identical with the flow direction. Based on the calibration of the single pitot tube, the pressure-reversal point occurred at $\psi \pm 63°$ and with it also, a marked direction susceptibility, as seen in figure 1.

Cylindrical Tube with Openings (fig. 7)

The instrument consists of a cylindrical tube with two pressure leads connecting with the outside surface (reference 2). The location of the holes in the cylinder was first mathematically computed by determining the pressure distribution on the surface of the cylinder - yielding the pressure-reversal point at around 42°. Graphical differentiation established the maximum pressure change at 42° deflection with respect to neutral position; so the pressure orifices were located at these angular settings. The great deflections on the pressure indicators, even by very small rotations of the cylindrical tube, were indicative of the great susceptibility of the instrument to directions. With the test orifices at 42° angle, the static pressure p_o is measured by exact flow on the center line of the cylinder. The total pressure p_{tot} is measured by turning one orifice 42° in the flow direction, or by providing an orifice at angle 0. Figure 7 also shows the pressure variation plotted against angle of yaw ψ. As comparative instrument in these tests, a Prandtl tube with a recorded dynamic pressure of

$$p_{g_V} - p_{o_V} = \frac{\rho}{2} v^2$$

was employed. The coefficient k

$$k = \frac{p_g - p_o}{p_{g_V} - p_{o_V}} = \frac{p_g - p_o}{\frac{\rho}{2} v^2}$$

computed from these values, unfortunately varied with the distance of the test orifices from the tunnel walls - the rapid velocity decrease on the tunnel wall entailing a transverse flow along the stagnation line of the cylinder.

Different schemes resorted to in the attempt to remove this effect on factor k, were only partially successful; i.e., they lowered the effect but failed to remove it in its entirety. More elaborate investigations are under way. The transverse flow occurs, even in undisturbed free flow when, as always in pipe flow, spiral phenomena occur. In general, however, the cylindrical tube is very practical for determining the direction in two-dimensional flow, and can be used successfully. It is, in addition, simple to manufacture and easy to mount in closed wind tunnels.

b) <u>Three-dimensional flow-direction measurement - dynamic pressure claw with three pitot tubes (fig. 8)</u>.- The claw consists of three pitot tubes at 63° slope toward the median axis. Using two such claws in two planes at right angles to each other, a three-dimensional flow-direction measurement can be effected (or a two-dimensional, with only one claw). In the latter case the two outside tubes serve to swing the instrument in the zero position; then the central tube gives the total pressure, and the two on the outside, the static pressure. The claw can be used to special advantage on boundary flows since it - in contrast to the spherical pitot - manifests no measurable wall effect. The shape of the claw prevents the advance of an eventual transverse flow from reaching the instrument.

Since the three pitot tubes are close together, the instrument is suitable also by great path curvatures. The middle tube is in shaft-axis direction, or, in the second case, turned through 90°, and does not change its position by rotation around the shaft. In three-dimensional flow-direction measurements, with two pressure claws, the measurements must be made successively. For this reason, it is never certain that the second claw is actually in the same place as the first which, by unfavorable velocity distribution in the tunnel, inevitably leads to errors. Moreover, the oblique setting causes vortices on the two lateral pitot tubes which may falsify the actual pressure.

Pressure Claw with Five Pitot Tubes (reference 3)

This instrument (fig. 9) consists of five pitot tubes, of which each two tubes slope at about 63° toward the fifth and median tube. For practical use, the instrument is mounted as shown in figure 9, which permits yawing in the vertical and the horizontal planes. The axes of rotation intersect in the central test point, hence its position remains unchanged and the measurement is point by point. The opposite tubes are connected with a manometer each, so that when the axis of the instrument coincides with the flow direction, the paired-off pressures are zero. The flow angles are read on graduated disks. The zero reading on both angle graduations is to be obtained previously in the normal air stream. The velocity is measured by connecting the central with one of the outside pitot tubes.

However, this instrument, like the one with three pitot tubes, is extremely sensitive at the tips on account of the vortices. In other than homogeneous air flow, the necessary size of the instrument makes the findings unreliable. In closed tunnels, it is hardly practical because of its yawing mechanism, and even in direct wall proximity, the size of the head presents obstacles.

Spherical Pitot (reference 4) (fig. 10)

This comprises, aside from a spherical head, the shaft with the pressure tubes, the leads, and a scale. The pitot itself has five orifices on two meridians at right angles to each other. Pressure tubes lead from the orifices through the shaft toward the instrument end, as shown in figure 11. Three orifices (5, 2, and 4) at 45°, are located on the equator, orifices 1 and 3 on a meridian, each at 51° to the axis 2 to 0. The zero point on the scale lies on the plane of reference through the meridians 1, 2, 3. The five leads terminate in five U tubes as pressure gages. While on four of the pressure indicators, one free arm of the U tube connects with the outside air, the fifth records the difference in the pressure lines 4 and 5. A Prandtl pitot recording the static, dynamic, and total pressure, serves as comparative instrument. During measuring, the sphere is turned around axis ψ till pressure-difference indicators 4 and 5 indicate deflection 0. Then the meridian plane 1, 2, 3 is exactly in flow direction.. The setting $\psi = 0$ is ascertained on the scale disk, after which the pressures - measured on pressure gages 1, 2, 3, 4 - afford the coefficients for determining the flow angle δ, the rate of flow v, and the static pressure p_{st}.

With p_{tot_1}, p_{tot_2} ... denoting the deflections on the individual test orifices 1:4, we have:

$$p_{tot_1} = p_{stat} + k_1 \frac{\rho}{2} v^2$$

$$p_{tot_2} = p_{stat} + k_2 \frac{\rho}{2} v^2$$

$$\vdots \qquad \vdots \qquad \vdots$$

where

p_{tot}	total pressure (mm, water)
p_{static}	static pressure (mm, water)
k_1, k_2	nondimensional factors of the individual orifices
ρ	air density
v	flow velocity

Angle δ follows as function of p_{tot_1} to p_{tot_4} from

$$k_{1,2,3,4} = \frac{p_{tot_3} - p_{tot_1}}{p_{tot_2} - p_{tot_4}}$$

The flow velocity v follows from

$$\frac{p_{tot_2} - p_{tot_4}}{k_{2,4} \frac{\rho}{2}}$$

$k_{2,4}$ being ascertained by superposition of k_2 on k_4. The coefficients were determined mathematically and experimentally. The static pressure follows from

$$p_{stat} = p_{tot} - k \frac{\rho}{2} v^2$$

The theoretical calculation of the coefficients was carried out by potential theory on the assumption of a fictionless, stationary flow. Figure 12 gives a comparison between the theoretically computed (reference 5) and the experimentally defined curve of the coefficient. The calibration curve for orifice 1, where the disturbing effect of the shaft is least, served for comparison. The spheres were explored in the calibration test system (fig. 13). The effects of an eventual change in the air humidity of the barometer reading and of the temperature during the experiment must be allowed for in the calibration. The calibration curve of the sphere shown in figure 14, is indicative of satisfactory flow. For recording flow direction - total, static, and dynamic pressure - the use of spherical pitots is recommended. According to figure 15, the drag coefficient of the sphere is practically constant between $R_e = 4.0 \times 10^3$ and 1.5×10^5, equivalent to a speed range of from 11.5 to 430 meters per second for the employed sphere diameters.

Angular deflections up to about ±60° proved to be the limit of application of spherical pitots. By rapid directional changes, the measurement is very time-consuming as a result of the great inertia of the water column in the U tubes. Despite all attempted reductions in the dimensions of the spherical head, a really accurate test result cannot be secured with the spherical pitot.

Spherical Pitot without Transverse Flow Effects (fig. 16)

This design followed the normal type of spherical pitots, but with special attention to the spindle which, to secure a symmetrical pressure distribution across the sphere surface, is placed rearward, so that the transverse flow forming on the spindle cannot creep forward to the test orifice and affect the pressure pattern. In order to keep orifice 2 at the same place while yawing about angle ψ, it is located on the extension of the spindle axis. Introduction into the flow requires a slightly greater hole in the tunnel wall. The chief drawback of this design version is that, owing to the bend in the shaft the flow direction can only be measured up to a certain distance from the tunnel wall. On the most recent design versions, the sphere has a diameter of only 3 millimeters (reference 6), while the bent shaft has been retained. Since it can be passed through a hole of only 6 millimeters, its use is very convenient.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.

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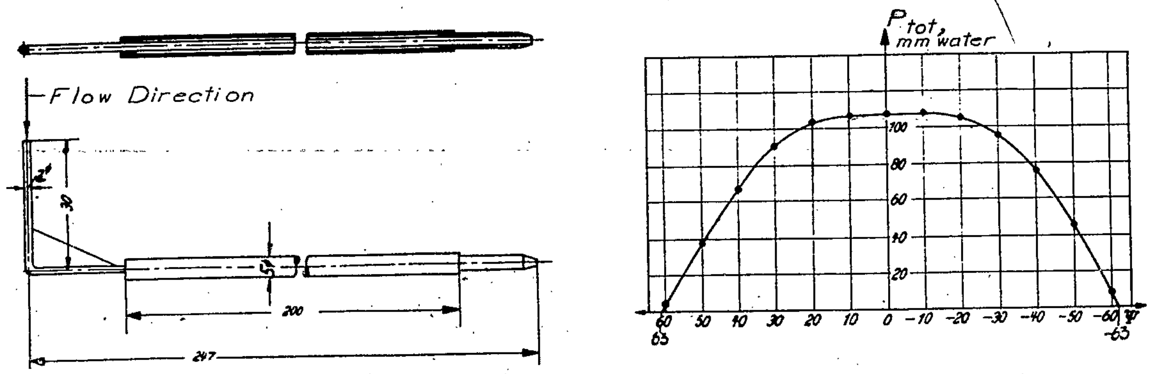

Figure 1.- Pitot tube and pressure variation for the impact opening by yawing.

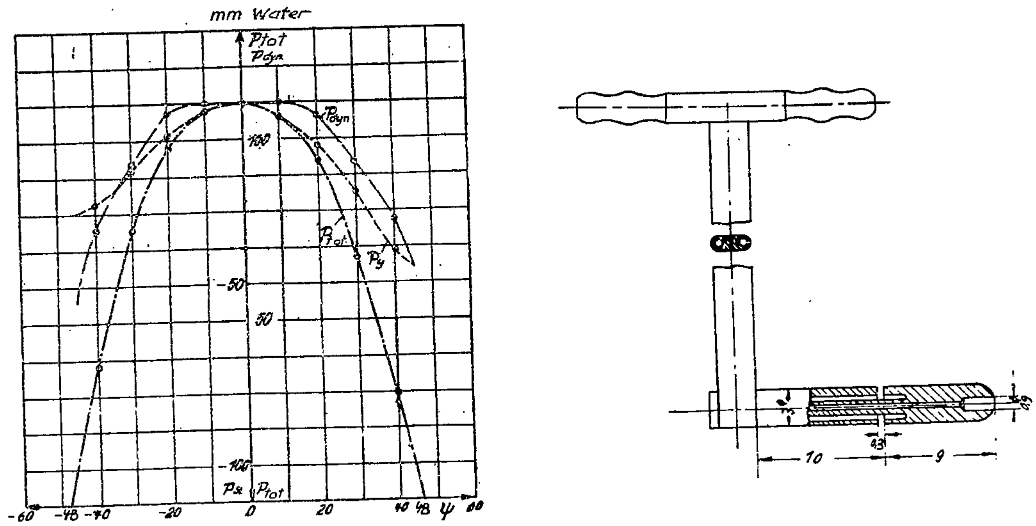

Figure 2.- Prandtl pitot and pressure variation obtained by yawing the total head tube.

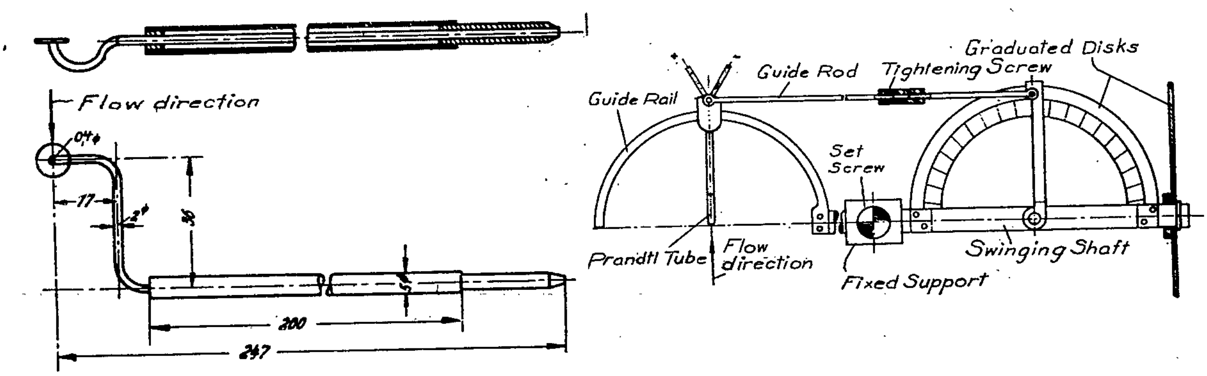

Figure 3.- Yawing arrangement for determining the flow direction with a Prandtl tube.

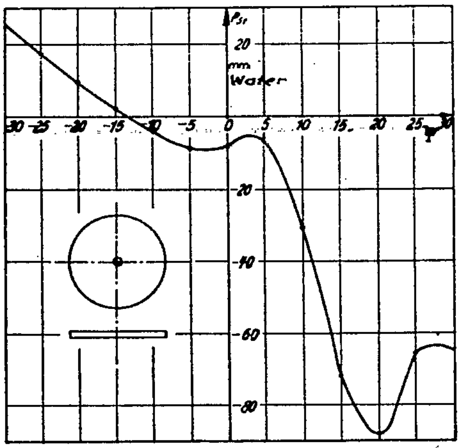

Figure 4.- Sers plate and pressure variation at different flow angles.

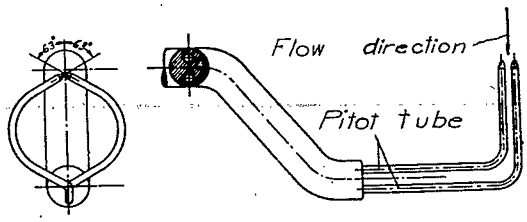

Figure 6.- Flow direction instrument consisting of two pitot tubes set at 63^{o}.

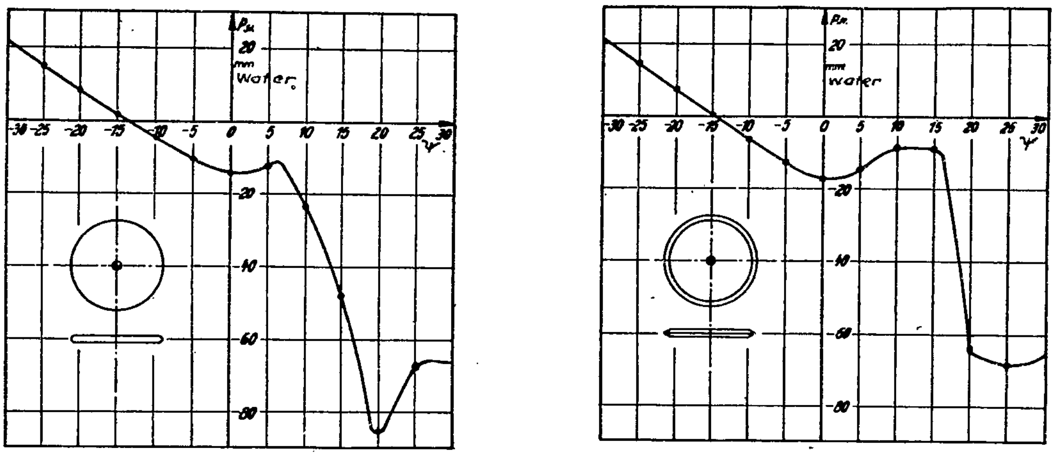

Figure 5.- Pressure plotted against angle of flow and for different plate edge designs.

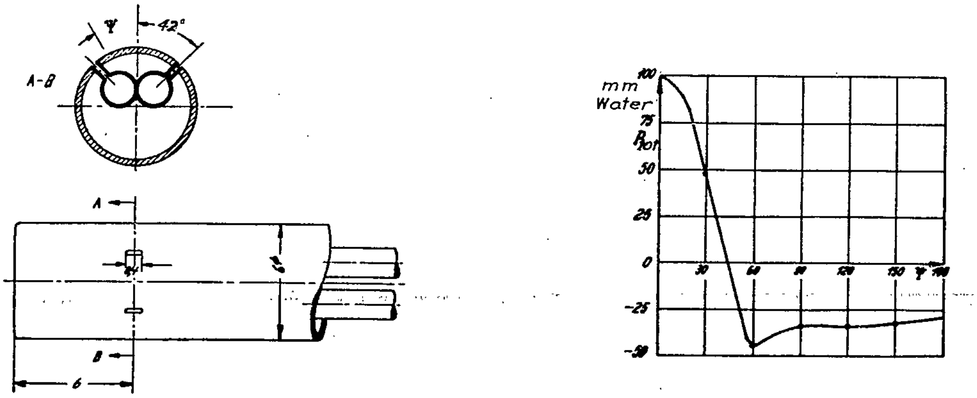

Figure 7.- Cyindrical tube used for recording two-dimensional flows and pressure variation on the cylinder surface in relation to angle of yaw.

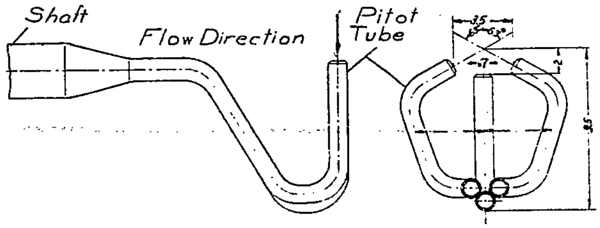

Figure 8.-Pressure recorder with 3 pitot tubes.

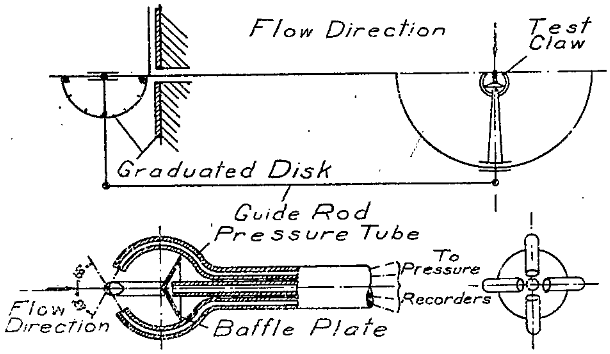

Figure 9.- Pressure recorder with 5 pitot tubes.

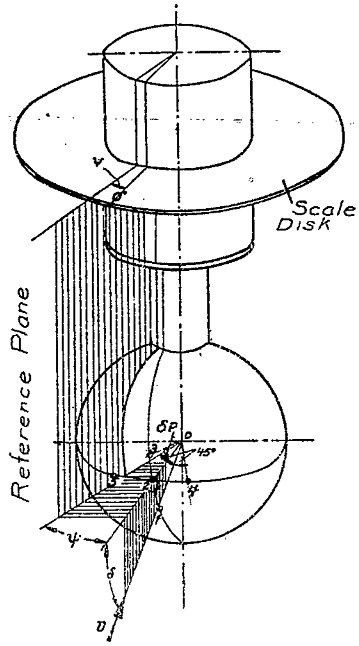

Figure 10.-Principle of spherical pitot, (identification of angles).

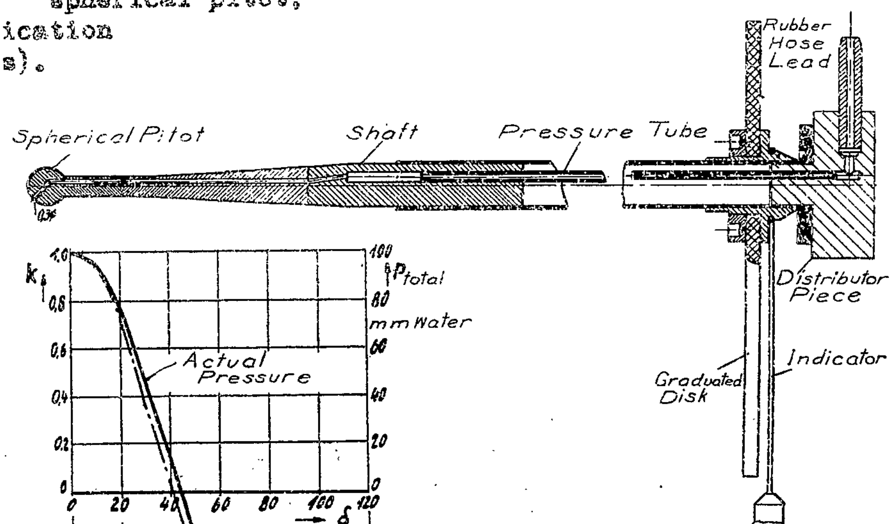

Figure 11.- Design of spherical pitot with angle recording device.

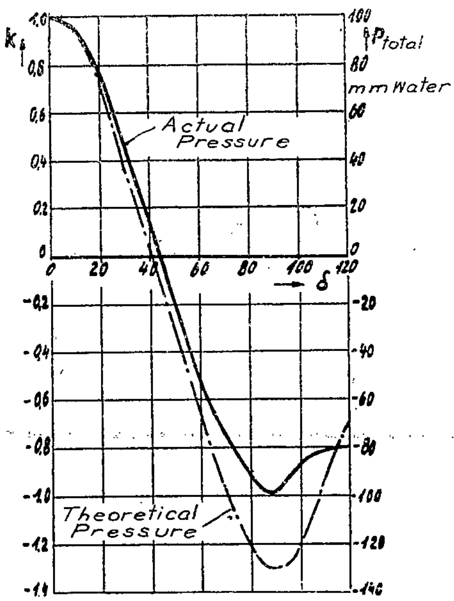

Figure 12.-Calculated and actual pressure curve.

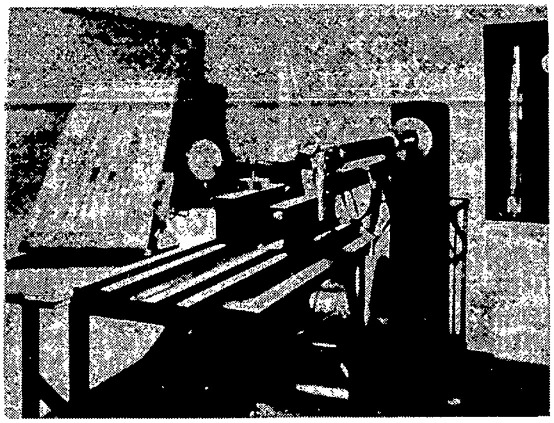

Figure 13.-Calibration set-up.

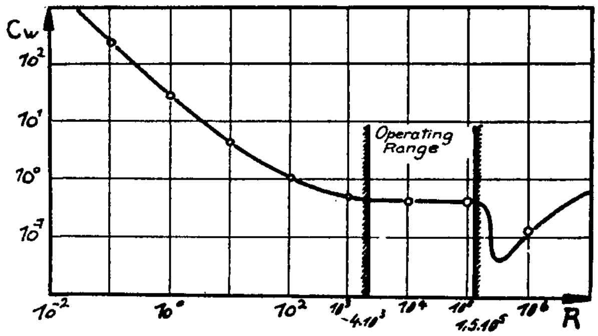

Figure 15.- Sphere drag coefficients plotted against Reynold's number.

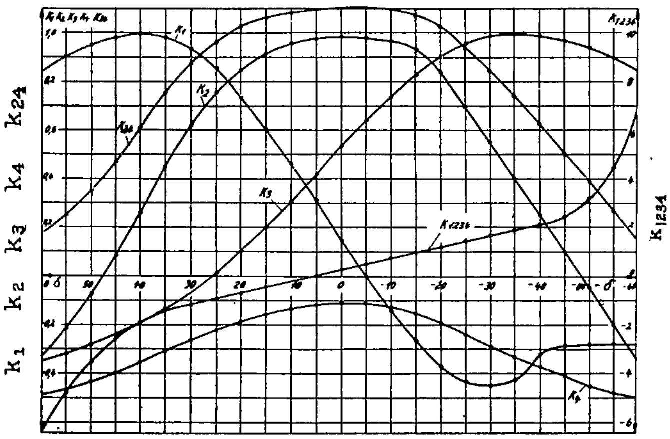

Figure 14.- Calibration curves taken in homogeneous stream.