Session 6 - Pressure Probes

DEVELOPMENT OF A CALIBRATION BENCH FOR SMALL ANEMOCLINOMETER PROBES

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ABSTRACT

The probes used for measuring three-dimensional flows in wind tunnels and turbomachine test stands are generally of small dimensions, and have to operate in broad velocity, incidence and pressure domains.

The Aerodynamics Department at ONERA has developed a special test bench that reduces the cost and makes it easier to calibrate these probes.

The present paper describes the capabilities of this new test bench, which currently operates in the envelope of $0 < M \leq 4$, $0 \leq \theta \leq 80°$, $0.05 \leq P_t \leq 9b$, $15° \leq T_t \leq 50°C$.

The nozzle exit diameter is 40 mm.

1 - INTRODUCTION

Measuring three-dimensional flow in wind tunnels and turbomachine test stands now calls for more and more discrete instruments, and with better and better performance.

The measurement means most commonly used are optical instruments (laser) or probes (multihole pressure probes, hot-wire probes and thermocouples) and these often complement each other.

But probes are intrusive instruments, so an effort is therefore made to miniaturize them, while at the same time attempting to make them operate through as wide as possible envelope of incidence angles, velocities and pressures.

These miniaturized probes, difficult to construct and designed as they are to operate through broad parameter domains, often have complex responses requiring modern computer facilities to make the most of the data generated.

The probes themselves must be calibrated first and the final occuracy of the measurements will depend on the accuracy of this calibration (including positional measurements) and also on the fineness of the grid and on the methods of numerical analysis.

For lack of any better way, the users themselves often have to calibrate these instruments in their own test facilities, which are costly and poorly suited to this tasks. This is why ONERA's Experimental Aerodynamics Division has developed a specific test bench for calibrating small probes.

2 - CALIBRATION BENCH (figure 1)

The bench was installed in 1989 on the premises of the S5Ch wind tunnel at Chalais-Meudon. It is connected to the wind tunnel compressed air supply and vacuum pumps, an to its data acquisition and analysis system. Il also benefits from the experience acquired at S5Ch in calibrating and using miniaturized multihole probes, chiefly for tests of straight or annular cascades in transonic and supersonic flows.

2.1 - Aerodynamic Circuit (figure 2)

The bench is designed for continuous operation with a mass flow of 1 kg/s of less, with a dry air supply of 9 bar.

A 30 kW heater regulates the supply air temperature, stabilizing it to within 2°C at levels between 15°C and 50°C, which is what is needed for hot-wire calibrations. A 10 μ dust filter is also installed.

The supply pressure is regulated to between 0.05 and 9 bar by a valve upstream in the circuit. The chamber containing the calibration device is proof-tested at 3 bar absolute. Another valve downstream regulates the pressure in the chamber, and serves as a second throat for slightly supersonic tests.

The circuit outlet is either connected to the vacuum pumps or is vented to the atmosphere. The use of vacuum pumps allows to initiate a continuous Mach 4 flow.

2.2 Calibration device

This device presented on Figs. 3 and 4 includes :

- a settling chamber with a baffle, a mixer and supply pressure and temperature measurements ;
- a modular nozzle mount that can be fitted either with :
  . an axisymmetric subsonic nozzle
  . a slightly supersonic two-dimensional nozzle

- . any of six axisymmetric supersonic nozzles for Mach 1.35/1.50/2.0/2.5/3.0 and 4.0

- the probe translation and orientation mecanism is designed to hold the measurement point at the center of the nozzle exit plane :

  - . The usual "θ" and "Φ" angles, allows high angles of incidence ($0 \leq \theta \leq 80°$), while the Φ motion defines the probe reference x axis ;

  - . The motion "Ψ" is used to align the x axis with the wind. The θ and Ψ motions can be used for pure (α, β) displacements, but only through small angles (< 10°) ;

  - . The X movement is used to place the probe head in the nozzle exit plane ;

  - . The Z movement is currently being developed to position more complex probes that have their own "θ" motion system for use in rotating turbomachine test stands.

2.3 Nozzles (Figures 5, 6 and 7)

The axisymetric subsonic nozzle has a 40 mm exit diameter. The downstream valve is used to adjust the velocity through this nozzle. This valve is generally sonic, which ensures good flow stability.

The slightly supersonic nozzle (M < 1.35) is of two-dimensional geometry. The flexible upper surface can be deformed in order to obtain the best possible Mach number distribution on the lower surface. When using this nozzle, the chamber pressure is adjusted by the second throat and set equal to the nozzle exit pressure. The probe head is placed slightly downstream of the nozzle exit plane so that the aerodynamic field of the probe does not interfere with that of the nozzle. The probe is positioned manually, while viewing a Schlieren visualization of the shock waves ; this technique which is easy to use gives a satisfactory adjustment. A porous-wall system with auxiliary suction is currently being studied and should be even more versatile.

The supersonic nozzles are axisymetric (this type of nozzles are simpler and therefore less costly to machine) and have an exit diameter of 40 mm. To initiate high Mach numbers with low supply pressures, a guide is placed at the base of the nozzle with a slit through which the probe is passed, at high angles of incidence.

3 - MEASUREMENT MEANS AND METHODS

3.1 Measurement System

The calibration bench is connected to the S5Ch wind tunnel Bull SP5 mini-computer. This computer is used to manage the test and acquisition process and also to control the probe movements on instructions from a "Microcontrole" terminal.

The pressures are measured with "Statham" differential transducers with a reference line pressure that is calibrated, checked and measured by a "Digiquartz" secondary standard.

The measurements are taken at stabilized levels and are processed locally, shortly thereafter.

The hot-wire probes are calibrated with their own measurement system, which has the advantage of using the same equipment as during a test.

3.2 Probe Adjustment

The zero-Φ position is optically adjusted before the test. The probe holes (or the probe wires) serving as reference are aligned with the normal to the plane described by the X axis through its angular displacement θ.

The zero-α, zero-ß position is adjusted in the wind, by looking for the θ and Ψ positions where the probe is insensitive to the Φ motion.

3.3 Determination of local calibration Mach number

Preliminary classical pitot-static probe have caracterized the flow in the nozzles. Figure 8 shows the Mach number distribution in the different nozzles.

The reference Mach number is defined for each calibration test : for subsonic and transonic calibration cases, it is measured at the nozzle wall, 5 mm upstream of the exit plane ; for supersonic tests, it is decuced from the ratio of the central hole pressure (when the probe is at $\theta = 0$) to the supply pressure.

3.4 Probe Orientation

The probe can be "θ-Φ" or "α-ß" calibrated ; but in most cases the θ-Φ calibration is preferred because it is simpler and faster.The probe is moved θ-wise while Φ is kept constant. The angles of incidence α and sideslip ß are then calculated from the known θ and Φ values.

4 - EXAMPLES OF CALIBRATION BENCH USE

4.1 Examples of probes calibrated

Figures 9 to 15 show some probes that are commonly used and that have to be calibrated. The "BP" type probe of figure 9 measures accurate local static pressures if the gradients are small and if the local wind direction is known.

The temperature probe of figure 10 can be used for measuring the total temperature in the boundary layer over a heated surface. This probe has to be calibrated to determine its heat recovery factor as function of the Mach and Reynolds numbers.
The multihole probes of figures 11, 12 and 15 are used for measuring velocity vector directions and amplitudes, as well as the local total pressure in subsonic and supersonic flows (for measuring three-dimensional flows, at least three unaligned holes are needed). Miniaturization (dia. 1 or 1.5 mm) is desired for these probes in order to reduce the measurement control volume and the choking effects. They are suitable for averaged measurements.

Instantaneous values can be measured using the hot-wire probes of figure 13.

4.2 Examples of Calibration Results

- Five-hole probe calibration

Figure 16 shows the response of holes # 2 and 5 of a five-hole probe, at Mach 0.3, 2 and 3. The data of this graph (together with equivalent data for holes # 1, 3, 4) will, taken with other Mach number values, go into making up the calibration file of the probe, as it is used by the postprocessing software (see section 5).

- Hot-wire probe calibration

Figure 14 shows an example of the response of # 1 wire of a four-wire probe at Mach 0.4, calibrated at 3 bar between Mach 0.1 and 0.6, and up to 30° of incidence.

It must be emphasized that the calibration bench enables to analyze the effect of the supply temperature at various stabilized temperature levels between 15°C and 50°C.

5 - POSTPROCESSING SOFTWARE

The test data are stored in a calibration file containing the measurement of each wire or hole at each grid point (Mach, θ, Φ) through the domain explored (typically, 6750 data points are used, i.e. 33750 values for a five-hole probe calibrated in the envelope of $0.2 < M \leq 4$, $0 \leq \theta \leq 60°$).

In the case of multihole pressure probes, a program is available that can calculate the Mach number, θ, Φ and P_t parameters for an unknown flow. This program processes the raw data P_1 to P_n directly from the calibration file. The method is based on trilinear interpolations in the small (Mach, θ, Φ) domain encompassing the solution. This domain is determined by iteration. The data reduction of one measurement point requires approximately 0.6 sec computing time.

For flattened 3-hole probes, a single angle can be calculted (these probes are used in boundary layers or with "zero" "methods").

In the case of probes with five or more holes, three configurations are generally considered : small angles ($\theta \leq 5°$) medium angles (above 5° and as far as the pressure measured by the central hole is the largest) and finally high angles. The method is valid as long as the pressures vary significantly and reliably as a function of the Mach number, θ and Φ (an "unreliable" case would be, for example a variable separation as a function of the Reynolds number).

Figure 17 gives an example of the occuracy that can be achieved for $0.2 \leq M < 0.7$, and for $0 \leq \theta \leq 60°$ with a five hole probe.

The differences between the values measured and those calculated are plotted as a function of the measured angle θ. The measured values are those generated during tests that went into making up the calibration file but also those generated during confirmation tests conducted outside the calibration points.

These differences reflect the uncertainty associated with the calculation method and the random pressure and positional measurement errors ; but they do not reflect possible systematic errors. (Measuring the absolute pressure, the probe position, and the reference Mach number are all other problems).

6 - CONCLUSION

The small-probe calibration bench installed on the S5Ch wind tunnel premises in 1989 is in its final development phase.

The first calibrations carried out on five-hole and four-wire probes have validated the test bench operation for subsonic and supersonic flows. The transonic domain is currently being explored. The test bench operation envelope is summarized in figure 18.

The next step in the test bench validation process will be to calibrate the elbow probes used in transonic annular cascade test.

In addition to increasing the calibration envelope, this facility reduces drastically the calibration duration and cost.

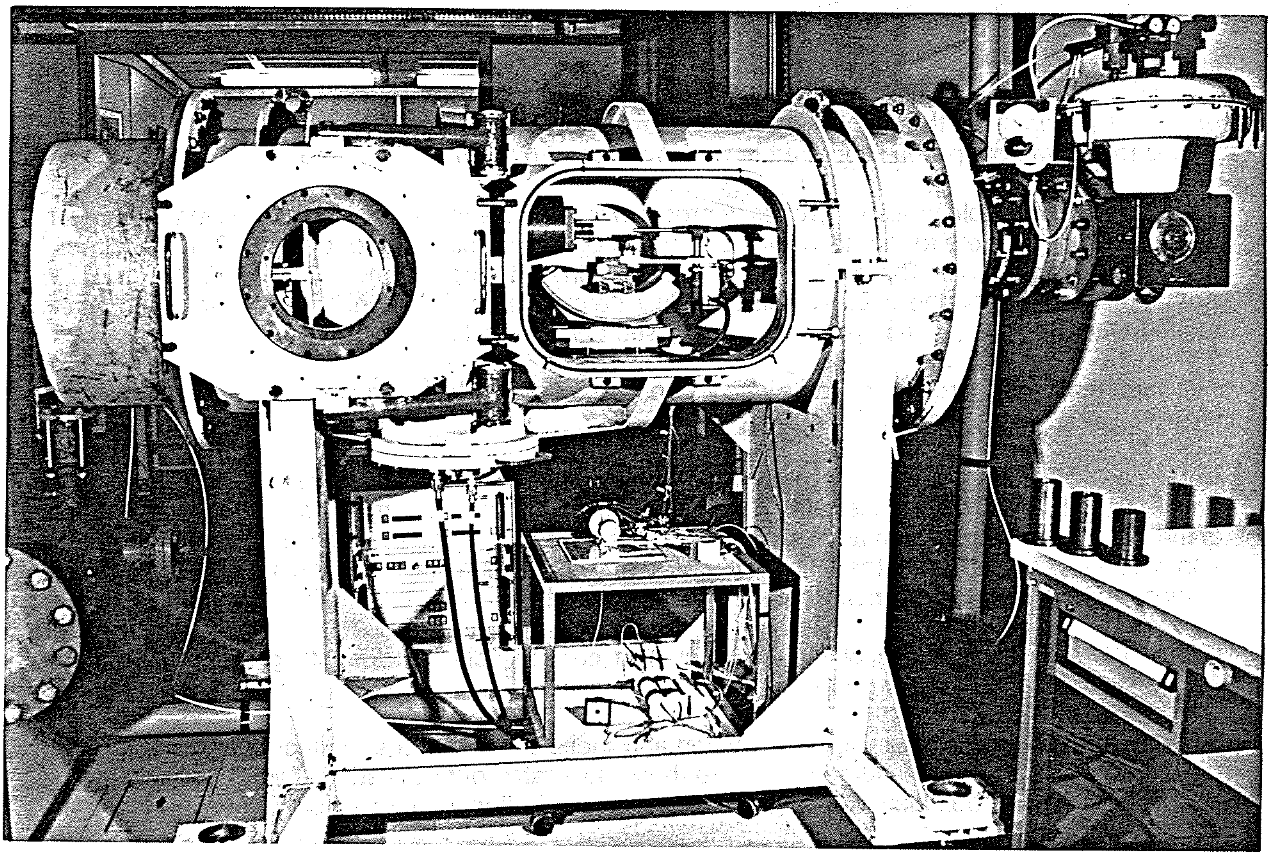


Fig. 1 - General view of calibration facility.

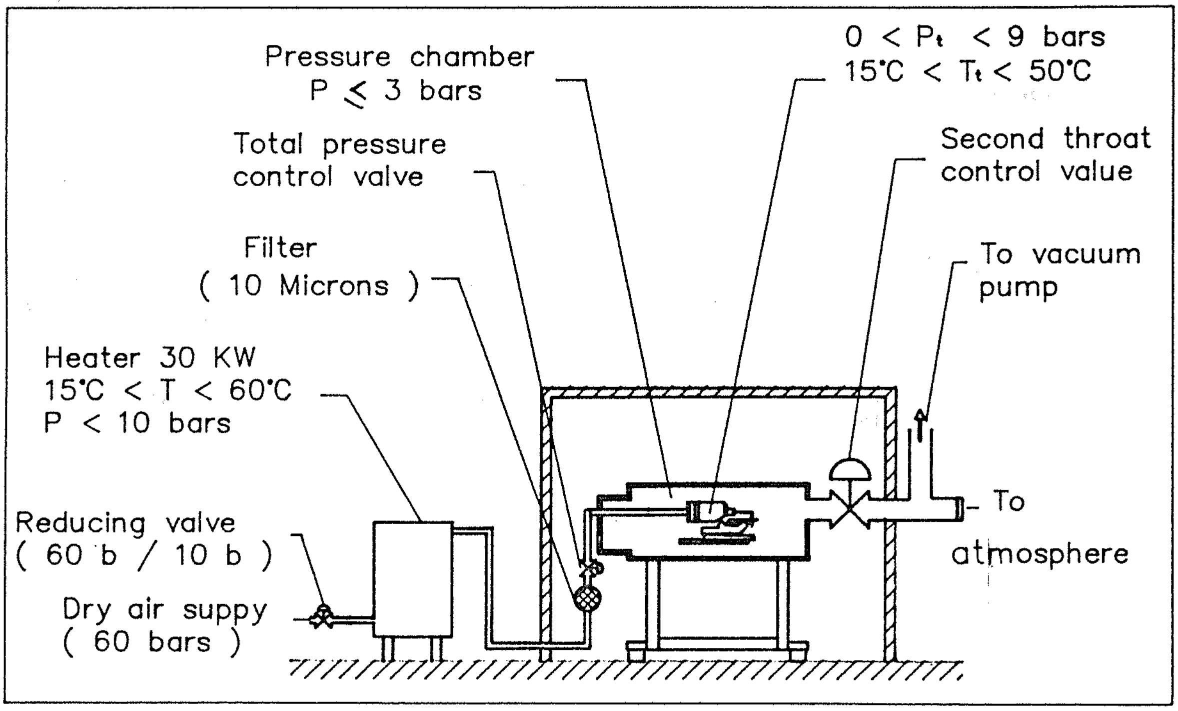


Fig. 2 - Sketch of calibration facility.

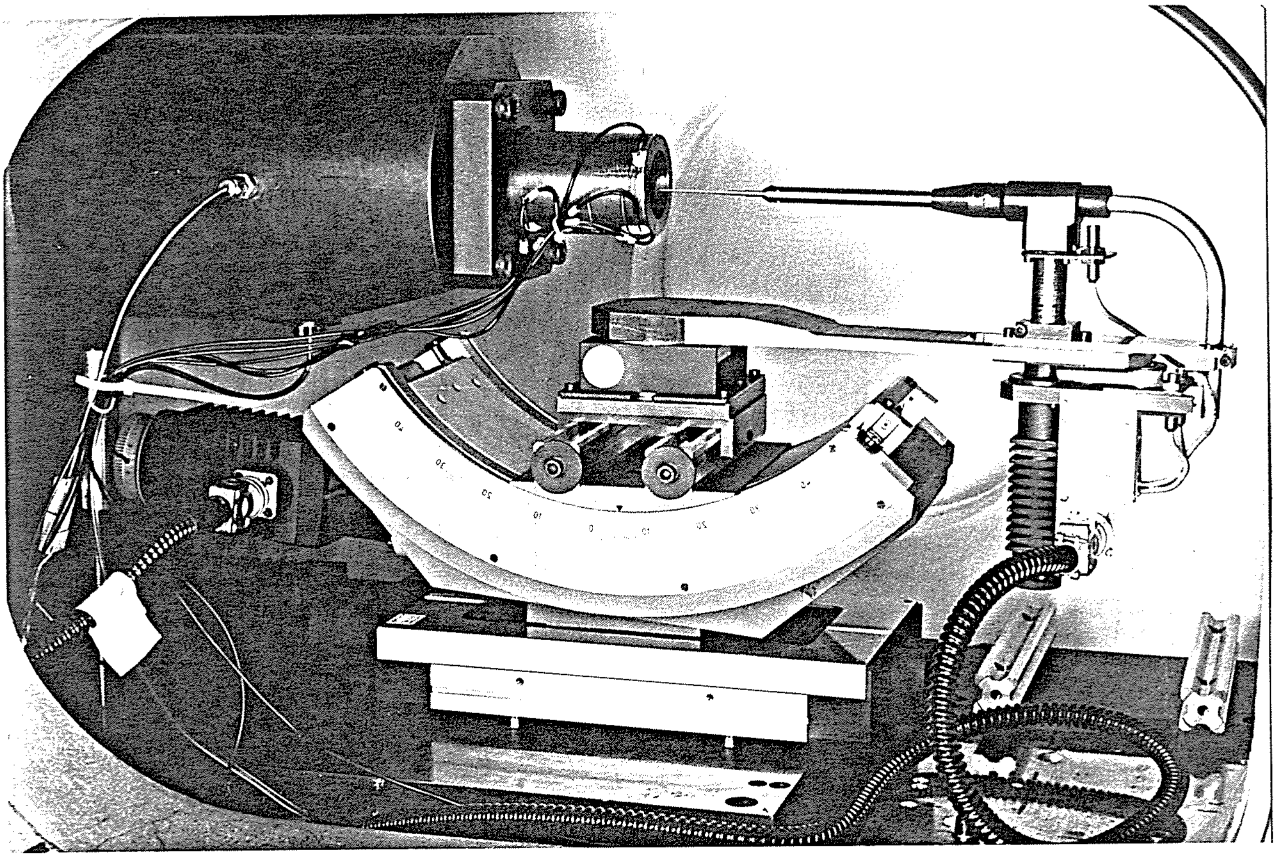
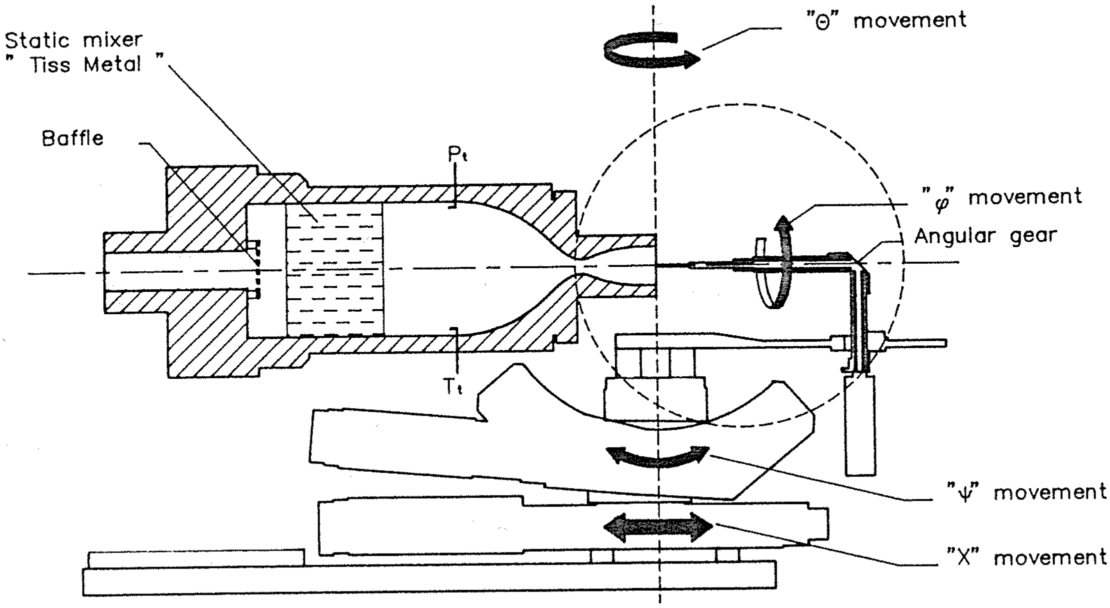


Fig. 3 - Probe positioning mechanism.



(all displacements controlled by "Microcontrole" stepping motors)

Fig. 4 - Sketch of probe positioning mechanism.

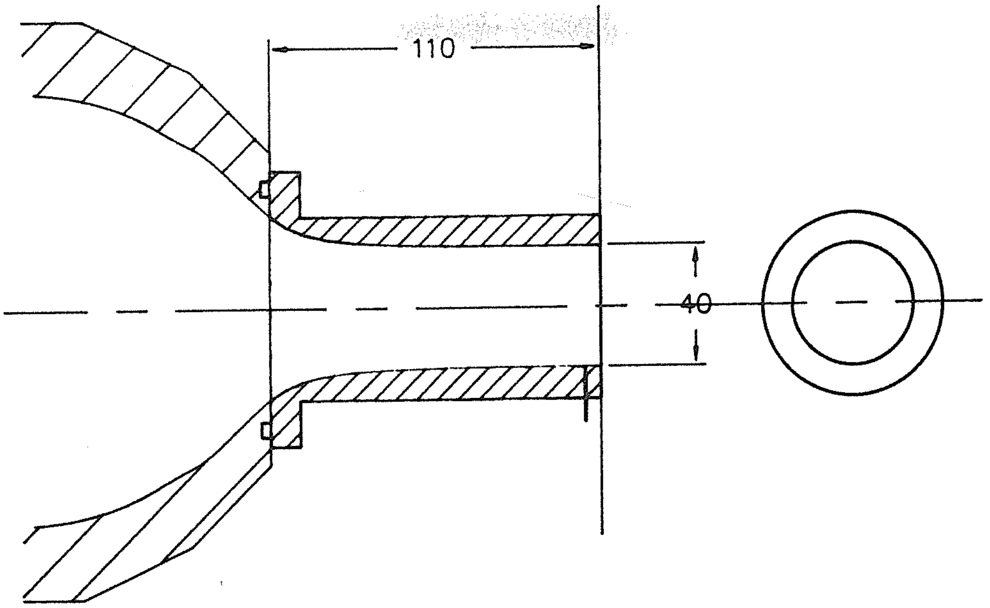


Fig. 5 - Subsonic nozzle.

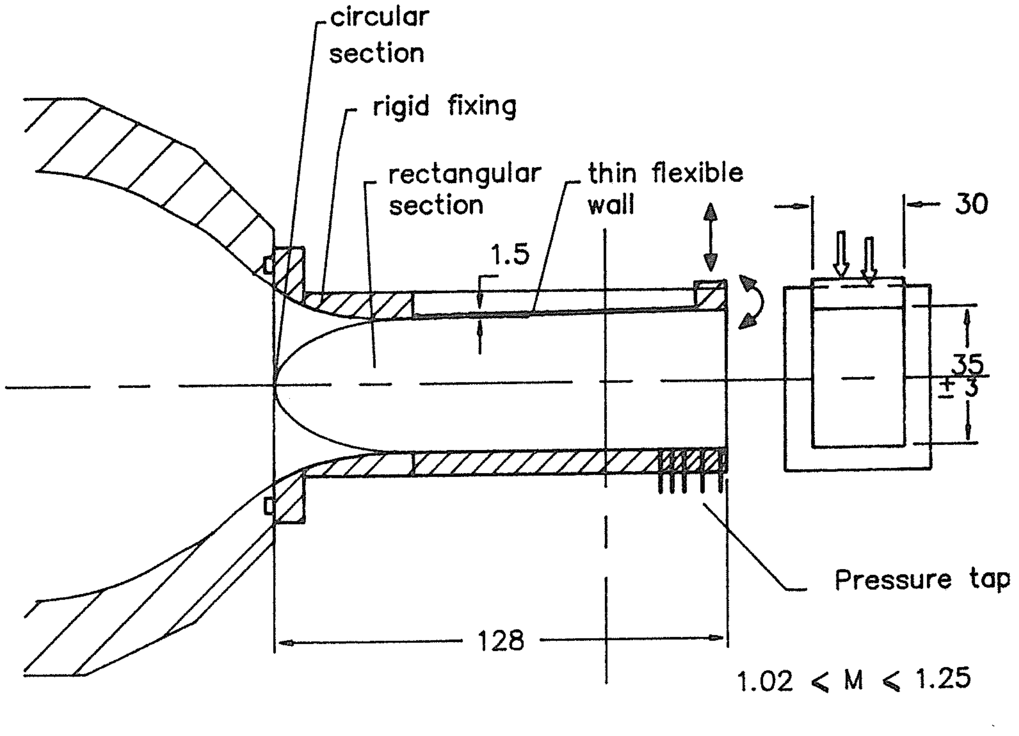
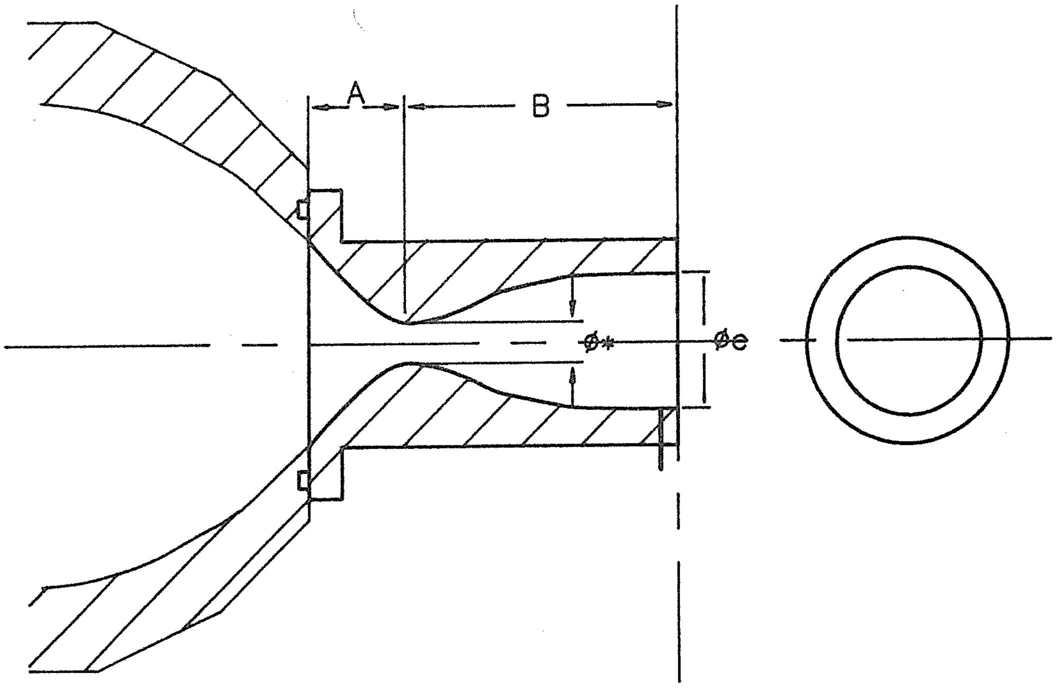


Fig. 6 - Low supersonic nozzle.



Nozzle	A	B	ø*	øe
M = 1.35	40.76	42.24	38.34	40.00
M = 1.50	34.60	50.00	36.90	40.00
M = 2.00	34.13	69.99	30.80	39.98
M = 2.50	36.10	87.00	24.65	39.99
M = 3.00	34.38	99.97	19.44	39.98
M = 4.00	32.01	119.98	12.22	39.98

Fig. 7 - Supersonic nozzles.

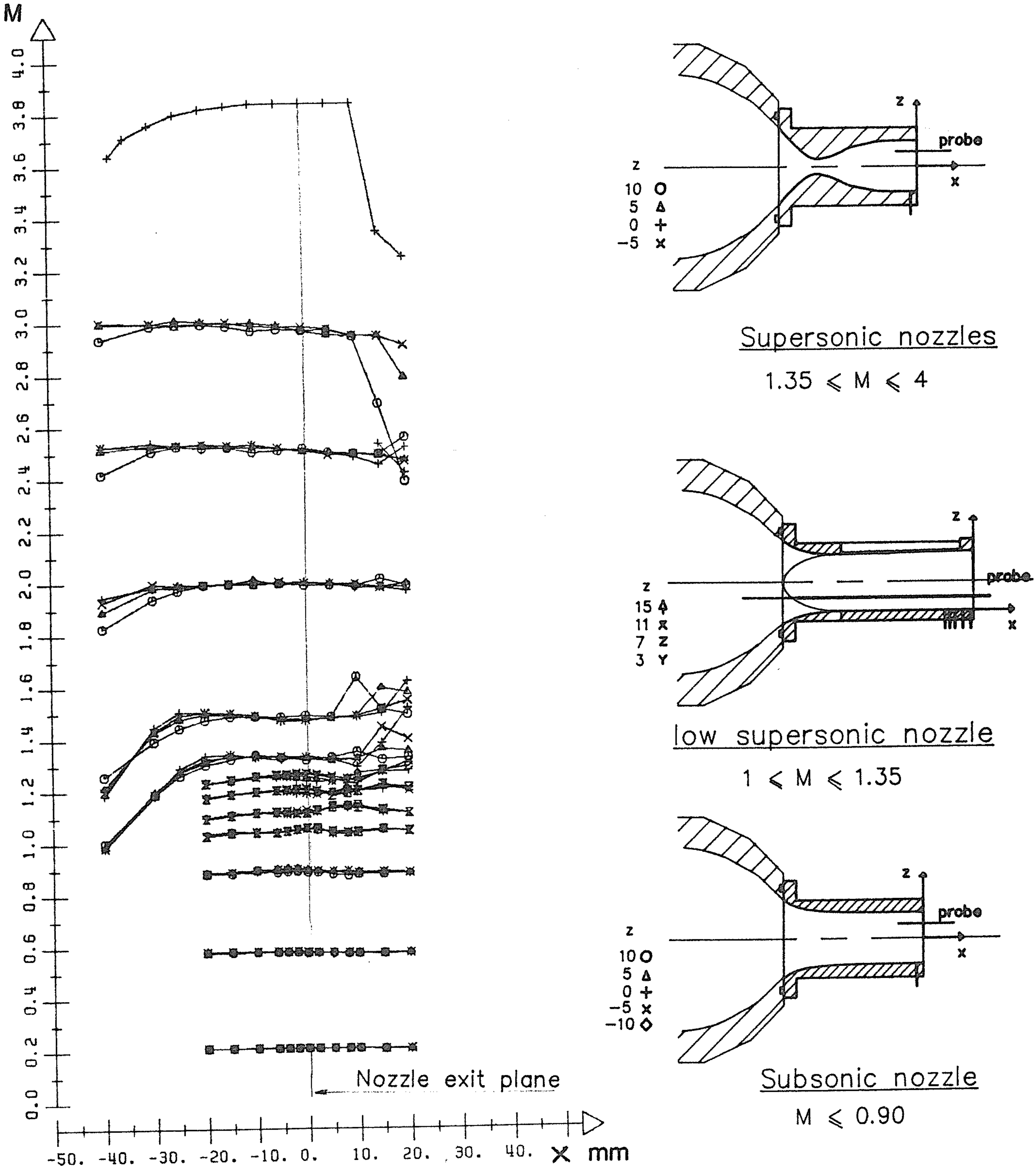


Fig. 8 - Mach number distribution in the different nozzles.

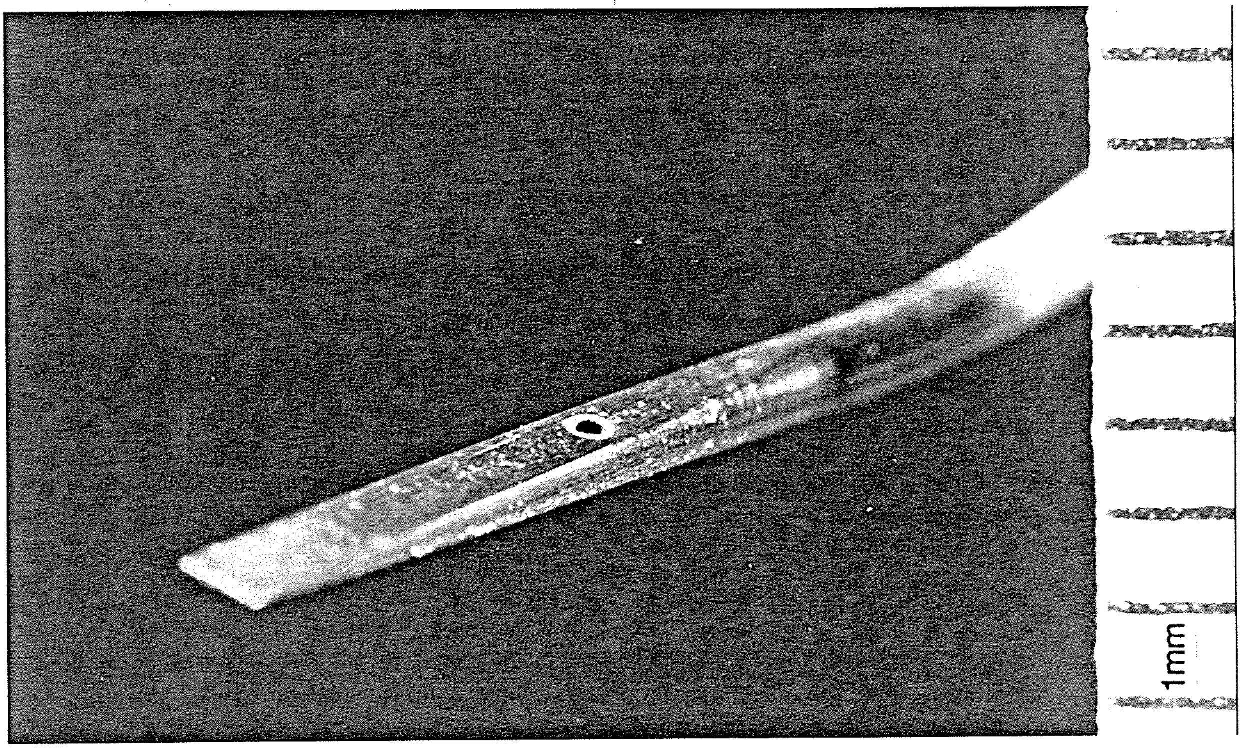


Fig. 9 - Static "BP" pressure probe.

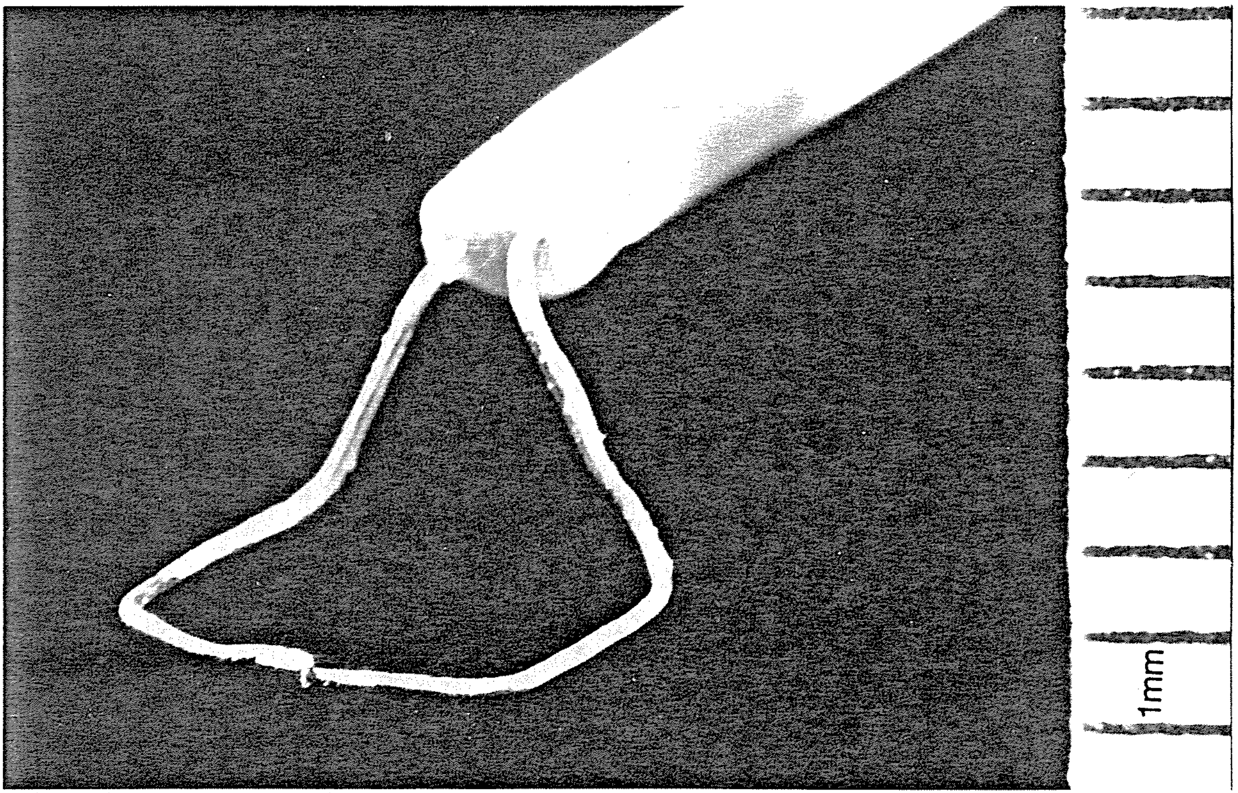


Fig. 10 - Total temperature probe (thermocouple).

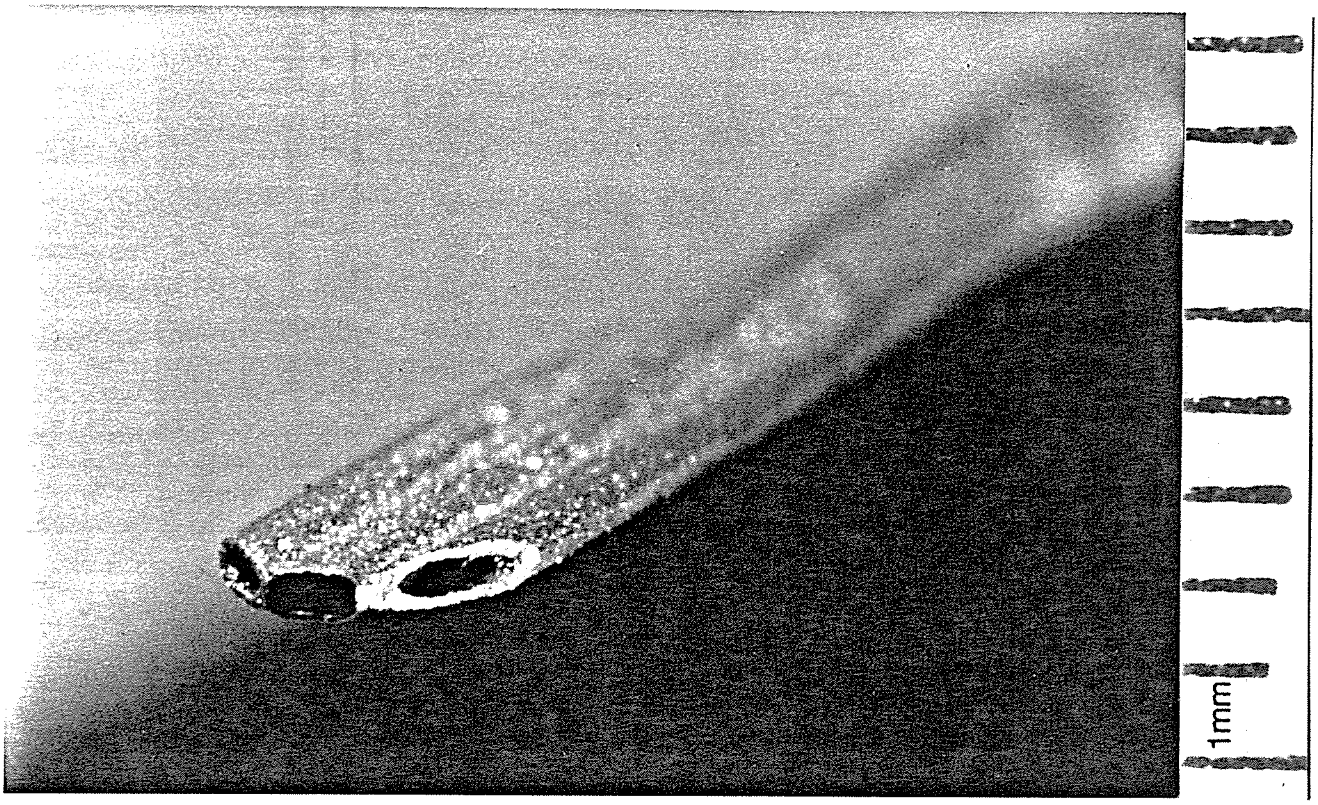


Fig. 11 - Three hole probe.

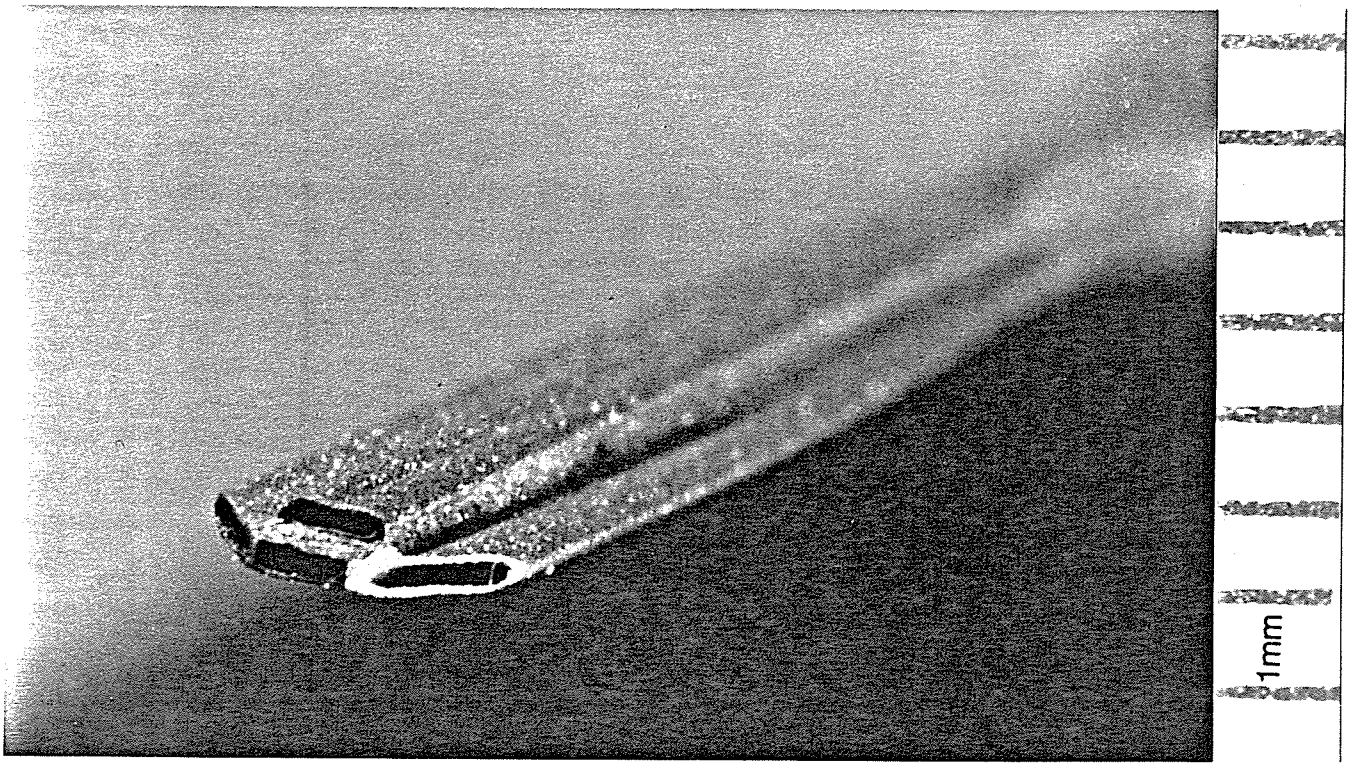


Fig. 12 - Four hole probe.

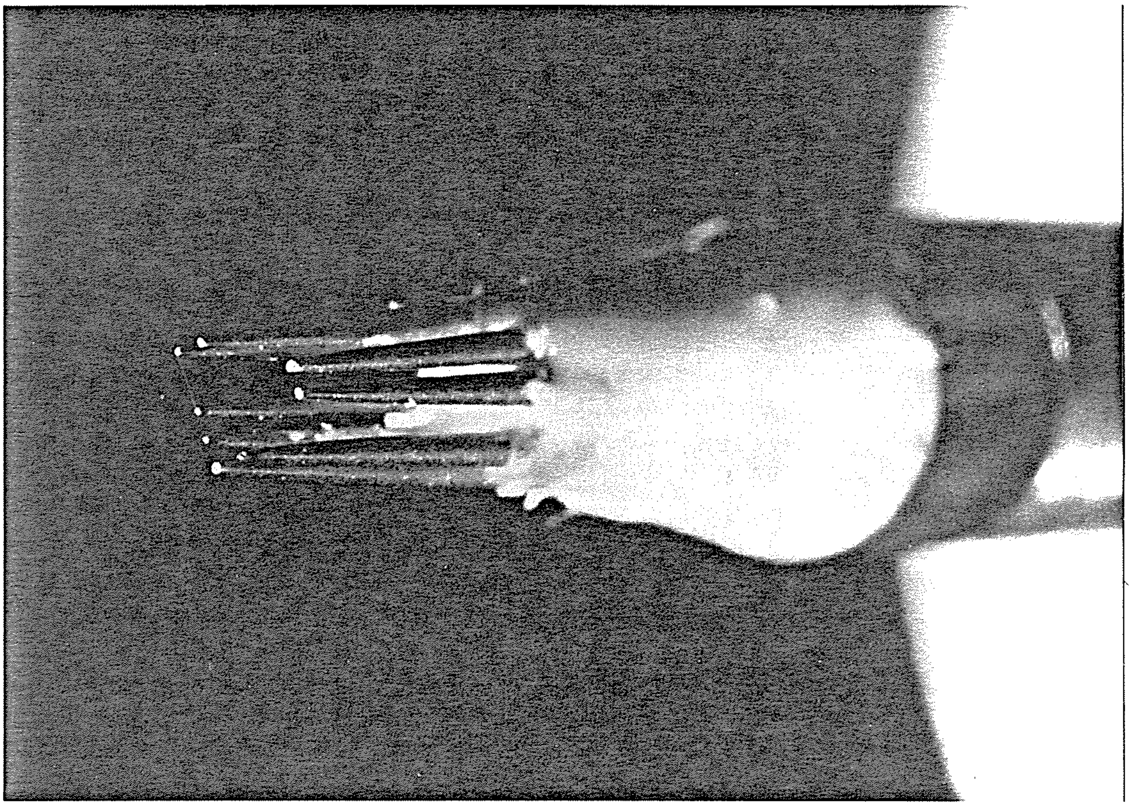


Fig. 13 - Four hot wire probe.

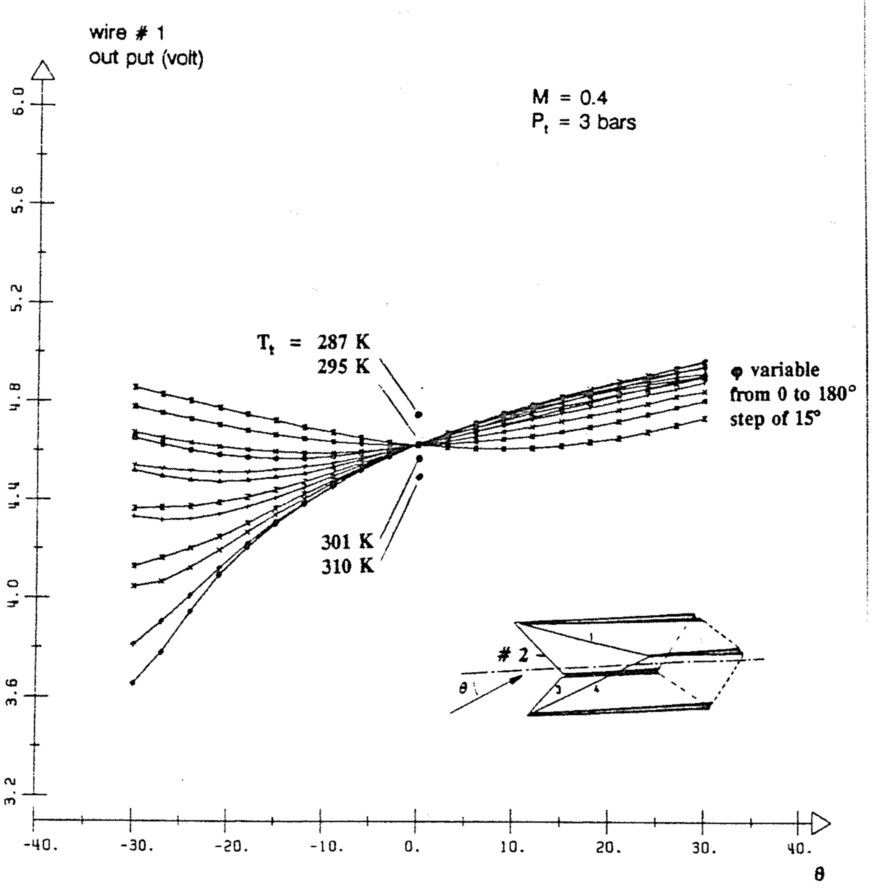


Fig. 14 - Example of four hot wire probe calibration data.

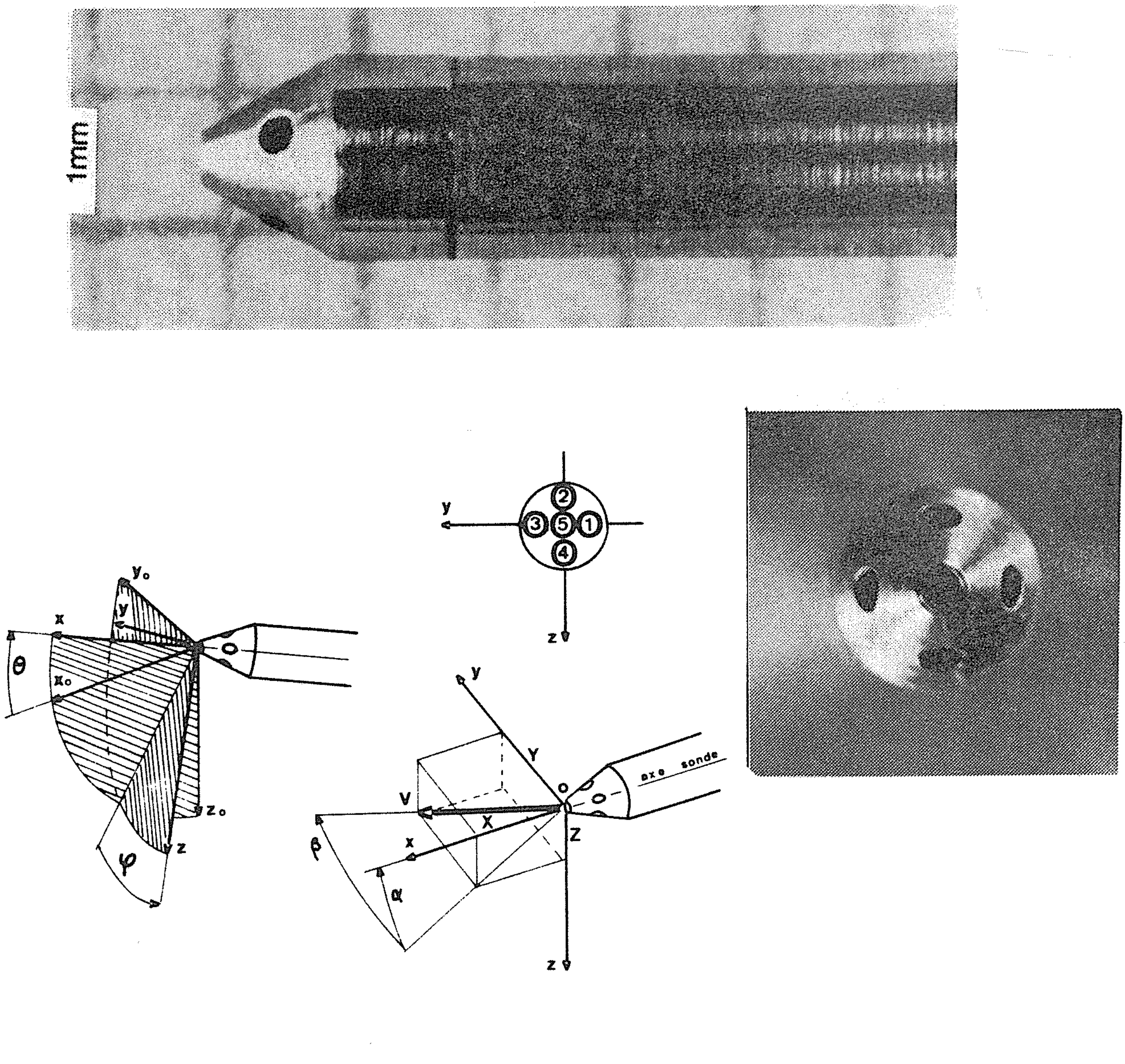


Fig. 15 - Five hole probe.

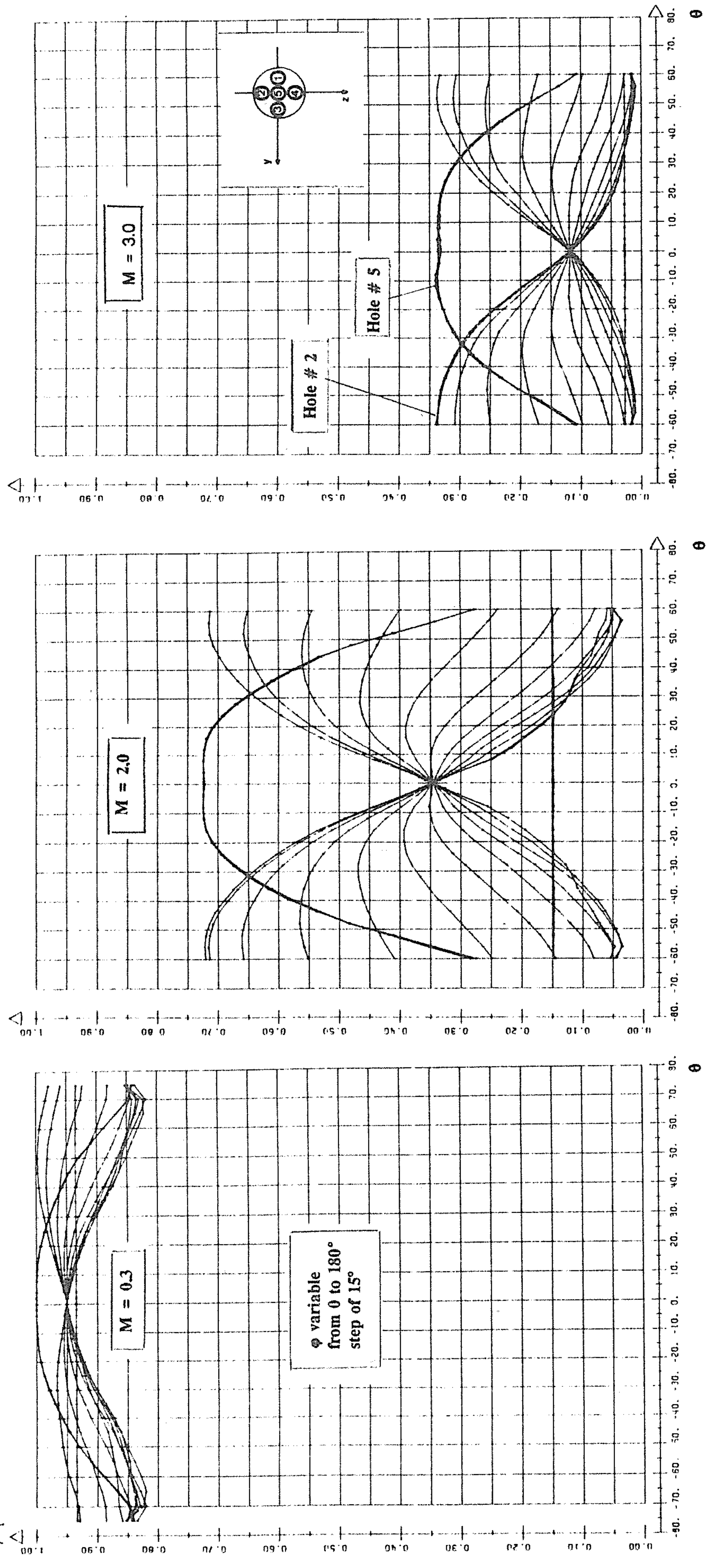
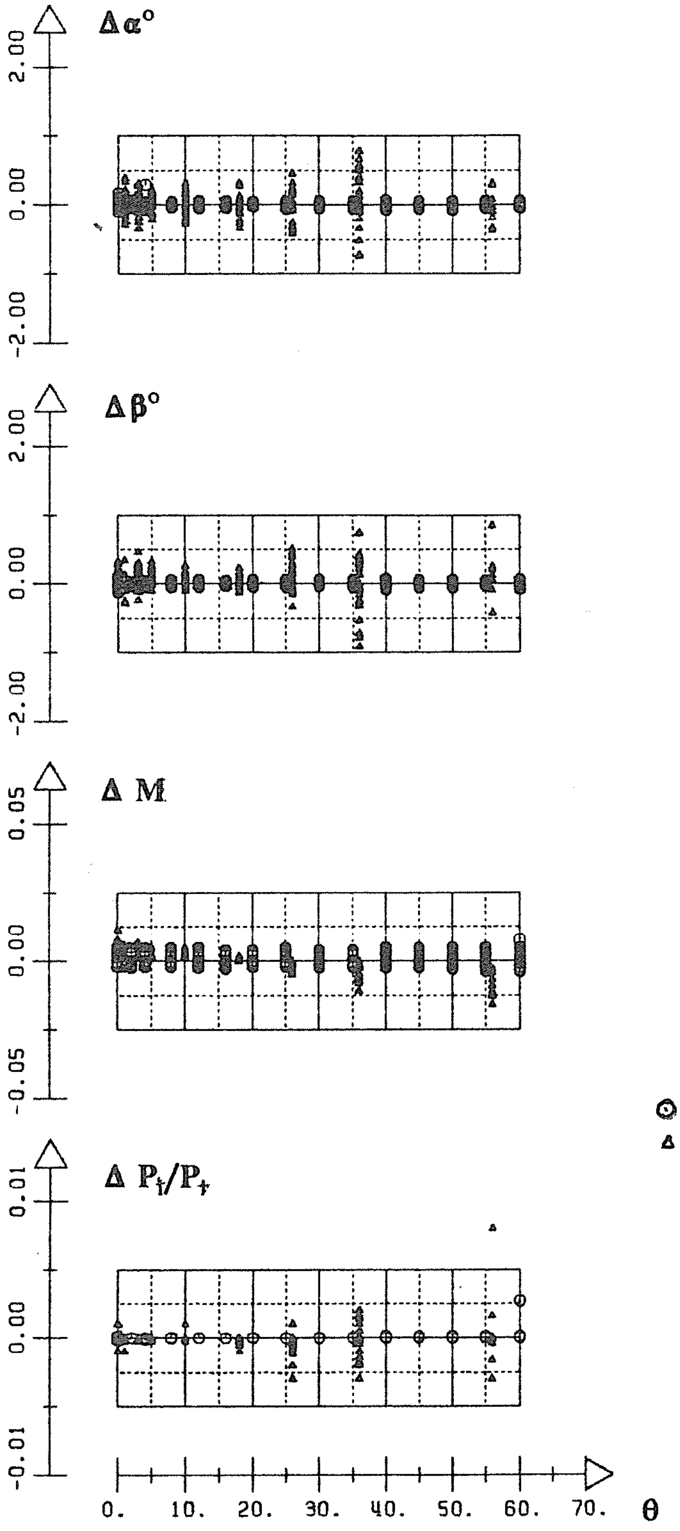


Fig. 16 - Example of five hole probe calibration data.



FIVE-HOLE PROBE

$0.2 < M < 0.7$

P_t = 1 bar

$\Delta\alpha$, $\Delta\beta$, ΔM , $\Delta P_t/P_t$ represent the difference between values measured during the calibration process and values calculated from the final calibration file.

○ Values used to built the calibration file.

▵ Values not used to built the calibration file.

Fig. 17 - Control of five hole probe calibration accuracy.

Nozzle exit diameter 40 mm

Probe head dimension < 5 mm

0,1 ⩽ Mach number ⩽ 4

0° ⩽ Pitch angle ⩽ 80°

0.05 bar ⩽ Total pressure ⩽ 9 bars

15°C ⩽ Total temperature ⩽ 50° C

2.10^5 ⩽ Flow unit Reynolds number ⩽ 55.10^6

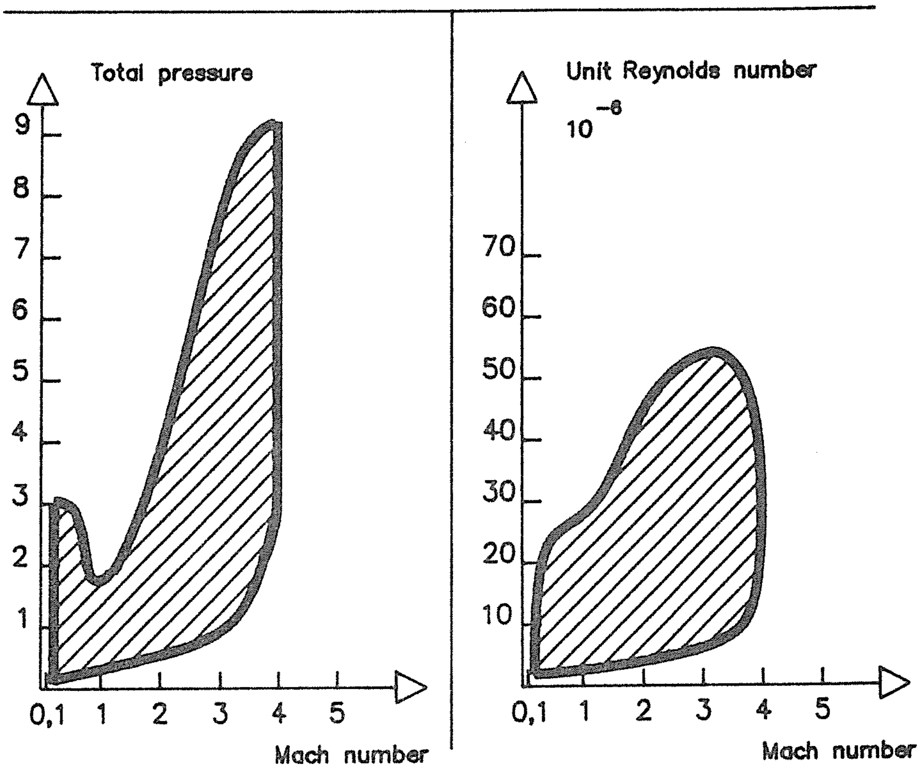


Fig. 18 - Probe calibration facility