Change of Flow Conditions due to the Introduction of an Aerodynamic Probe during Calibration.

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ABSTRACT.

Aerodynamic probes have to be calibrated in a well known flow prior to use for measurements. Such calibrations are mostly performed as a routine, but it is always necessary to carefully consider the precision of the results. Uncertanties may arise from several sources, both from the probe itself as well as from the calibration nozzle, and may take several forms. Non-repetitiveness and non-uniformity are two examples of uncertainties that are fairly easy to detect. Others are more related to the calibration and test facilities and appear thus only if the tests are repeated in other nozzles.

Indications exist in the literature that probe calibrations do not always give identical results in different wind tunnels. Especially the calibration coefficients for determining the static pressure show some discrepancies.

In the present study calibration results from a "half-opened" and a "closed" calibration wind tunnel are presented. It is found that, for subsonic flow conditions, the introduction of a probe into the flow modifies the conditions all the way up to the air source, including the working conditions of the compressor. The reason for this is believed to be found in the losses introduced by the probe. It is also concluded that the manner in which the effective static pressure is determined during the calibration, as well as the nozzle geometry, largely influences the data.

In choked supersonic flow the working conditions of the compressor is obviously not influenced by the introduction of the probe. However, the bow shock from the probe stem will be positioned at different locations for different types and sizes of calibration tunnels. The effective static pressure in the tunnel can again, as for the subsonic flow conditions, be falsified.

NOMENCLATURE.

A_{sonic}	Critical surface $(M = 1)$	
A_{probe}	Surface at probe position	
K_1	Calibration factor for pitch angle	$K_1 = \dfrac{P_4 - P_5}{P_1 - \dfrac{P_2 + P_3}{2}}$
K_2	Calibration factor for total head pressure	$K_2 = \dfrac{P_{teff} - P_1}{P_1 - \dfrac{P_2 + P_3}{2}}$
K_3	Calibration factor for static pressure	$K_3 = \dfrac{P_{teff} - P_{seff}}{P_1 - \dfrac{P_2 + P_3}{2}}$
K_4	Calibration factor for yaw angle	$K_4 = \dfrac{P_2 - P_3}{P_1 - \dfrac{P_2 + P_3}{2}}$
M	Machnumber	
P_1, P_2, P_3, P_4	Measured pressures with the wedge probe WP11	
P_5	Defined as $0.5 * (P_2 + P_3)$	
ΔP_t	$Pt_{\text{with probe}} - Pt_{\text{without probe}}$	
ΔP_s	$Ps_{\text{with probe}} - Ps_{\text{without probe}}$	
$\hat{P}_t$	Total pressure behind the shock	
$\hat{P}_s$	Static pressure behind the shock	
δ_1	Displacement thickness	
$\hat{\delta}_1$	Displacement thickness behind the shock	

Subscripts:

eff	Effective value
outlet	Open exit of the test facility
s	Static value
t	Total head (=stagnation)

INTRODUCTION.

Problems regarding the reliability of pressure measurements with aerodynamic probes have been discussed at several of the conferences "Measuring Techniques in Transonic and Supersonic Flow in Cascades and Turbomachines". During the 6th conference [Lyon, 1981] it was decided to initialize a joint project by calibrating the same probe in different calibration wind tunnels and to compare the results. The conclusions from the project, which was named "European Workshop on Probe-Calibration", were presented at the 7th conference [Aachen, 1983]. The main findings from the probe calibrations on one cone probe and one wedge probe was the fairly large discrepancy in the results, especially in regards to the determination of the static pressure [Broichhausen and Fransson, 1984]. Among the possible explanations for these differencies were put forward:

- Different ways of determining the effective static pressure in the test section (for example by 1: measuring the static pressure on the side walls of the test section, before entering the probe to be calibrated into the flow field; 2: idem but with the probe in the test section; 3: determining the effective static pressure with a static pressure probe before entering the probe to be calibrated into the nozzle)
- Size of test section
- Form of the test section (opened, closed, half-opened)
- Losses in the calibration tunnel
- Interference between the probe and the tunnel side walls or shear layers respectively
- Probe blockage effects
- Different data acquisition techniques.

Other effects that come to mind are, for example, the air humidity and in which manner the presence of the probe might alter the characteristics of the whole flow, including all the way up to the air source.

PREVIOUS RESULTS AND OBJECTIVES.

Fig. 1a shows the scatter in the calibration coefficient for the static pressure as determined from the calibrations on the wedge probe in the "Workshop on Probe Calibrations" [Broichhausen and Fransson, 1984]. The static pressure coefficient

$$K_3 = \frac{p_{t,eff} - p_{s,eff}}{p_1 - \frac{p_2 + p_3}{2}}$$

is represented versus effective Mach number in 11 different calibration nozzles. It is seen that the most calibrations were performed for subsonic flow conditions and that a large scatter is present not only for transonic flow velocities but also at moderately Mach numbers. The results presented were obtained in different types of calibration wind tunnels (opened, closed, half-opened) with test section dimensions ranging from 75 mm to 203 mm (Fig. 1b).

The results indicated that the shape and size of the test section influences the calibration in a systematic manner [Broichhausen and Fransson, 1984, pages 92 and 118], but it was not clear if all the discrepancies appeared because of the difference in the wind tunnels or because of other factors mentioned in the introduction, such as the data acquisition techniques.

During the discussion of the results presented in the "Workshop on Probe Calibrations" it was also not established how the probe itself influences the flow field in the calibration wind tunnel.

The first objective of the present investigation is thus to study the influence of the nozzle geometry on the calibration coefficient K_3, while keeping the same:

- nozzle
- compressor and upstream settling chamber
- instrumentation and measuring equipment
- data acquisition and reduction techniques.

The second objective put forward is to look into the change of the flow field in a calibration nozzle due to the introduction of an aerodynamic probe in the test section.

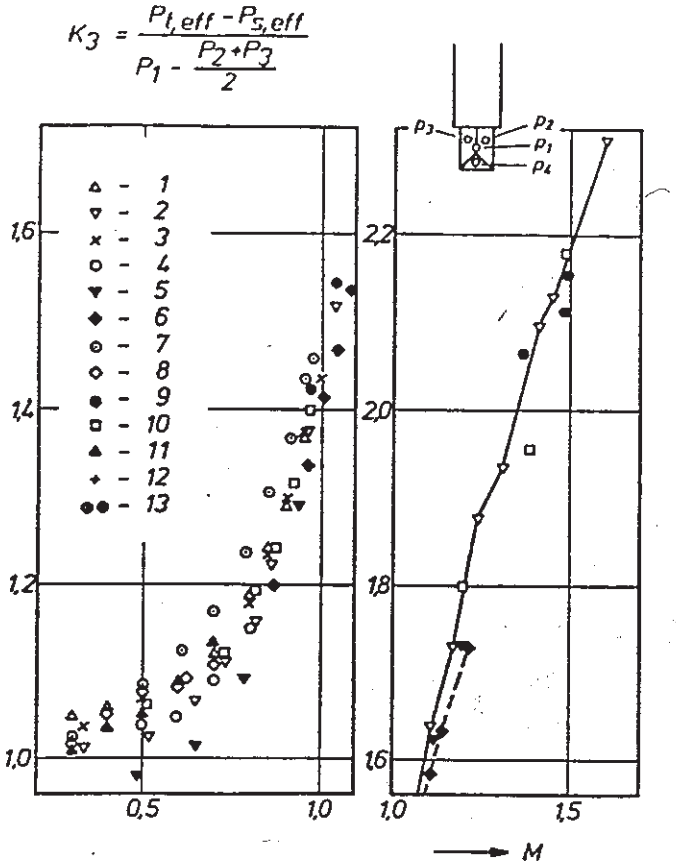


Fig. 1a: Calibration coefficient K_3 in 11 different calibration wind tunnels for the probe "WP11" [Broichhausen and Fransson, 1984, page 88].

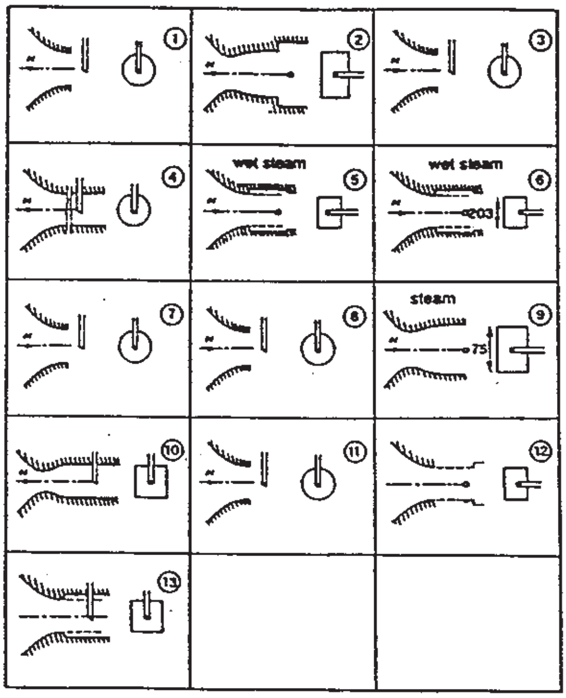
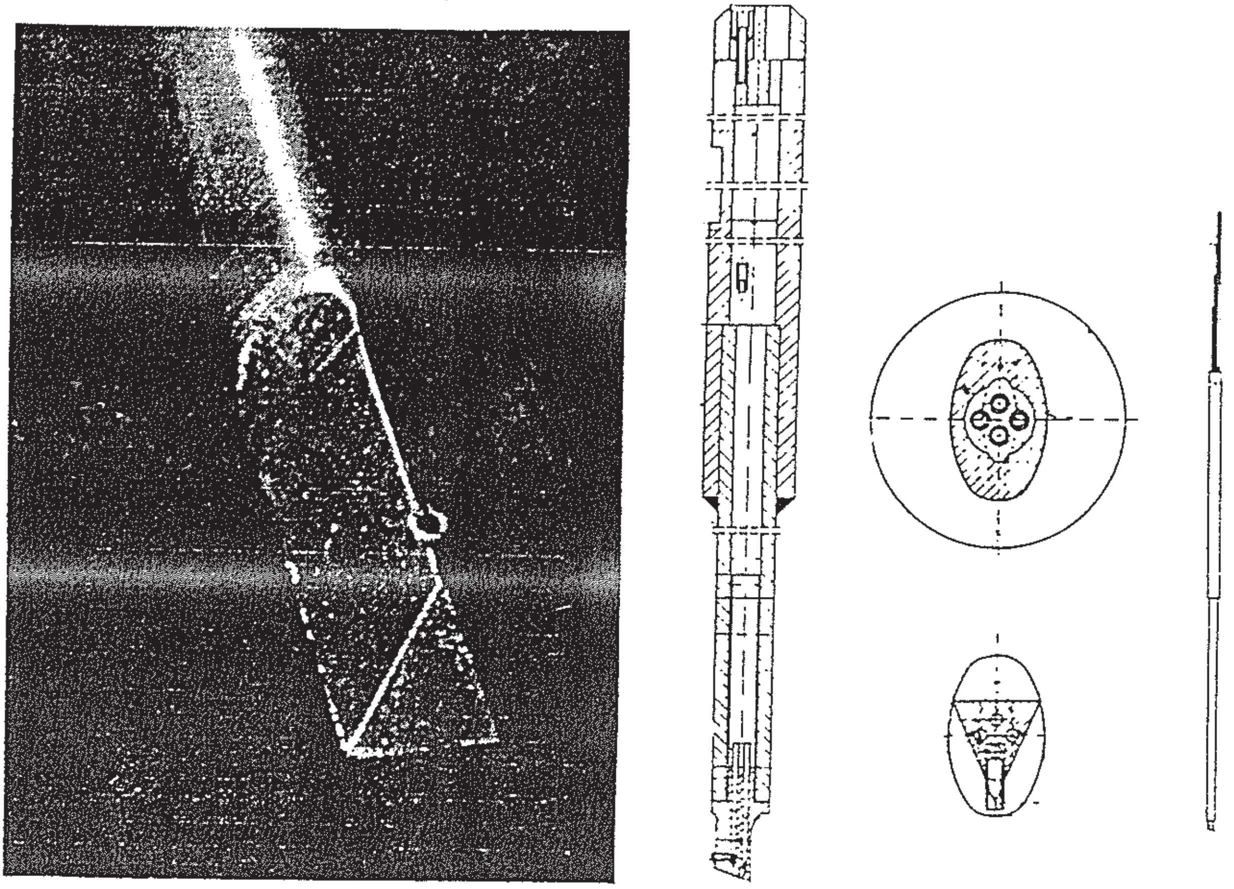


Fig. 1b: Schematic view of calibration nozzles employed in the "European Workshop on Probe Calibrations" [Broichhausen and Fransson, 1984, page 73].

EXPERIMENTAL SET-UP.

The same aerodynamic wedge probe as employed during the previously mentioned workshop was used for the present tests (Fig. 2, see also [Broichhausen and Fransson, 1984, pages 76-81]). The length of the wedge part of this probe is rather small (6 mm). The pressure tappings P_2 and P_3 are thus somewhat sensitive to pitch angle variations. The diameter of the pressure tappings are 0.4 mm, and the shaft has an elliptic shape (Fig. 2b).

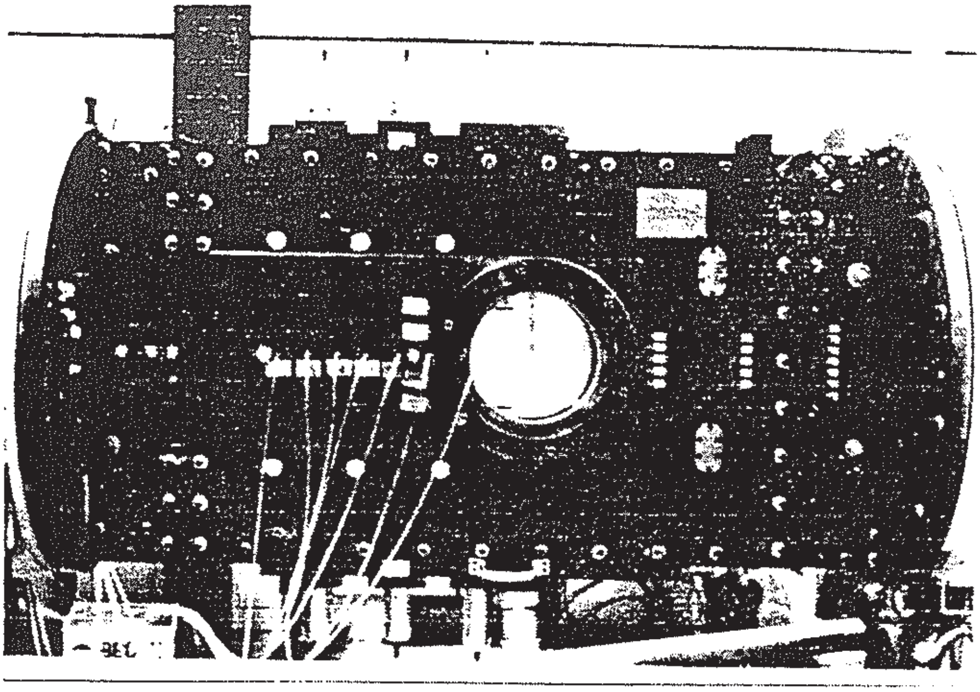


a: Photo

b: Principle design

Fig. 2: Wedge probe WP11.

The calibrations, both the ones during the workshop in 1982 and the present ones, were carried out in a Laval nozzle with a width of 100 mm (Fig. 3). For the present tests this nozzle was used as both "half-open" and "closed", and with two different heights of the test section, 130 and 160 mm. The nozzle in this form is schematically shown in Fig. 4, where it is also indicated that the probe is inserted into the tunnel from above in a position that corresponds to 25.5 mm downstream of the nozzle exit (i.e. end of the liners) in the case of the "half-opened" test section.



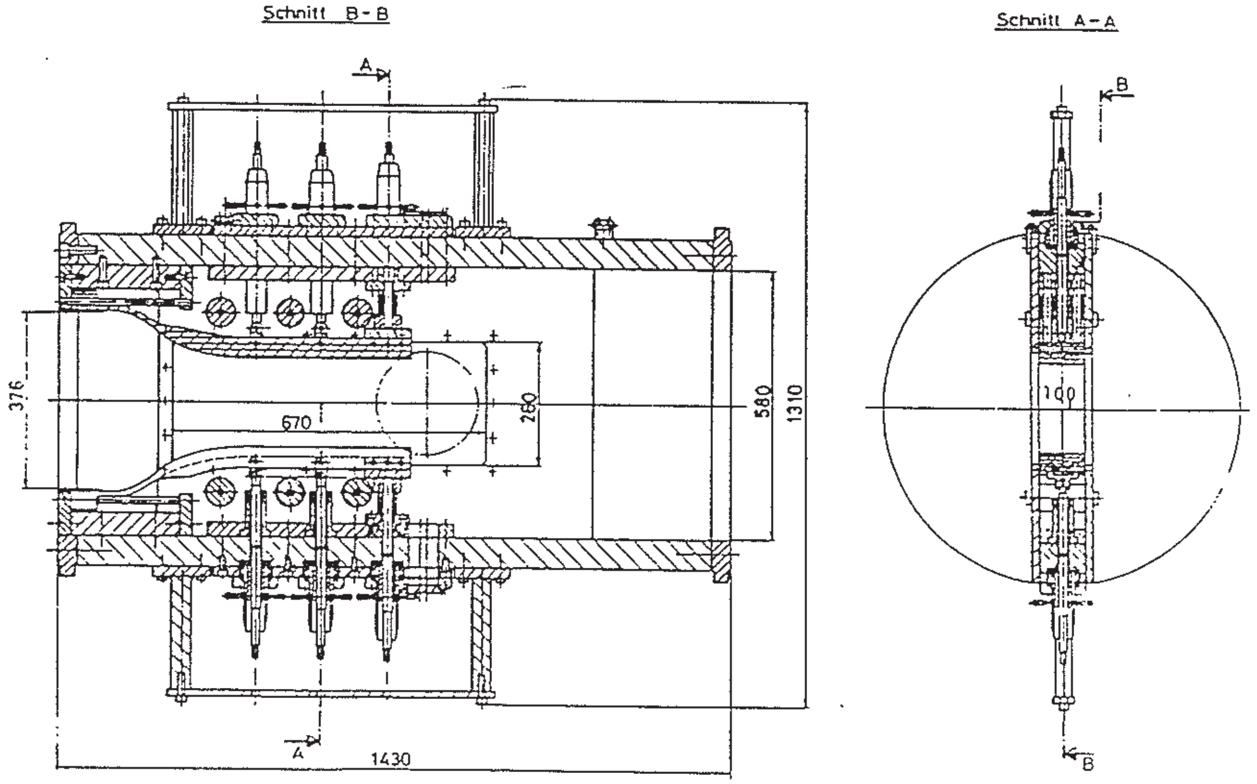


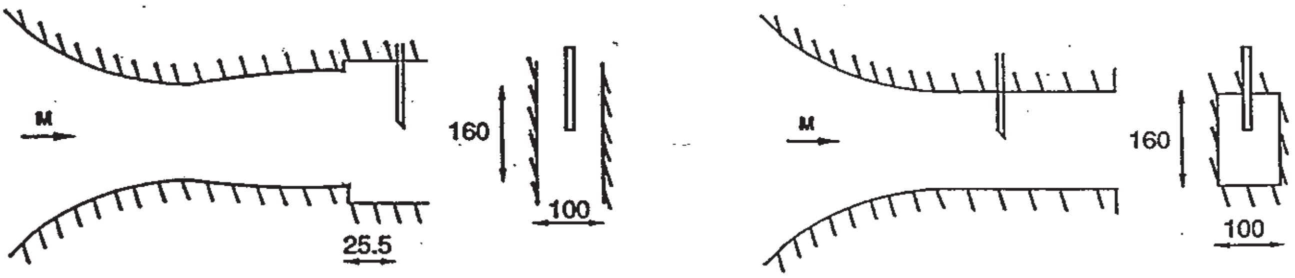
Fig. 3: Laval nozzle "TL-1" at EPF-Lausanne.

The liners in this facility are flexible, and the Mach number in the test section can be regulated between M≈0.3-1.6. Air from a continuously running four stage radial compressor (pressure ratio 3.5, mass flow 10 kg/sec) is feed into the nozzle through a system of pipes, together with a heat exchanger and a plenum chamber.

The stagnation pressure and temperature are measured in the upstream plenum chamber, and the effective static pressure is determined from the side wall pressure tappings (≈100). These tappings, which are used for control of the development of the flow, are situated on the tunnel side walls, from well upstream of the throat till downstream of the probe position. On one side wall, centered around the probe, another 450 static pressures can be measured.

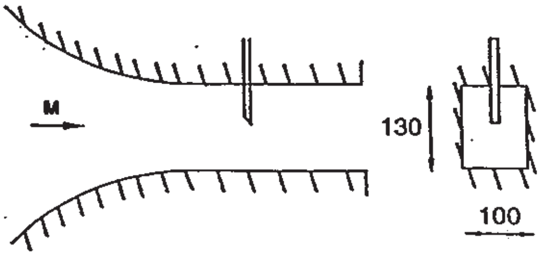
The effective static pressure is normally taken as the side wall pressure just upstream of the probe position for subsonic flow conditions and shortly upstream of the impingement of the shock wave for the supersonic flow cases.

Further instrumentation on the nozzle consists of Schlieren and laser holography interferometry visualizations.



a: "Half-opened", height 160 mm.

b: "Closed", height 160 mm.



c: "Closed", height 130 mm.

Fig. 4: Schematic view of the Laval nozzle "TL-1" at EPF-Lausanne in its set-up for the present tests.

PERFORMED TESTS AND DISCUSSION.

The results obtained in the Laval nozzle "TL-1"at the "Laboratoire de thermique appliquée et de turbomachines" (LTT) as part of the workshop data [Broichhausen and Fransson, 1984, page 88] are represented in Fig. 5, together with the data obtained during the present tests in the same nozzle. As the largest problems during measurements with an aerodynamic probe appear in the transonic flow regions, the present tests were performed at M=0.7, 0.9, 1,1 and 1.3 for the "half-open" and M=0.9 and 1.1 for the "closed" nozzle.

The first conclusion that can be drawn from Fig. 5 is that all results ("half-opened" performed in 1982 and both "half-opened" and "closed" data from 1988) fall upon the same curve. The earlier tests were obtained by determining the effective static pressure in the test section from the side wall static pressures **with** the probe WP11 in the tunnel. The present results were obtained both by determining the effective static pressure **with** the probe in the test section (open symbols in Fig. 5) and **without** the probe in the test section (full symbols).

Although the values fall on the same curve it is clearly seen that they do not fall together. This is especially noticed at Mach number 0.9. It is concluded (Fig. 5) that the three open symbols from the present tests (i.e. calibrations with the effective static pressure determined **with** the probe in the test section) are closely packed together, and that the three full symbols (i.e. calibrations with the effective static pressure determined **without** the probe in the test section) are also grouped together. However, a considerable difference is found in their position on the curve.

The reasons therefore may be found by examining the pressures measured in the Laval nozzle during the calibration (Table 1). It is found that, at subsonic flow velocities (M_{eff}≈0.9), different stagnation pressure levels, i. e. different working conditions of the compressor, had to be regulated in order to obtain identical effective Mach numbers in the different test sections **without** the presence of the probe. The constant Mach numbers but different stagnation pressures in the three nozzles ("half-opened", "closed large" and "closed small") obviously give different static pressures (Table 1). If the probe is then introduced into the flow it is seen that both the stagnation and the static pressure are modified. The change in the stagnation pressure ranges from an increase of 1% to 2%, and the change in static pressure from an increase of 3% to 7%. This obviously means that the effective Mach number in the nozzles has decreased, from M_{eff}≈0.90 to M_{eff}≈0.87.

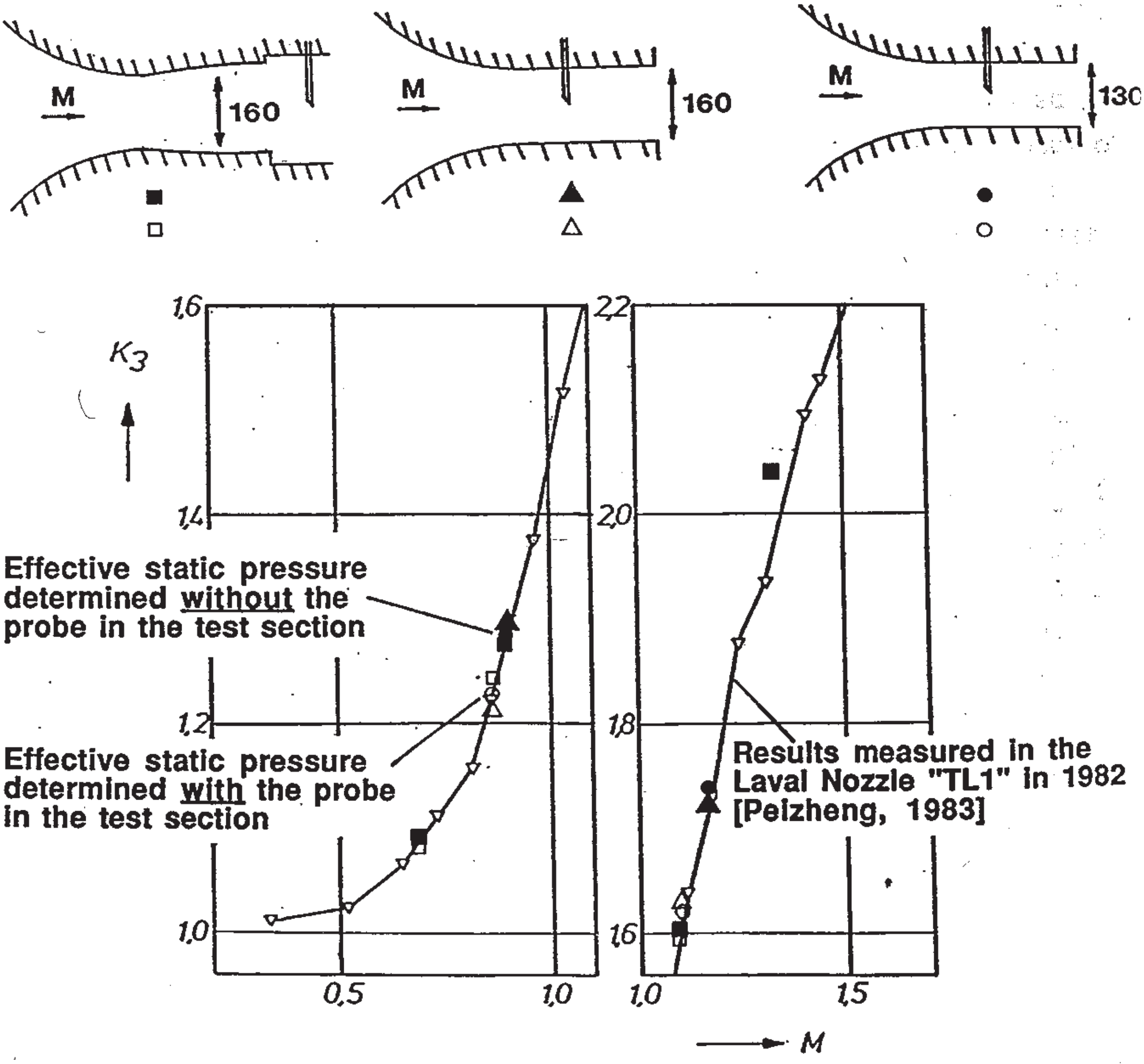
∇ : Results in the Laval Nozzle "TL-1" during the European workshop (1981-1983). P_t and P_s determined with the probe in the test section

Present results:

Pressure acquisition of P_t and P_s:

□ △ ○ : With the probe in the test section

■ ▲ ● : Without probe (Ideal flow)

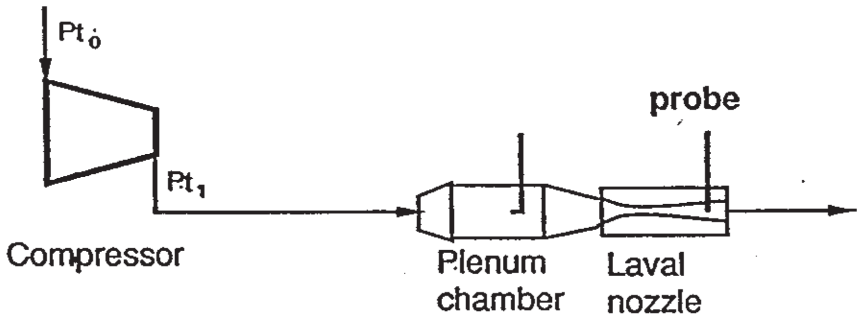


Effective static pressure determined <u>without</u> the probe in the test section

Effective static pressure determined <u>with</u> the probe in the test section

Results measured in the Laval Nozzle "TL1" in 1982 [Peizheng, 1983]

Fig. 5: Results from calibrations of probe WP11 in the Laval nozzle "TL-1".



ΔPt = Pt with probe - Pt without probe
ΔPs = Ps with probe - Ps without probe

Channel	Half open	Closed (large)	Closed (small)
$Pt_{without\ probe}$ mbar	1453	1684	1594
$Pt_{with\ probe}$	1458	1700	1605
$Ps_{without\ probe}$ mbar	869	993	946
$Ps_{with\ probe}$	887	1040	980
$\frac{\Delta Pt}{Pt-Ps}$ %	0.9	2.4	1.8
$\frac{\Delta Ps}{Pt-Ps}$ %	3.2	7.1	5.4
$M_{without\ probe}$ mbar	0.89	0.90	0.90
$M_{with\ probe}$	0.87	0.87	0.87
$K3_{without\ probe}$ mbar	1.28	1.29	1.28
$K3_{with\ probe}$	1.25	1.23	1.24

Table 1: *Pressures measured during the present calibrations in the Laval nozzle "TL-1" for subsonic flow conditions,* $M_{eff}\approx 0.9$.

The value of the calibration coefficient K_3 has also decreased, wherefore the calibration points in Fig. 5 seem to be situated on a single curve. This is however the case only as the same stagnation and static pressures were used in the calculation for both M_{eff} and K_3. If a nozzle with a pre-measured Mach number distribution would be used while measuring the stagnation and static pressures for the calibration coefficient K_3 during the calibration, the effective Mach number would be considered to be $M_{eff}\approx0.90$ (i.e. at the position of the open symbols), while the value of K_3 would be considered to belong to the full symbols. In such a case the open and full symbols would not fall on the same curve. Similarly, if a static pressure probe has been used to determine the effective Mach number in the test section and if the dimensions and mounting of the probe to be calibrated are not identical to the ones of the static pressure probe, it appears that a discrepancy can be introduced in the calibration. The reason therefore is found in a T-S diagram. In Fig. 6 it is seen that, as the outlet flow conditions for an open air loop are identical with and without a probe in the test section (atmospheric conditions) and as the losses in the test section are different with and without the probe, the stagnation pressure level (i.e. operating conditions of the air source) changes by introducing or taking out the probe in the test section.

The flow in the test sections of the three nozzles are, for identical effective Mach numbers, similar without a probe in the tunnel. With probe this is, however, not the case as concluded from Figs. 7. Here the side wall lines of constant isentropic Mach numbers in the test sections are represented, as determined from 450 pressure tappings spaced 5 mm apart. The probe is inserted through the upper wall at x=22.5 mm. It is seen that the flow is accelerated around the probe, with the smallest acceleration for the "half-opened" test section (as expected as here the flow has a larger area to expand, Fig. 7a), and the largest absolute acceleration for the "closed large" test section (Fig. 7b).

In the case of a **supersonic flow** ($M_{eff}\approx1.1$) in the test section the phenomena are somewhat different (Table 2). As the flow is choked in all three nozzles, the stagnation pressure is the same for identical effective flow Mach numbers. The static pressure is thus also the same. When a probe is introduced in the test section, the stagnation pressure in the plenum chamber does not change if the flow remains choked. This is seen in Table 2. However, the same is not true for the effective static pressure if this is measured just upstream of the influence of the shock wave. In the "half-open" nozzle the shock wave is positioned just upstream of the probe shaft (Fig. 8a), wherefore the effective static pressure is only slightly influenced.The losses in the shock is represented in the T-S diagram in Fig. 8a as §.

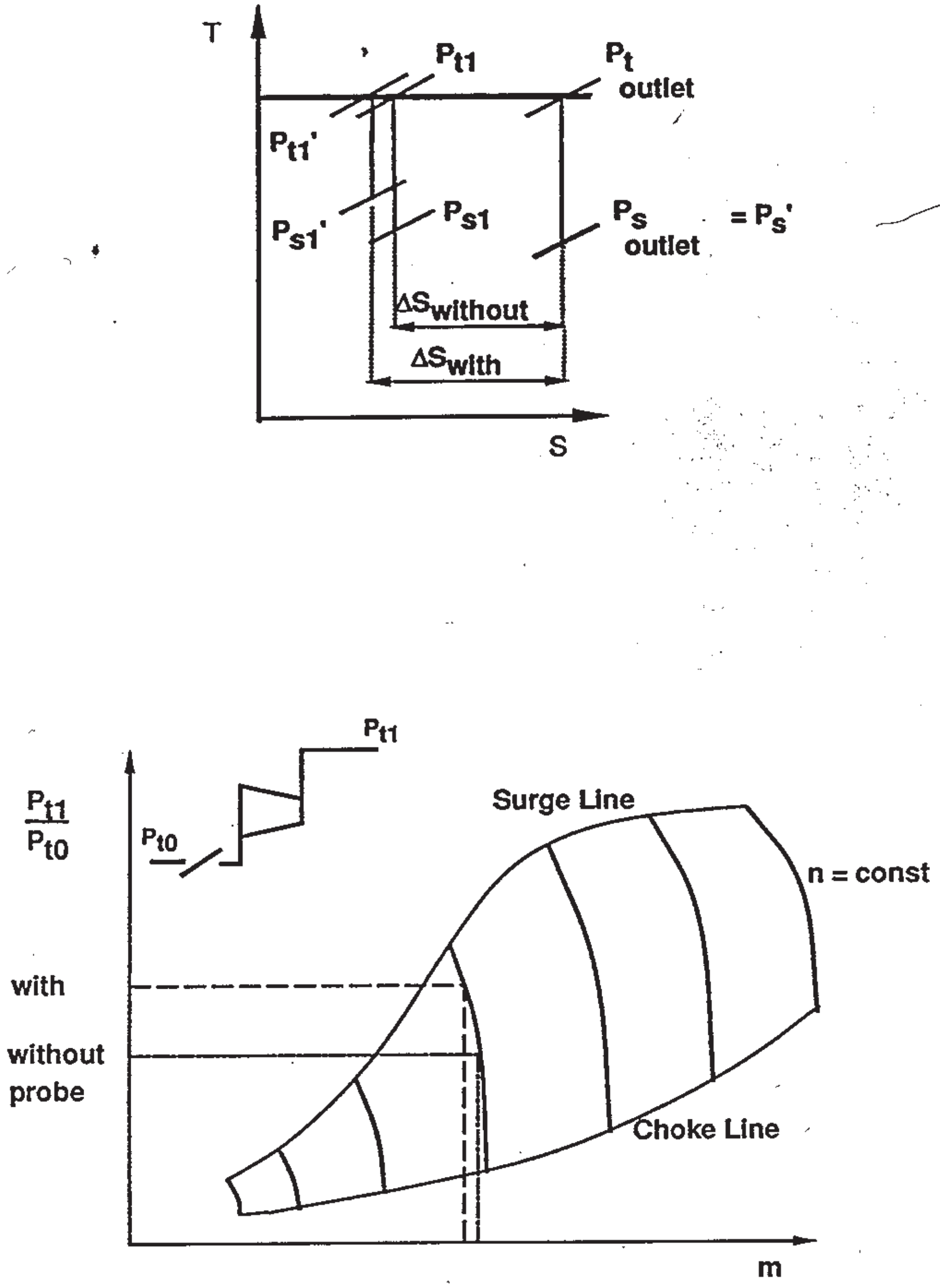
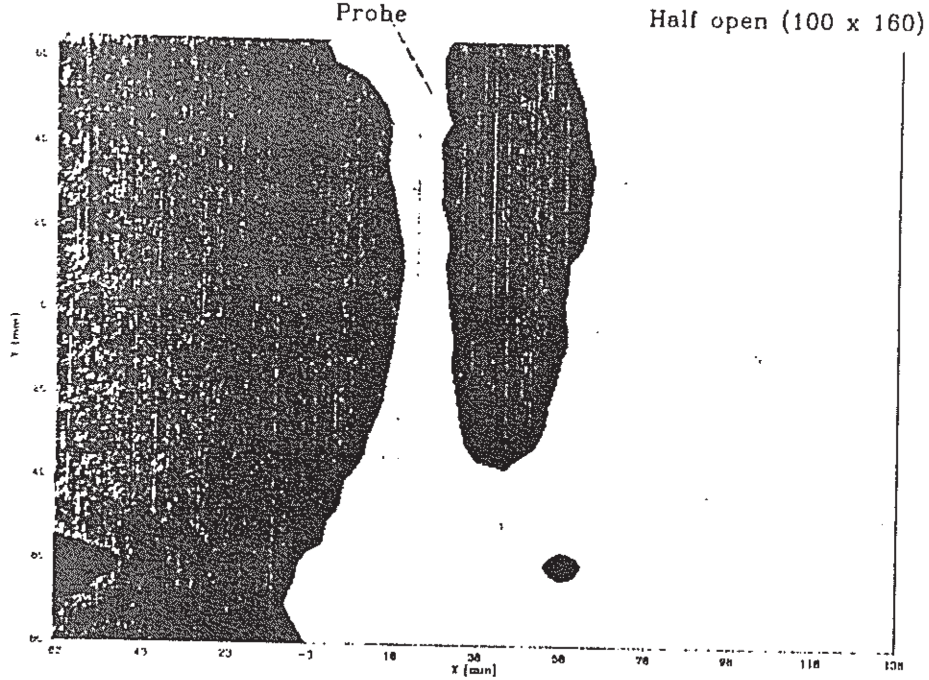
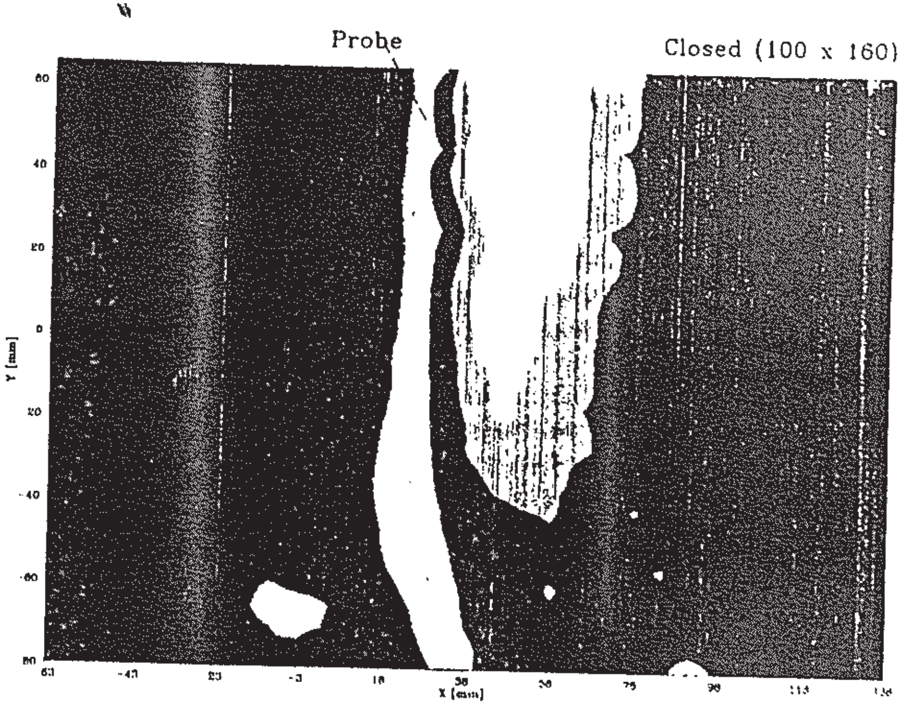


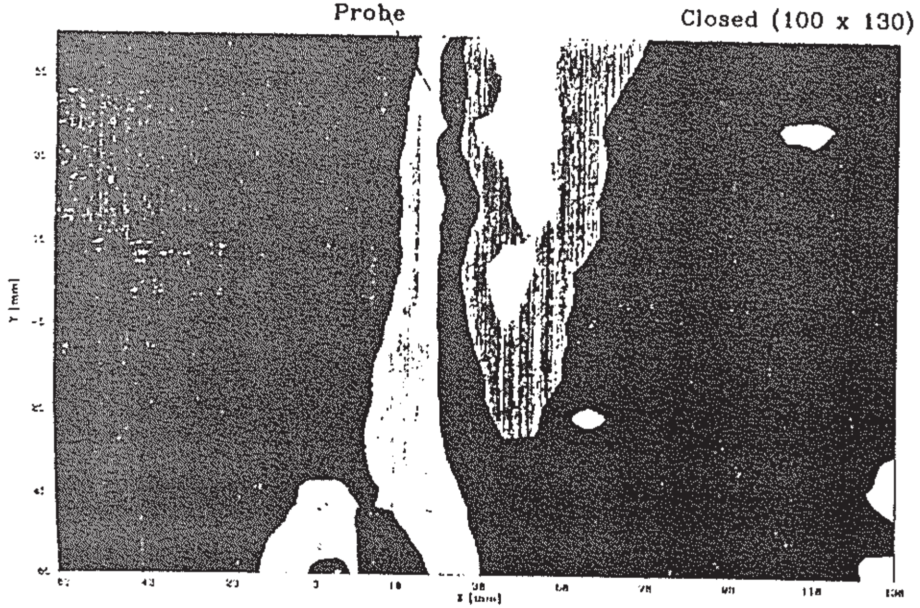
Fig. 6: Change of subsonic flow conditions by introducing a probe in the test section.



a: "Half-open" test section, 100*160 mm.



b: "Closed " test section, 100*160 mm.



c: "Closed" test section, 100*130 mm.

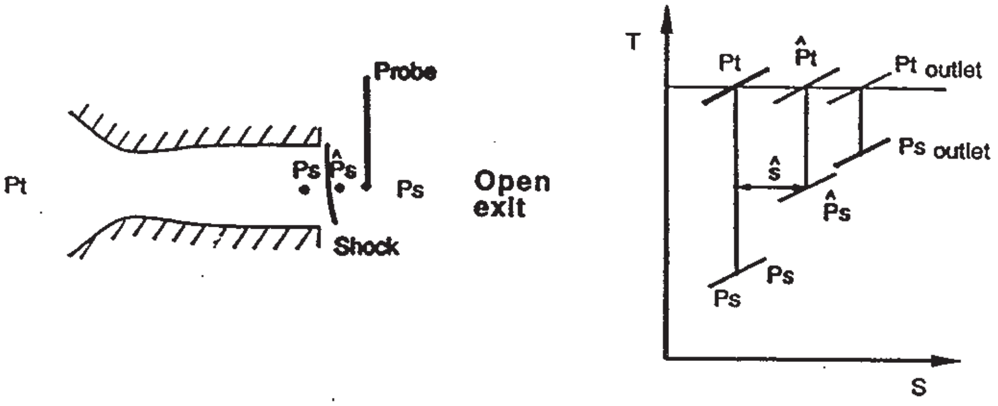
Mach Number (isentropic)

☐	ABOVE 0.97
☐	0.96 – 0.97
▨	0.95 – 0.96
▨	0.94 – 0.95
▨	0.93 – 0.94
▨	0.92 – 0.93
■	0.91 – 0.92
■	0.90 – 0.91
☐	0.89 – 0.90
▨	0.88 – 0.89
■	0.87 – 0.88
■	0.86 – 0.87
■	0.85 – 0.86
■	BELOW 0.85

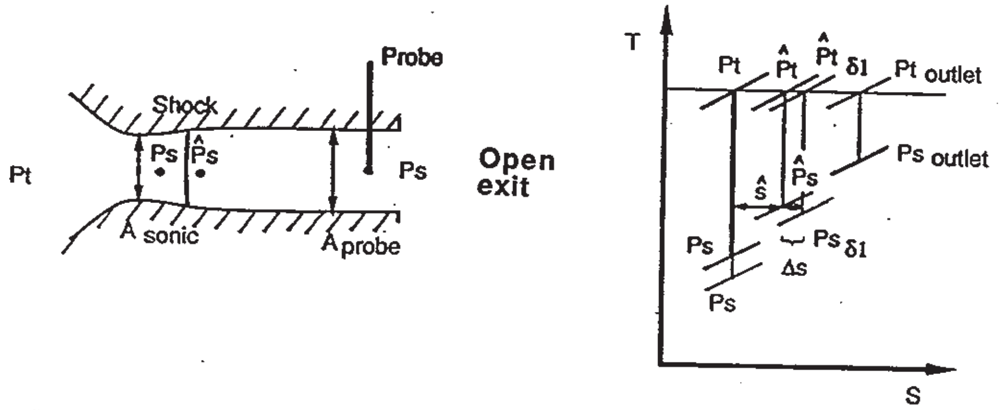
Fig. 7: Side wall isentropic Mach numbers, as determined from 450 static pressure tappings on one side wall, with the probe WP11 in the test section. Subsonic flow $M_{\infty}=0.9$

Channel	Half open	Closed (large)	Closed (small)
$Pt_{without\ probe}$ mbar $Pt_{with\ probe}$	2011 2011	2020 2020	2019 2018
$Ps_{without\ probe}$ mbar $Ps_{with\ probe}$	948 955	906 969	901 974
$\frac{\Delta Pt}{Pt-Ps}$ %	0.0	0.0	0.0
$\frac{\Delta Ps}{Pt-Ps}$ %	0.7	6.0	7.0
$M_{without\ probe}$ mbar $M_{with\ probe}$	1.09 1.09	1.13 1.08	1.14 1.08
$K3_{without\ probe}$ mbar $K3_{with\ probe}$	1.61 1.60	1.73 1.63	1.74 1.62

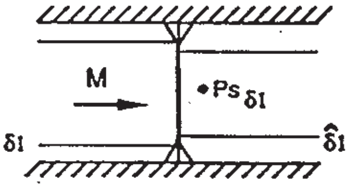
Table 2: *Pressures measured during the present calibrations in the Laval nozzle "TL-1" for supersonic flow conditions,* $M_{eff} \approx 1.1$.



a: "Half-open" nozzle



b: "Closed" nozzle



$$\begin{cases} M=1.1 \\ \hat{\delta}_1 - \delta_1 \cong A_{sonic} - A_{probe} \end{cases}$$

c: Illustration to shock-boundary layer interaction in a "closed" nozzle.

Fig. 8: Position of bow shock from probe in different types of calibration tunnels.

In the case of a "closed" channel, on the other hand, the bow shock from the probe is pushed quite a long distance upstream and becomes positioned just downstream of the throat (Fig. 8b). A possible explanation for this is the additional losses in the "closed" channel as regards to the "half-opened" one because of the shock-boundary layer interaction (Fig. 8c and the T-S diagram in Fig. 8b where the additional losses are represented by Δs). As the outlet flow conditions are fixed (atmospheric) the equilibrium of the flow can only be found if the rest of the losses (i. e. the shock losses) decrease. The only manner in which the flow can achieve this is the displacement of the shock upstream into a region of lower pre-shock Mach number.

The pre-shock static pressure (=effective static pressure) has thus a higher value in the case with probe in the test section than in the case without.

The effective Mach number and the calibration coefficient for the static pressure (K_3) are thus largely influenced by the fact that the probe has been introduced into the flow field. The difference in the vertical positions of the open and full symbols at an effective Mach number of $M_{eff} \approx 1.1$ (K_3-values in Fig. 5) is therefore small for the "half-open" and large for the "closed" nozzles.

The above discussion has been made on the basis of the calibration factor for the static pressure (K_3). As the effective static pressure does normally not enter explicitly in the calibration factors for stagnation pressure and flow angles (see the nomenclature for an example of definitions), these are not influenced. However, the effective Mach number is still influenced in the same way.

CONCLUSIONS.

A wedge probe has been studied in three different nozzles, operating in the transonic flow domain, as regards to its characteristics concerning calibration tunnel effects. The three different nozzles were all connected to the same air source and supply pipes. It has been found that the method used for determining the effective static pressure in the calibration nozzle can have a significant influence on the results from the calibration.

It has further been shown that all calibration coefficients as well as the measured effective stagnation and static pressures, and thus the effective Mach number, varies with the nozzle type and nozzle geometry.

In subsonic flow the presented results show the same tendencies as noted from the "European Workshop on Probe Calibrations", which indicated that a decrease in nozzle dimensions increased the absolute value of the calibration coefficient for the static pressure (K_3). However, the discrepancies between results from the different calibration tunnels were larger in the earlier workshop investigation than in the present study. The main reason therefore is believed to be because of the geometrical differences studied in the two investigations. In the workshop-results the ratio between the largest and the smallest nozzle was 8.2 whereas it was 1.2 in the present case.

It is concluded that the introduction of a probe with a blockage area of only 1.5% of the test section can alter the working conditions of a large air supply. This has to be considered while comparing different calibration results, and also when calibration coefficients are used in order to determine conditions in an unknown flow field.

For supersonic flow conditions (i. e. choked flow) the stagnation pressure level does not change when the probe is introduced into the flow field. However, depending on the type and dimensions of the calibration nozzle the bow shock from the probe stem will be positioned at different locations. The manner in which the effective static pressure is determined again influences the Mach number and calibration coefficient for static pressure.

It is thus concluded that the calibration data are influenced by the measurements of the effective static pressure, as well as the pressures on the probe. As the conditions during a measurement with the calibrated probe are not identical with the conditions during the calibration the above treated factors should be carefully considered during a data reduction.

REFERENCES.

Bois, G.; Editor; 1981
Proceedings of the 6th conference on "Measuring Techniques in Transonic and Supersonic Flows in Cascades and Turbomachines"
Ecole Centrale de Lyon, 1981.

Broichhausen, K.-D.; Fransson, T. H.; 1984
Proceedings of the "European Workshop on Probe Calibrations 1981-1983".
Institut für Strahlantriebe und Turboarbeitsmaschinen, Rhein-Westfälische Technische Hochschule Aachen, Mitteilung Nr. 84-02.

Broichhausen, K.-D.; Gallus, H. E.; Editors; 1983
Proceedings of the 7th conference on "Measuring Techniques in Transonic and Supersonic Flows in Cascades and Turbomachines"
Rhein-Westfälische Technische Hochschule Aachen, Mitteilung Nr. 84-01.

Jiang Peizheng; 1983
Eichexperiment der Keilsonden WP11 und WP4 in dem Machzahlbereich $0.3 < M < 1.6$
Ecole Polytechnique Fédérale de Lausanne
Laboratoire de thermique appliquée et de turbomachines, Report No. TM -1-1983.