INVESTIGATION OF THE REYNOLDS-NUMBER EFFECTS ON PROBE MEASUREMENTS IN SUPERSONIC FLOW

by

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1. INTRODUCTION

The accuracy of probe measurements depends on the similarity of the flows during calibration and measurement. This similarity especially has to extend to the composition of the gas, the compressibility effects (Mach-number) and the viscosity effects (Reynolds-number). Therefore a complete probe-calibration has to cover an independent variation of Mach- and Reynolds-number at different flow angles. In order to reduce the remarkable efforts that this complete calibration brings about, in the present contribution conversion formulas for flows with different Reynolds-numbers are established on the basis of the similarity laws and examined as to their validity by means of experimental investigations.

2. EXPERIMENTAL SET-UP

The experimental investigations were performed in a closed-loop calibration channel for Mach-numbers up to 1.8. The gas-temperature can be kept constant during the test by means of a cooler. Thus with equal geometries and velocities the Reynolds-number is only dependent on the static pressure. A variation of the static pressure (respectively the Reynolds-number) is acchieved by combining the losed loop with an air-compressor and a vacuum-pump. In this way the flow conditions shown in Fig. 1 can be realized. In the operation points marked by full symbols probe calibrations were performed for different Reynolds-numbers. These investigations were carried out at four different probe types (Fig. 2).

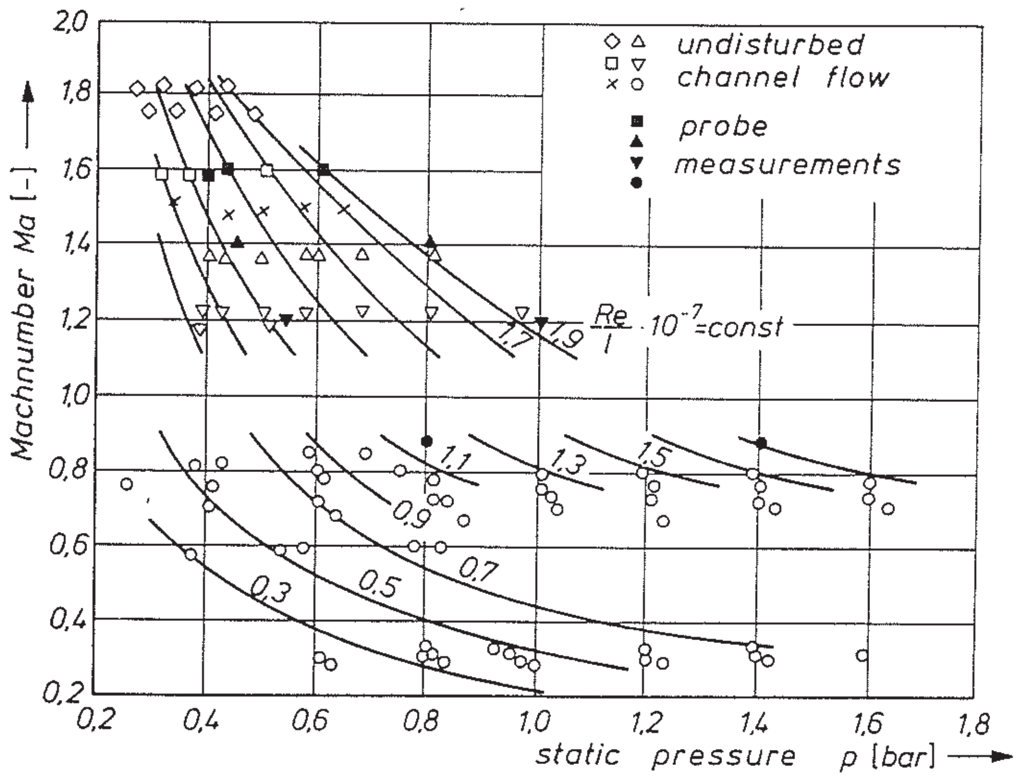

Fig. 1: Characteristic of the test section in the closed loop

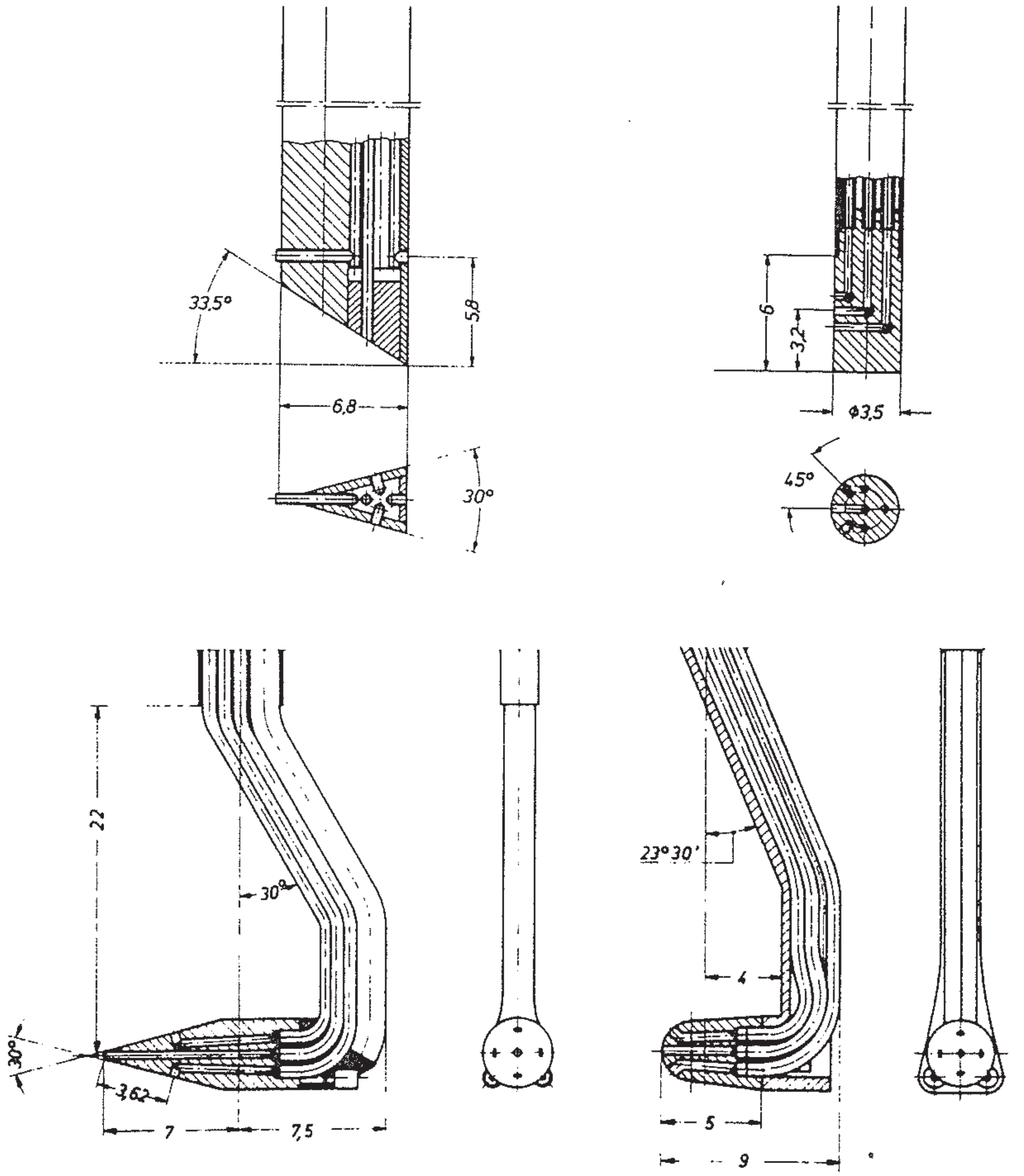

Fig. 2: Investigated probe types

3. EVALUATION OF THE PROBE-CALIBRATIONS

In order to get the calibration functions depending on flow angle and Mach-number the following dimensionless characteristic values are set up by the pressures measured at the probe head (Fig. 3).

$$k_\alpha = \frac{p_3-p_1}{\Delta p} \qquad k_\beta = \frac{p_4-p_2}{\Delta p} \qquad k_M = \frac{\Delta p}{p_o} \qquad (2.1)$$

with $\Delta p = p_o - \frac{p_1+p_3}{2}$

The non-dimensional calibration spheres, which are generated in this way (Fig. 4) are approximated according to |1| by a polynomial function F_n.

$$\left.\begin{array}{l}\alpha\\ \beta\\ Ma\\ p_t\\ p\end{array}\right\} = F_n\ (k_\alpha, k_\beta, k_M)\ ;\ n = 1,5 \qquad (2.2)$$

Measuring with the calibrated probes the characteristic values k_α, k_β, k_M are computed from the pressures $p_o, \ldots, p_4$. By means of the different polynomial functions F_n (2.2) the flow properties α, β, Ma, p_t, p then can directly be determined.

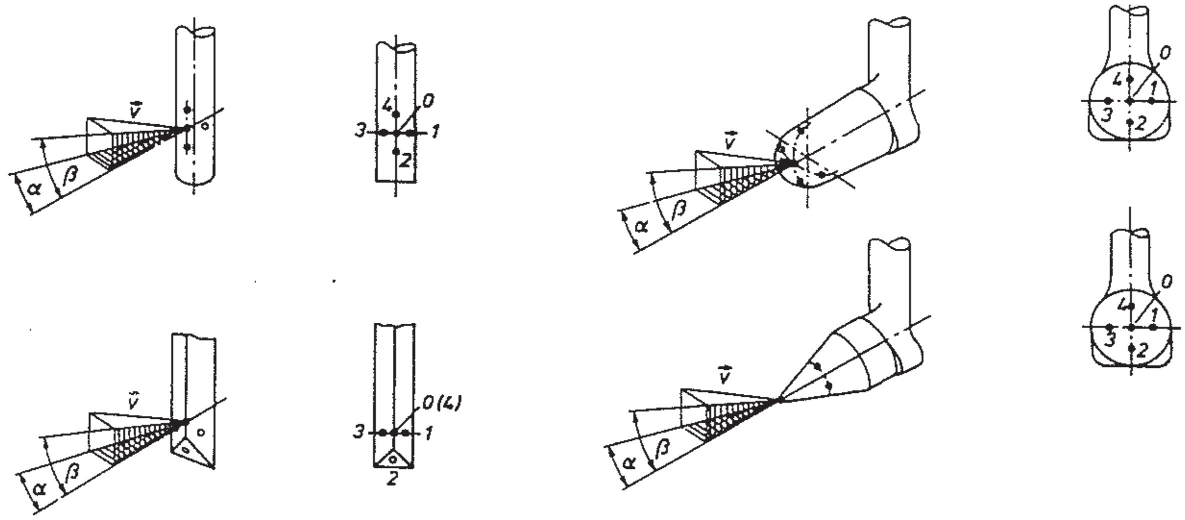

Fig. 3: Flow angles and pressure taps at the probe head

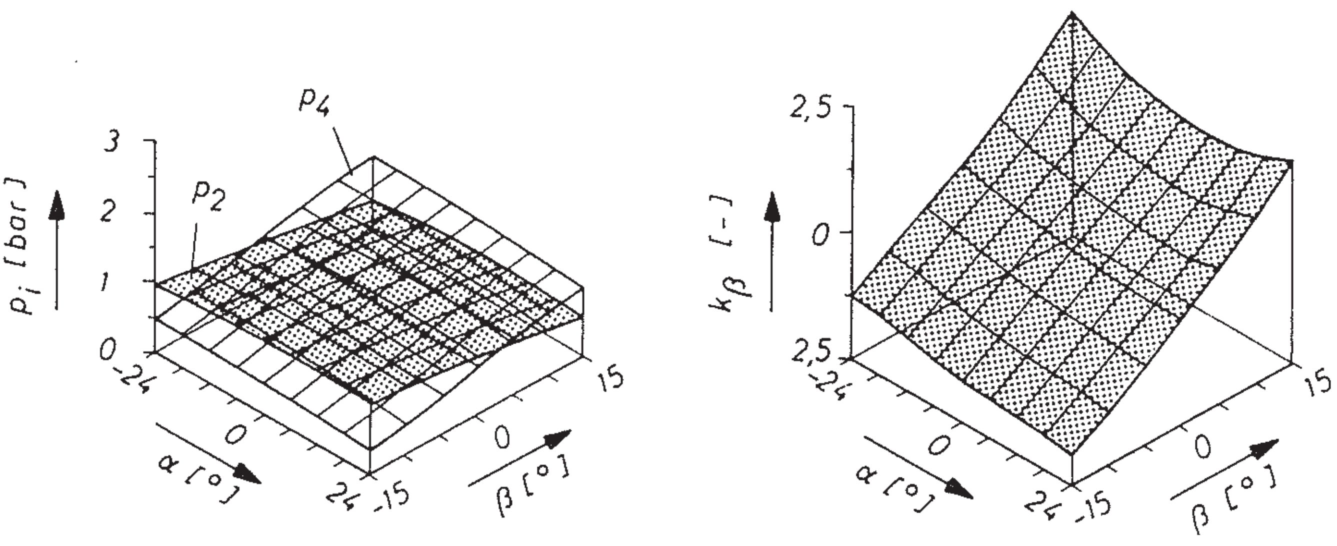

Fig. 4: Pressures at the vertical pressure taps and non-dimensional characteristic k_β

4. INFLUENCE OF THE REYNOLDS-NUMBER

If probe-measurement and calibration - as Fig. 1 shows - are performed at a different Reynolds-number (i.e. static pressure) level but at the same Mach-numbers also the pressures indicated by the pressure holes are different in measurement and calibration. The dimensionless characteristics, however, do not differ remarkably. This shows a comparison of Fig. 4 and Fig. 5. In these figures the pressures of the vertical pressure holes (p_2, p_4) and the corresponding dimensionless characteristic k_β are plotted as a function of the flow angles α and β. The Mach-number is the same for both figures, but the Reynolds-numbers are different. As the characteristic-spheres are nearly the same for both Reynolds-numbers, the determination of the flow properties by means of this non-dimensional characteristics results in nearly the same values, though the static pressure level is different in reality. To avoid such errors a calibration has to cover both Mach- and Reynolds-number.

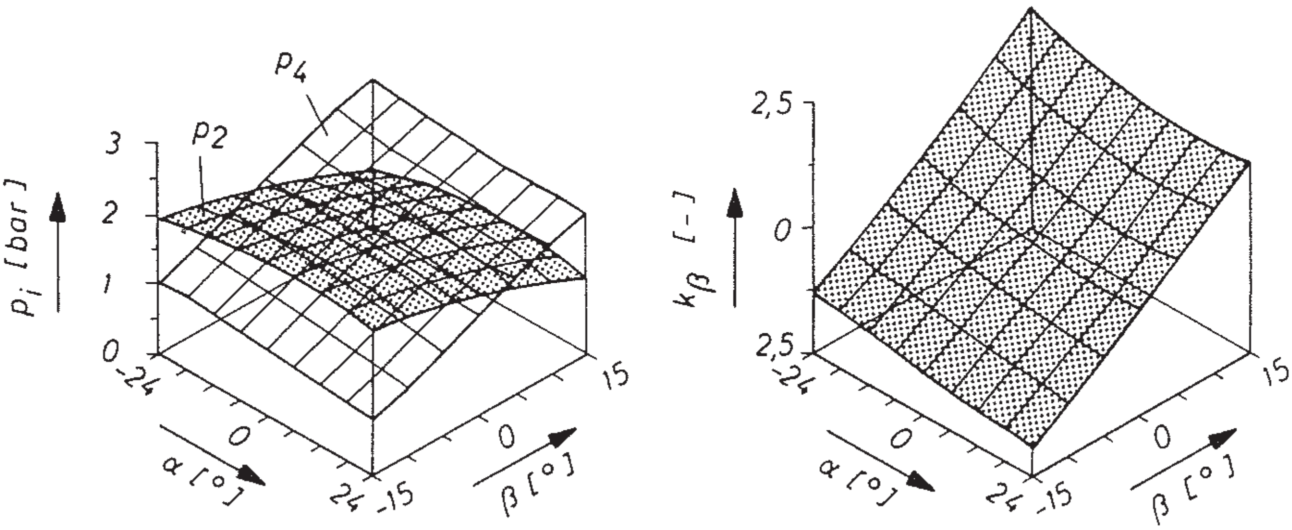

Fig. 5: Influence of increased Reynolds-number on pressures and non-dimensional characteristic k_β (in comparison to fig. 4)

5. CONVERSION FORMULAS COVERING REYNOLDS-NUMBER EFFECTS

To reduce the remarkable efforts for such a complete calibration, conversion formulas regarding the flow around probes at different Reynolds-numbers can be established, as shown in detail in |2|. From the assumption, that the Euler-Numbers, established with the pressures p_i at the different pressure holes

$$Eu = \frac{p_i - p}{p_t - p} \tag{5.1}$$

remain the same at different Reynolds-numbers the pressures p_i can be converted.

$$p_{iC} = p_{tC} + (p_i - p_t)\frac{p_C}{p}\,\frac{\left(1+\frac{\kappa-1}{2}Ma_C^2\right)^{\frac{\kappa}{\kappa-1}} - 1}{\left(1+\frac{\kappa-1}{2}Ma^2\right)^{\frac{\kappa}{\kappa-1}} - 1} \tag{5.2}$$

In this formula additionaly the Mach-number ratio can be defined on the basis of the similarity laws |3| to

$$\frac{Ma_C^2}{Ma^2} = \frac{p}{p_C} \sqrt{\frac{T_{tC}}{T_t}} \qquad (5.3)$$

This conversion formula for the pressures measured at the pressure holes according to |3| gives satisfactory results for subsonic flow and zero flow angles.

Without the aforementioned assumptions, starting from the ratio of the Reynolds-numbers Re_c/Re, the static and total pressures in different flows can be transformed as follows:

$$\text{(static pressure)} \quad p_{iC} = p_i \frac{Re_C}{Re} \sqrt{\frac{T_C}{T}} \frac{Ma}{Ma_C} \frac{\mu(T_C)}{\mu(T)} \qquad (5.4)$$

$$\text{(total pressure)} \quad p_{iC} = p_i \frac{Re_C}{Re} \frac{(A/A^*)_C}{A/A^*} \sqrt{\frac{T_{tC}}{T_t}} \frac{\mu(T_C)}{\mu(T)} \qquad (5.5)$$

with A/A^* : sonic area ratio

Finally the ratio of the local lift-coefficients can be determined on the basis of the small-perturbation-theory |4|. From this theory one can derive the following relation for the conversion of the pressures measured at the lateral pressure holes:

$$p_{iC} = p_{tC} - \frac{p_t - p_i}{p\ Ma^2}\ p_C\ Ma_C^2 \sqrt{\frac{Ma^2 - 1}{Ma_C^2 - 1}} \qquad (5.6)$$

6. COMPARISON OF CONVERSION-FORMULAS AND EXPERIMENTAL RESULTS

In order to evaluate the conversion-formulas the four probes (Fig. 2) were calibrated for the same Mach-numbers but with different Reynolds-numbers (Fig. 1). The pressures measured at the holes of the probe head are plotted for the different probes as a function of the yaw angle α in Figs. 6 to 8 and marked by

● $Re/l \cdot 10^{-7}$ 1,9

▲ $Re/l \cdot 10^{-7}$ 1,15

The pressure values marked by letters in these figures correspond to those pressures, which result from the conversion from high Reynolds-numbers to the lower Reynolds-number level by means of the aforementioned conversion formulas. The correlation between symbols and conversion formulas is explained in the following table:

symbol	equation
A	combination of (5.2) and (5.3)
D	(5.2)
E	(5.5)
H	(5.4)
Z	(5.6)
X, Y	equal pressure coefficients

Furthermore the percental errors which are caused by the different conversion formulas, are plotted in these figures as bar charts.

The best results are achieved - not only for the total-pressure-hole (Fig. 6) but also for the lateral and vertical pressure holes (Fig. 7) - by means of the conversion formula for the free-stream total pressure (5.5, symbol E). The error caused by this Reynolds-number correction formula can be neglected within the limits of the measuring-accuracy. Only in the case of the pressure p_2 of the wedge-type probe in the case of big yaw and pitch angles (Fig. 8) greater errors occur. So this probe should be adjusted to the flow angle to get better results. The remarkable exactness of this conversion-formula can be explained by a partial stagnation of the flow within the pressure-holes, since these holes have a relatively big diameter (Ø = 0,4 mm) in comparison with the probe head (Ø = 3 mm). So f.ex. the head contour no longer corresponds to an exact cone. Therefore the pressures, measured at the pressure holes 1,...,4 in the case of coaxial flow ($\alpha=\beta=0$) are higher than those resulting from a theoretic calculation of the flow around the probe head.

Worse results are achieved by (5.2) as well as by the conversion of the hole-pressures corresponding to the static free-stream pressure (5.4) and a conversion based on linear theory (5.6). The combination of (5.2) and (5.3), which is suitable for subsonic flows according to |3|, gives no satisfactory results in supersonic flows.

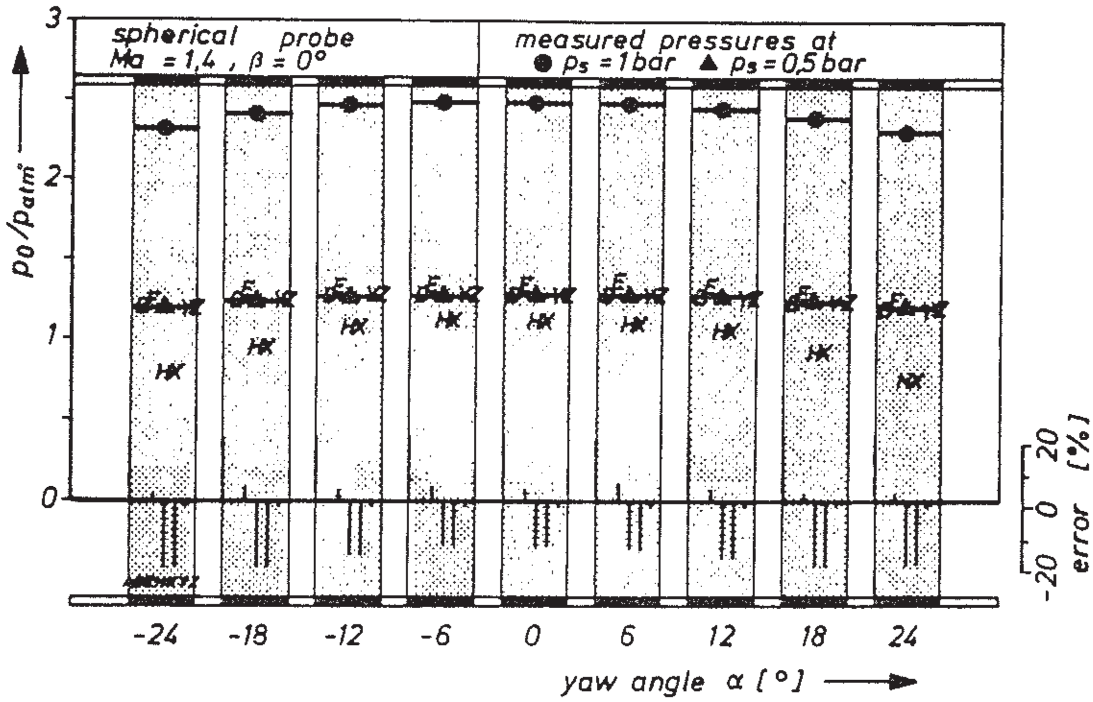

Fig. 6: Experimental data and results of the conversion formulas (total pressure tap)

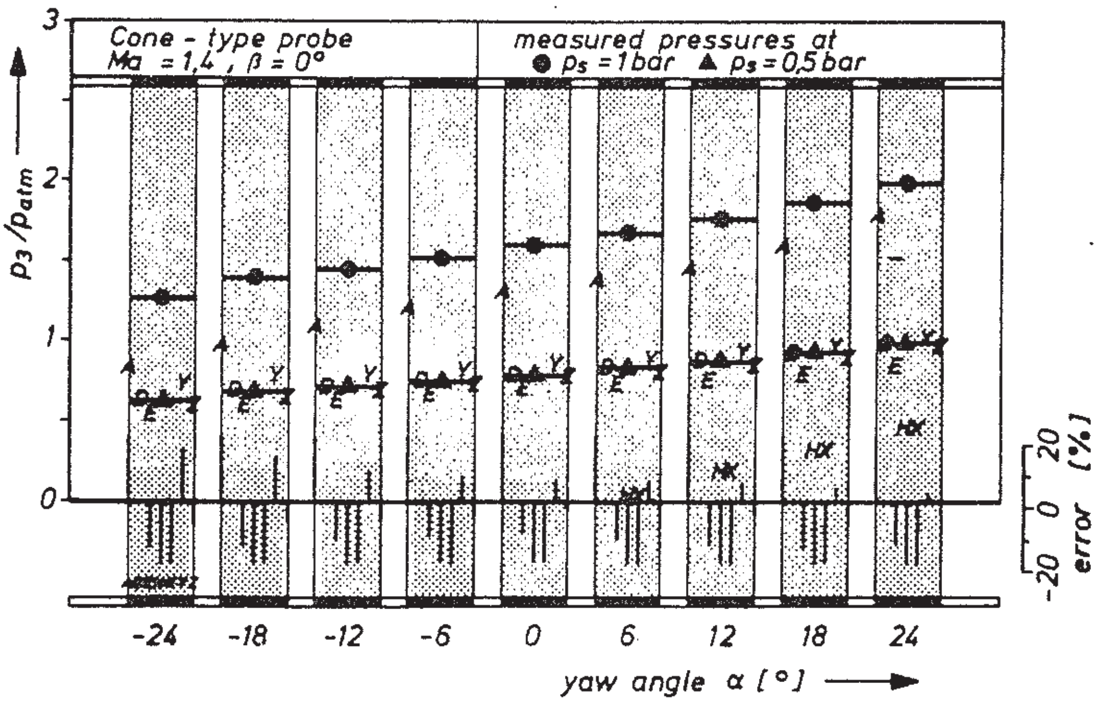

Fig. 7: Experimental data and results of the conversion formulas (lateral pressure tap)

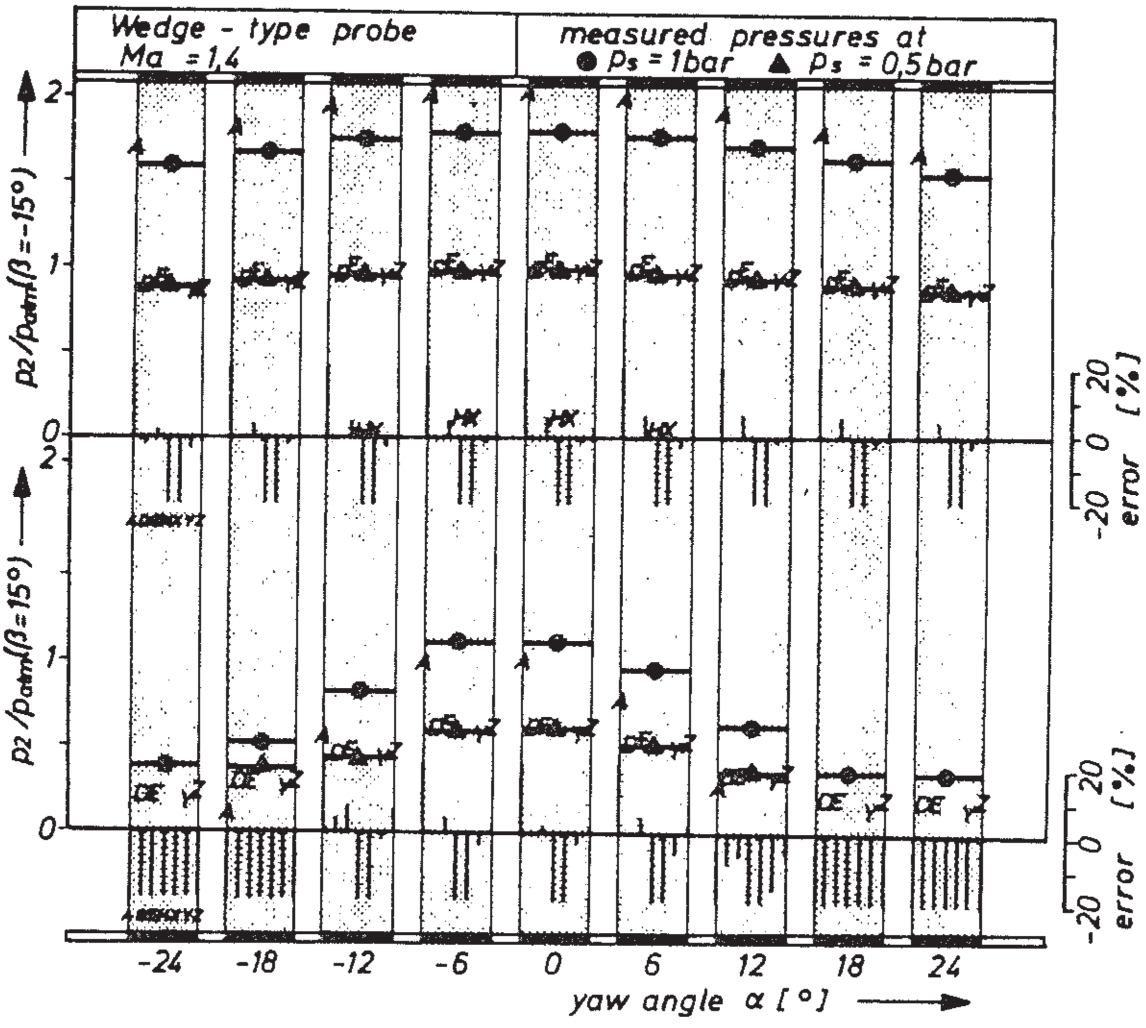

Fig. 8: Influence of a pitch-angle-variation on the accuracy of the conversion formulas in the case of the wedge type probe

7. CONCLUSIONS

The present investigations deal with an analysis of measuring errors due to different Reynolds-number in calibration and measurements. The experimental data referring to four different probe types showed that these errors must not be neglected. In order to avoid them, different conversion formulas were established, which allowed the conversion of the hole-pressures at different Reynolds-number levels. A comparison of results of the conversion formulas and experimental data showed, that the aforementioned errors lie within the range of the measuring accuracy if the hole-pressures are treated in analogy to the total pressure. By the use of the corresponding conversion formula an expensive calibration with independent variation of Reynolds- and Mach-number can be avoided in most cases.

8. REFERENCES

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Symbols

C	Conversion (subscript)
Ma, Re	Mach-, Reynolds-number
l	characteristic length
p_i $i = 0,..,4$	pressures at probe taps
p, p_t	static, total free-stream pressure
T, T_t	static, total free-stream temperature
α, β	yaw, pitch angle
μ	viscosity