COMPARATIVE INVESTIGATIONS ON FRICTION DRAG MEASURING TECHNIQUES IN EXPERIMENTAL AERODYNAMICS *

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W. NITSCHE, C. HABERLAND and R. THÜNKER

Institut für Luft- und Raumfahrt, Technische Universität Berlin, Berlin (F. R.G.)

ABSTRACT

For practical friction drag investigations in wind tunnel or free flight tests, the applicability of some well known friction drag measuring techniques (sublayer fence, surface hot-film, Preston tube) as well as of some recently or newly developed techniques (wall-fixed hot-wire, computational Preston tube method, wall-fixed double hot-wire) in typical aircraft boundary-layer flows is investigated. The emphasis is on the influence of additional test parameters (pressure gradient, heat flux or changed temperatures, compressibility) as well as on applications of the respective techniques in transition flows, separated or re-attached and three-dimensional flows. Additionally, some aspects concerning practicability, constructional and electronical efforts are discussed and summarized comparatively in a synoptic table.

1. INTRODUCTION

Performance optimization of a system whether it be an aircraft, a ship or a ground vehicle requires the knowledge of pressure drag as well as of friction drag created by the flow. Hence, considerable effort has been made in the past, to develop reliable friction drag measuring techniques suitable for wind tunnel and full scale flight tests.

In practical aerodynamics, experimental investigations to determine wall friction forces on solid surfaces are necessary due to the following three main reasons :

- Advanced performance optimization of modern aircraft requires an accurate prediction of the friction drag (e.g. Fig. 1a, skin friction distribution on a NACA 0025 wing section [1]). The skin friction experiments enable improved numerical methods in fluid dynamics to be verified with respect to the wall shear stress distribution as well as to the location of transition points and separated flow regions.

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- Skin friction laws used for estimated drag prediction (e.g. skin friction coefficient dependent on Reynolds number, Fig. 1b) need to be based on experiments.

- Local wall friction forces are one of the main quantities of interest in experimental boundary-layer investigations, as the local wall shear stress represents a substantial part of the boundary-layer similarity parameters (non-dimensional wall distance, non-dimensional velocity and additional flow parameters as depicted in Fig. 1c for strongly non-adiabatic turbulent flows [2]).

The present paper deals with the applicability of some well known friction measuring devices (surface hot-film, sublayer fence, Preston tube) as well as on some newly or recently developed techniques (wall-fixed hot-wire, computational Preston tube method, wall-fixed double hot-wire) in experimental aerodynamics, as summarized in Fig. 2.

The emphasis of these investigations is on the reliability of these measuring techniques in typical aircraft boundary-layer flows, i.e. the influence of additional test parameters such as pressure gradient, compressibility, variable temperatures, three-dimensional effects and limitations in separated and transition flows are discussed.Therefore, the first part of this paper deals with the underlying pinciples of each measuring technique and the calibration methods derived therefrom and, when necessary, with possible extensions concerning the mentioned flow parameters. Applicability in more practical flows (boundary-layer flows with additional parameters of influence, transition flows, 3-D flows, separated and re-attached flows) is discussed in the second part. Finally, the paper concentrates on some problems concerning practical aspects of use of the particular methods, and the experimental and constructional as well as electronical effort. The relative merits of the investigated methods are comparatively summarized in a synoptic table which may be helpful in choosing the best suited method with respect to the particular test condition.

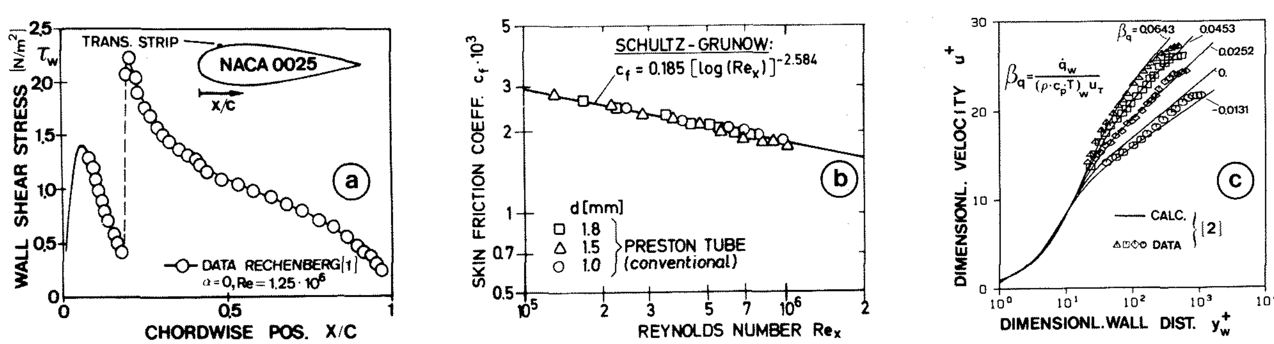


Fig. 1 : Main applications of wall shear stress measurements in aerodynamics

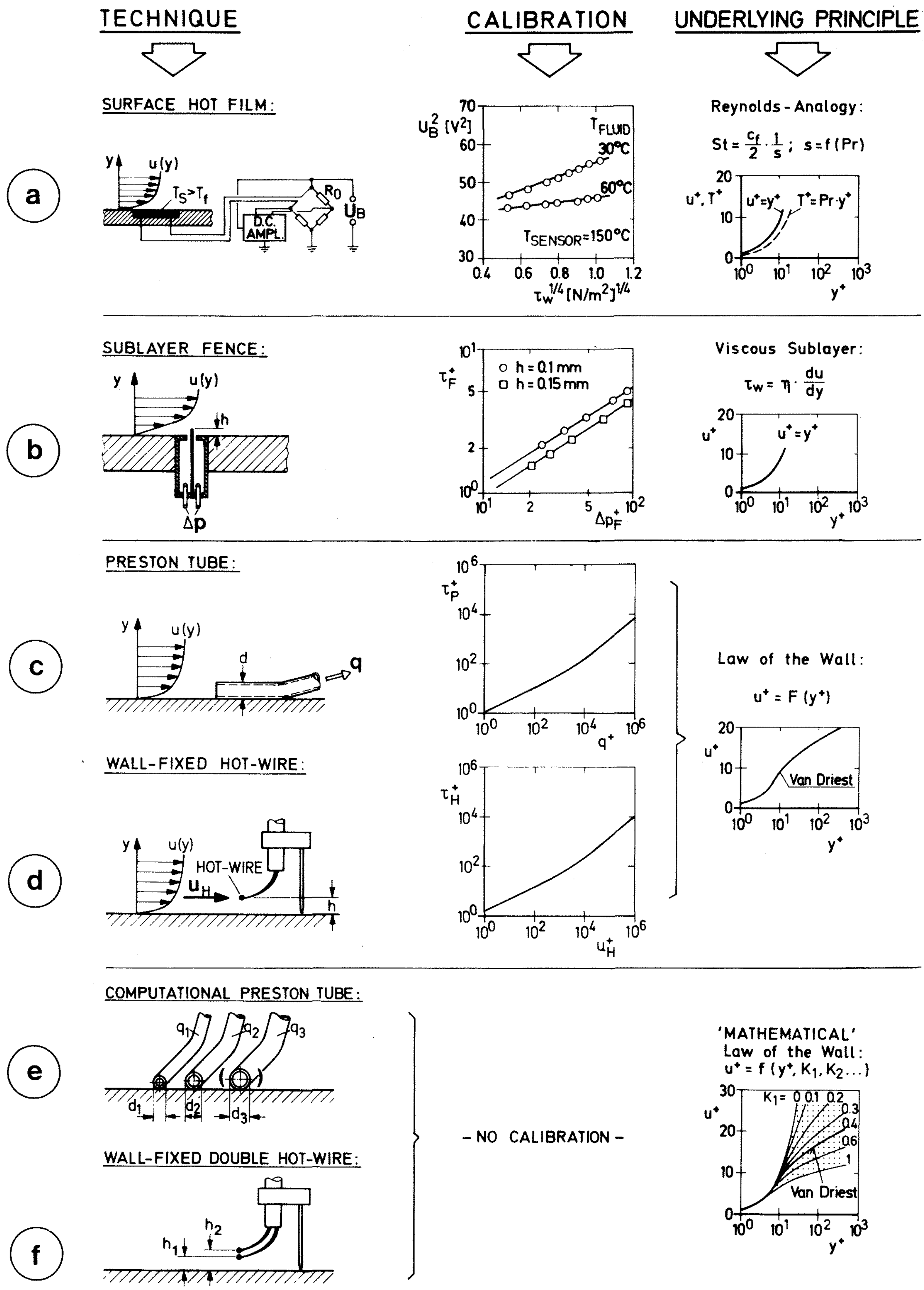


Fig. 2: INDIRECT SHEAR STRESS MEASURING TECHNIQUES

2. NOTATIONS

A, B	calibration constants
A^+	Van Driest's constant
a	speed of sound
$c_f = \tau_w/(\rho u_\infty^2)$	skin friction coefficient
c_p	specific heat
D, D_1, D_2	pipe diameter
d, d_1, d_2, d_3	Preston tube diameter
$d^+ = u_\tau d/\nu$	non-dim. Preston tube diameter
F_1, F_2, F_1^*, F_2^*	calibration functions
h	fence height, wall distance
K	displacement factor
$K_{1,2,3}$	iteration parameter
k_s	equivalent sand roughness
$k^+ = u_\tau k_s/\nu$	b.-l. roughness parameter
l	characteristic length
$M_\tau = u_\tau/a_w$	friction Mach number
p	static pressure
$p^+ = [\nu/(\rho u_\tau^3)]\frac{dp}{dx}$	b.-l. pressure parameter
Δp	differential pressure (fence)
$\Delta p_F^+ = \Delta p h^2/(4\rho\nu^2)$	non-dim. differential pressure
$q^+ = q d^2/(4\rho\nu^2)$	non.-dim. dynamic pressure
q	dynamic press.(p-tot. - p-stat.)
$\dot{q}_w$	heat flux rate
$\dot{Q}$	heat flux
R_O	operating resistance
$Re = u_\infty l/\nu$	Reynolds number
$Re_{u_\tau} = u_\tau l/\nu$	shear stress Reynolds number
s	Reynolds-analogy factor
St	Stanton number
T	temperature
u	mean flow velocity
$u_\tau = \sqrt{\tau_w/\rho_w}$	shear stress velocity
$u^+ = u/u_\tau$	non-dim. mean velocity
$u^+_H = 1/2(u_H h/\nu)^2$	non-dim. velocity (hot-wire)
U_B	bridge voltage
w	cross flow velocity
$w^+ = w/u_\tau$	non-dim. cross flow velocity
x	mean flow co-ordinate
y	distance from wall
$y^+ = u_\tau y/\nu$	non-dim. distance from wall
z	cross flow co-ordinate
α	cross flow angle
$\beta_q = \dot{q}_w/(\rho c_p T)_w \cdot u_\tau$	b.-l. heat flux parameter
δ	b.-l. thickness
$\delta^+ = u_\tau\delta/\nu$	non-dim. b.-l. thickness
$\varkappa$	v. Karman constant
$\lambda = 8\tau_w/(\rho u_m^2)$	friction factor
η	dynamic viscosity
ν	kinematic viscosity
ρ	density
τ	shear stress
$\tau^+_P = \tau_w d^2/(4\rho\nu^2)$	Preston tube } non-dim. shear stress
$\tau^+_F = \tau_w h^2/(4\rho\nu^2)$	fence } non-dim. shear stress
$\tau^+_H = \tau_w h^2/(\rho\nu^2)$	fixed hot-wire } non-dim. shear stress

Subscripts:

D	diameter
e	boundary-layer edge
E	entrance condition
f	fluid
F	sublayer fence
H	wall-fixed hot-wire
m	mean value
P	Preston tube
S	surface hot-film
w	wall condition
x	mean direction
z	cross direction
∞	free stream condition
0	reference condition

3. GENERAL REMARKS

The skin friction measuring techniques summarized in Fig. 2 are without exception indirect measuring methods that enable the determination of wall shear stresses by applying appropriate analogies (surface hot-film), boundary-layer similarity laws (sublayer fence, Preston tube, wall-fixed hot-wire) or generalized velocity distributions close to the wall (computational Preston tube, wall-fixed double hot-wire). As such assumptionscan lead to restrictions in practical use, the underlying principles of each measuring technique are to be outlined. In this connection, some possible extensions of the respective methods are also discussed.

3.1 Surface Hot-Film

The surface hot-film technique (uppermost in Fig. 2) is based on the analogy between local skin friction and heat transfer, which is used to the effect that the convective losses of a small electrically heated metallic sensor embedded in the wall and maintained at constant temperature can be correlated to the wall shear stress by means of individual calibration. In praxis the convective heat loss of the probe is assumed to be proportional to the electric power input to the sensor. Due to the use of a constant-temperature anemometer bridge circuit (fixed operating resistance of the hot -film) empirical calibration formulas usually correlate the squared bridge voltage with the shear stress by

$$U_B^2 = A + B\cdot\tau_w^n \; ; \; n = 0.25\text{-}0.3 \; . \qquad (1)$$

The calibration constants A and B depend on the flow and sensor temperature as well as on the properties of the wall or probe support material. Fig. 3 exemplifies the strong influence of different temperatures on a McCROSKY-type [3] gauge calibration, demonstrating the chief difficulties in using the surface hot-film technique (flow temperature changes of 1 °C result in more than 5 % shear stress measuring errors).

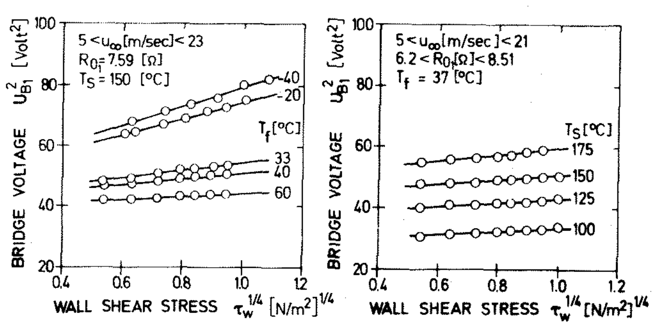


Fig. 3 : Surface hot-film calibration curves for changed temperatures

In practical wind tunnel investigations and free flight tests steady temperature conditions cannot be assumed, and due to this, a more general calibration procedure taking into account these temperature effects has been developed in [4]. The proposed calibration method is based on an integral heat balance of the surface hot-film and correlates the ratio of conductive heat losses (to the wall) to the convective heat losses (to the fluid) with

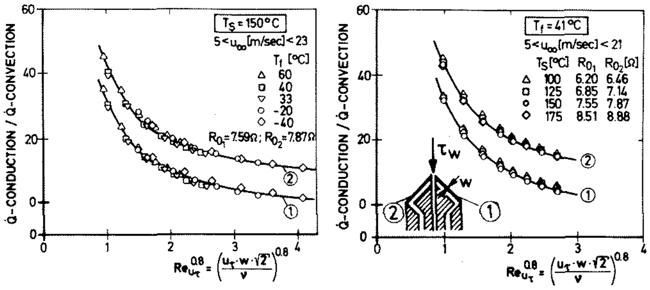


Fig. 4 : Surface hot-film calibration including temperature effects

the shear stress velocity Reynolds number of the sensor

$$\dot{Q}\text{-cond.}/\dot{Q}\text{-conv.} = f(Re_{u_\tau})\ ;Re_{u_\tau} = u_\tau l/\nu. \quad (2)$$

As shown in Fig. 4, the resulting calibration curves are valid for changes in flow temperatures as well as in sensor temperatures and thus enable sufficient friction drag measurements e.g. in flight tests with variable flow temperatures by means of a precalibration of the hot-film in a wind tunnel at almost arbitrary temperatures.

3.2 Sublayer Fence

The sublayer fence technique (b in Fig. 2) is based on the similarity law of the viscous sublayer

$$u^+ = y^+ \;;\; u^+ = \frac{u}{u_\tau}\ ,\ y^+ = \frac{u_\tau y}{\nu}\ . \quad (3)$$

The measured differential pressure of the fence is correlated to the local wall shear stress assuming a relationship between this pressure and the velocity distribution close to the wall. This correlation is determined empirically and usually formulated as a calibration curve of the type

$$\tau_F^+ = A(\Delta p_F^+)^n;\ \tau_F^+ = \frac{\tau_w h^2}{4\rho\nu^2}\ ,\Delta p_F^+ = \frac{\Delta p h^2}{4\rho\nu^2}, \quad (4)$$

shown in Fig. 5. Whereas A and n are empirical constants, the calibration parameters τ_F^+ and Δp_F^+ can be derived from the law of the wall variables, Eq. (3), taking half the height of the fence as the characteristic wall distance and assuming a fictitious flow velocity proportional to the measured differential pressure, yielding

$$\tau_F^+ = \left(\frac{u_\tau h/2}{\nu}\right)^2,\ \Delta p_F^+ = \frac{1}{2}\left(\frac{u_F}{u_\tau}\frac{u_\tau h/2}{\nu}\right)^2 \quad (5)$$

$$u_F = \sqrt{2\ \Delta p/\rho}$$

It is clear from this formulation that changes in the velocity distribution near the wall, e.g. through an imposed strong pressure gradient, could effect the respective sublayer fence calibration.

A feasible approach considering such influences is shown in the investigations on correction functions for Preston tubes [5]. As a Preston tube for small probe diameters is comparable to a sublayer fence regarding the boundary-layer similarity theory, this correction functions calculated on the basis b.-l. similarity laws can be applied to a fence using a transformation relation ship between

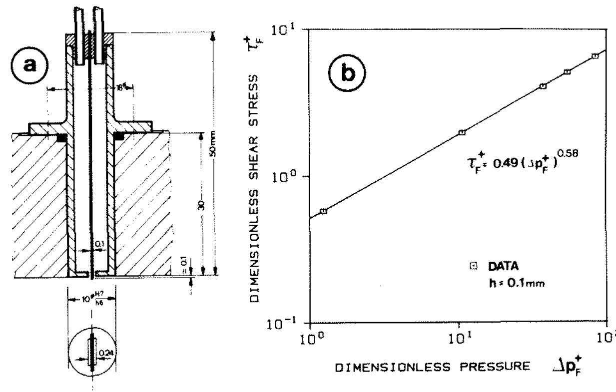


Fig. 5 : Sublayer fence technique ILR - fence (a) calibration curve (b)

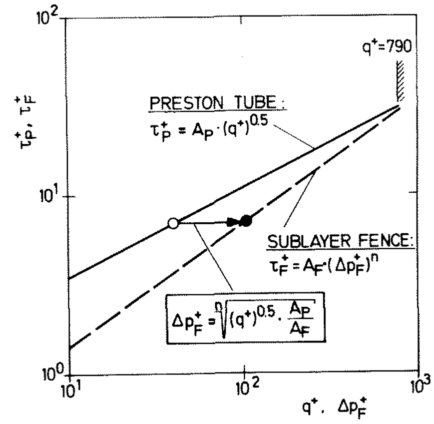


Fig. 6 : Transformation relationship between Preston tube and sublayer fence calibration curves

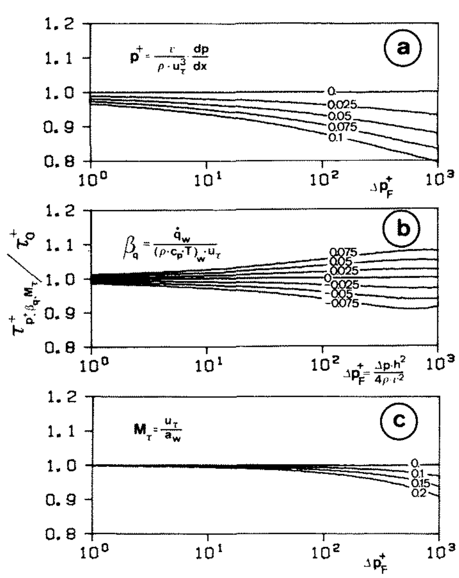


Fig. 7 : Sublayer fence correction functions for non-dim. pressure gradient (a) non-dim. heat flux (b) friction Mach number (c)

the lowest region of the Preston tube calibration curve and the particular basic calibration of the fence. Fig. 6 illustrates this transformation for the calibration curve of Fig. 5, and Fig. 7 the therewith calculated correction functions for non-dimensional pressure gradients (p^+), heat flux parameters (β_q) and friction Mach numbers (M_τ). However, due to the use of the individual transformation relationship of Fig. 6, these calculations do not posses general validity and are applicable only for the particular fence.

It is obvious from Fig. 7 that sublayer fences especially with small fence heights are relatively unsensitive to additional flow parameters, and therefore, the fence can be recommended as a reference measuring device in experimental shear stress investigations.

3.3 Preston tube

The Preston tube (ⓒ in Fig. 2) is a widely used shear stress measuring device due to its ease in construction and practicability. Similar to the sublayer fence technique, this method is based on the similarity law of the boundary-layer. However, due to the larger size of the Preston tube when compared to a fence the probe senses not only the viscous sublayer but the sublayer, buffer layer and logarithmic portion of the boundary-layer, i.e. the complete law of the wall

$$u^+ = \int_0^{y^+} \frac{2\,dy^+}{1+[1+4(\varkappa y^+)^2(1-\exp(-y^+/A^+))^2]^{0.5}} \qquad (6)$$

$$\varkappa = 0.4\ ;\ A^+ = 26 \quad \text{(VAN DRIEST [6])}$$

has to be supposed when applying this technique.

The correlation between the measured dynamic pressure of the probe and the respective wall shear stress is usually represented by an empirical calibration curve (see e.g. PRESTON [7], PATEL [8])

$$\tau_p^+ = F(q^+)\ ;\ \tau_p^+ = \frac{\tau_w d^2}{4\rho\nu^2}\ ,\ q^+ = \frac{q\,d^2}{4\rho\nu^2}\ , \qquad (7)$$

Fig. 8. The calibration parameters q^+ and τ^+_p can be obtained directely from the boundary-layer variables, Eq. (3), taking half the diameter of the probe as the characteristic length scale

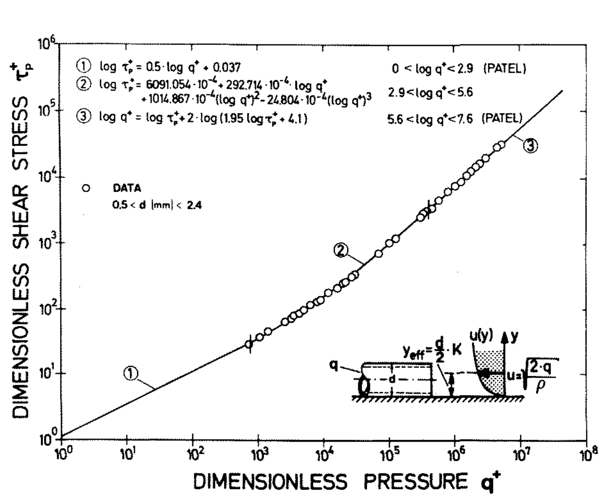


Fig. 8 : Preston tube calibration curve

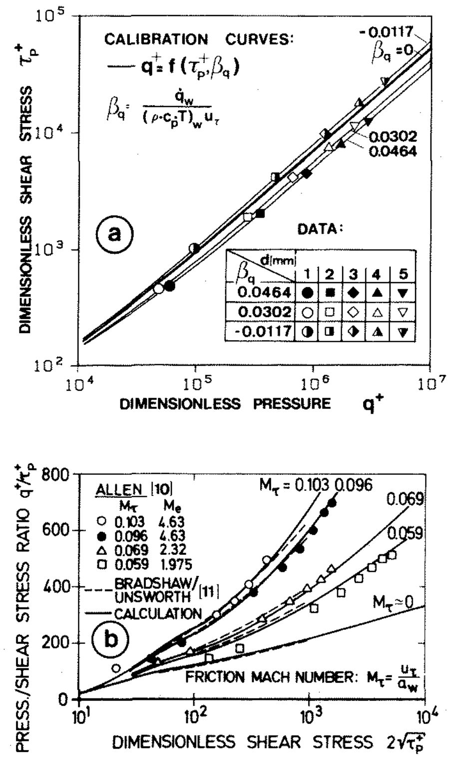


Fig. 9 : Preston tube calibration curves for non-adiabatic flows (a) compressible flows (b)

$$\tau_p^+ = \left(\frac{u_\tau d/2}{\nu}\right)^2\ ,\ q^+ = \frac{1}{2}\left(\frac{u}{u_\tau}\,\frac{u_\tau d/2}{\nu}\right)^2 \qquad (8)$$

and consequently, the calibration curve can be calculated from the law of the wall, Eq. (6), as shown in [9]. However, this computation additionally requires a relationship between the probe diameter and the effective wall distance, i.e. the location where the actual velocity corresponds to the measured dynamic pressure

$$y_{eff.} = \frac{d}{2}K\ ;\ K = f\left(\frac{u_\tau d}{\nu}\right) \simeq 1.3\ , \qquad (9)$$

which is implicit in the empirical calibration of Fig. 8 but must be known for the computation (for more details see [13]).

The direct relationship between the law of the wall and the calibration curve clearly indicates that unrestricted use of the classical calibration in boundary-layer flows whose law of the wall deviate from the standard case (turbulent pipe and flat plate flows) can lead to principle measuring errors. To overcome these restrictions and to enable dependable shear stress measurements in other flow types, one has to taken into account calibration curves that have been modified according to the respective boundary-layer laws [5] [9]. Fig. 9 exemplifies the need to consider extended calibration curves for changed wall laws and shows calculations for strongly non-adiabtic flows (9a) and incompressible flows (9b) as compared with experimental results.

For practical applications these computations can also be used to define correction functions for the influence of the respective boundary-layer

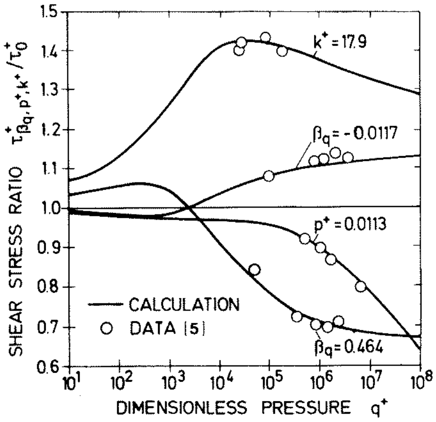


Fig. 10 : Preston tube correction functions

similarity parameters on the Preston tube readings [5], as summarized in Fig. 10 for wall roughness (k^+), pressure gradient (p^+) and heat flux (β_q).

3.4 Wall-Fixed Hot-Wire

The underlying principle of the newly developed wall-fixed hot-wire technique (d in Fig. 2) is comparable to that of the Preston tube method as both are based on the law of the wall formulated in Eq. (6). However, the measured velocity of a hot-wire at known wall distance can be correlated more directly to the local wall friction, as no displacement factor is required to establish the relationship between flow velocity, wall distance and shear stress. By substituting the characteristic length scale of the Preston tube calibration parameters (=d/2), Eq. (7), through the wall distance of the fixed hot-wire (=h), we formally obtain the calibration curve of this device

$$\tau_H^+ = f(u_H^+) \;\; ; \;\; \tau_H^+ = \frac{\tau_w h^2}{\rho \nu^2} \; , \;\; u_H^+ = \frac{1}{2}\left(\frac{u_H h}{\nu}\right)^2 \; , \tag{10}$$

which can now be directly computed from the law of the wall, Eq. (6), via

$$\tau_H^+ = \left(\frac{u_\tau h}{\nu}\right)^2 , \;\; u_H^+ = \frac{1}{2}\left(\frac{u}{u_\tau}\frac{u_\tau h}{\nu}\right)^2 \; . \tag{11}$$

For practical use, the thus computed calibration curve has been approximated by means of polynomial

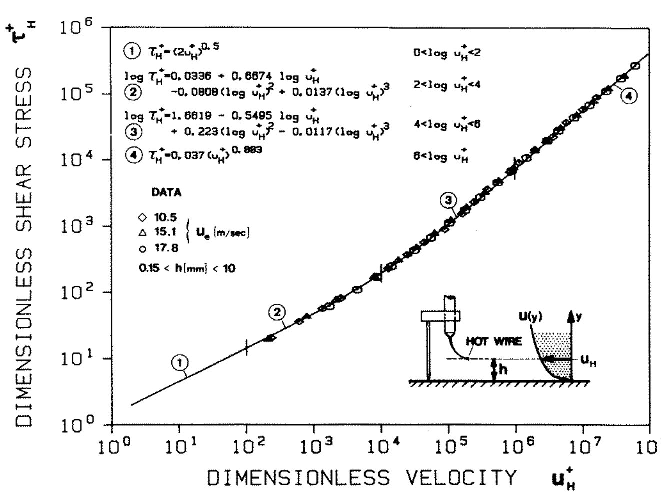


Fig. 11 : Wall-fixed hot-wire calibration curve

and exponential equations respectively, which correlate very well with some experimental data obtained in a turbulent flat plate flow using a sublayer fence as the reference device, Fig. 11.

Basically, the restrictions of this measuring technique in flows with additional parameters of influence (pressure gradient, heat flux etc.) are identical to those of the classical Preston tube method. However, this method can be regarded to be less sensitive to changed wall laws, as the hot-wire technique enables sufficient velocity measurements closer to a wall than wall Pitot tubes. It is obvious from Fig. 10 that the thus decreased wall distances as well as decreased Preston tube diameters diminish measuring errors caused by the additional flow parameters. However, it is self-evident that such hot-wire measurements in the immediate vincinity of solid surfaces must take into account the wall influence of hot-wire readings, e.g. see [12]. In praxis this becomes evident for dimensionless wall distances of $y^+ < 5$, which is expressed in terms of the wall-fixed hot-wire calibration parameters $\tau_H^+ < 25$ and $u_H^+ < 300$.

3.5 Computational Preston Tube Method

The classical Preston tube method as well as its extensions mentioned in section 3.3 must fail in boundary-layer flows with unknown law of the wall, as the necessary unambiguous correlation of a velocity corresponding to the measured Preston tube dynamic pressure to the wall shear stress via the boundary-layer law can no longer be formulated. This is clearly indicated by different wall shear stresses obtained from probes of different diameters when applying the standard calibration curve shown in Fig. 8 to such flows. To a certain extent, the computational Preston tube method (CPM, e in Fig. 2) is based on the reversal of this fact : First of all, in this computer aided method, which is outlined in detail in [13] and documented in [14], a calibration curve is no longer required, but the numerical procedure of calculating the calibration curve from boundary-layer similarity laws, as pointed out in 3.3, is directly applied to the measured dynamic pressures of basically two different sized Preston tubes. By means of variation of one of the free parameters $K_{1,2,3}$ in the extended wall law of Eq. (6)

$$u^+ = \int_0^{y^+} \frac{2(1+K_3 y^+)\,dy^+}{1+\left[1+4(K_1 y^+)^2(1+K_3 y^+)\left(1-\exp\left(-y^+\sqrt{1+K_3 y^+}/K_2\right)\right)^2\right]^{0.5}}$$

$$i = 0: \; K_1 = 0.4, K_2 = 26, K_3 = 0. \tag{12}$$

a velocity distribution is determined iteratively, satisfying both the measured corresponding flow velocities, and hence, yielding identical wall shear stresses. Fig. 12 exemplifies this iteration illustrating the shear stress determination in a laminar-turbulent transition flow by means of a K_1- variation. The basic computations based on Eq. (6) yield different shear stresses and velocity profiles ($i=0$, $K_1=0.4$ in Fig. 12) for the two probes, indicating the breakdown of the classical Preston tube method. However, through successive variation of the K_1- parameter these deviations can be decreased continuously, and vanish in the last computation step. The convergence of the iteration process can be recognized from the computed shear stresses, Fig 12b, as well as from the respective velocity profiles shown in Fig. 12a, which both converge and collapse on one another in the last step.

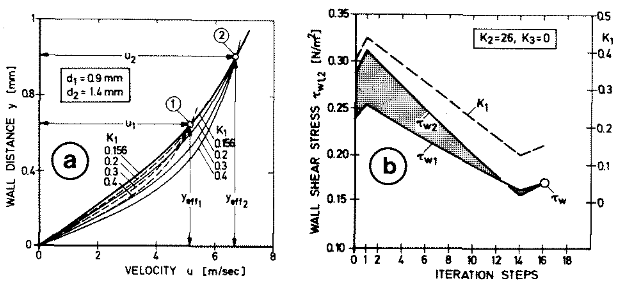


Fig. 12 : Boundary-layer iteration in the CPM

In case of uncertainties in dynamic pressure measurements, which can mainly result from errors in determining the associated static pressure, the use of three different sized tubes instead of the basically used two probes is recommended. For that purpose the computational iteration shown in Fig.12 is applied to three flow velocities at the respective wall distances, and hence, the truncation criteria of the two-probe method has to be changed (two probes : $\tau_{w_1} = \tau_{w_2}$; three probes : $\sum \Delta\tau_{w_i}$ = minimum), as depicted in Fig. 13a.

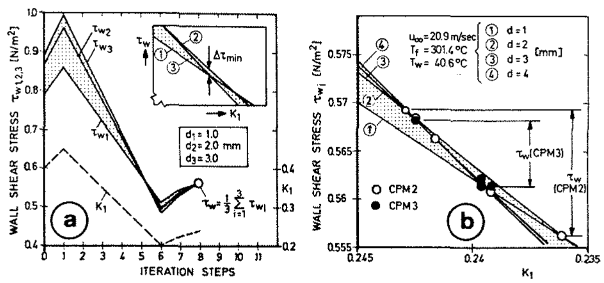


Fig. 13 : Shear stress iteration (CPM2 and CPM3)

The error sensitivity of the three probe procedure is obvious from Fig. 13b, which shows all the possible resulting wall shear stresses obained from two-probe and three-probe computations based on the data of four different sized Preston tubes in a strongly non-adiabatic turbulent flat plate flow ($\dot{q}_W \simeq 12\ 000\ W/m^2$).

3.6 Wall-Fixed Double Hot-Wire

The basic idea of this measuring method (lowermost in Fig. 2) is comparable to the computational Preston tube method. However, they differ solely in that the flow velocities at two fixed distances from the wall are now determined directly and not indirectly as in the CPM, where the velocities and effective wall distances are calculated from the measured dynamic pressures and from Eq. (9) respectively. Apart from this, the iterative shear stress evaluation procedure with the aid of the mathematical law of the wall, Eq. (12), is identical, and thus the computer program used in the wall-fixed double hot-wire technique corresponds closely to that of the CPM.

However, in contrast to the use of wall-attached Preston tubes this measuring technique as well as the basic *wall-fixed hot-wire method* mentioned in 3.4 requires preliminary tests to locate the hot-wires with respect to the wall. In the present investigations these wall distances have been determined by measuring the wake behind a thin wire (d=0.3 - 1.0mm) positioned outside the boundary-layer at known distance from the wall. Calculation of the center of area of the symmetrical wake Fig. 14a, results at first in a precise fixation of the hot-wire relative to the center line of the wake (y_0) and thus to the axis of the position-wire. Hence, together with the known wall distance of this wire, the absolute position of the hot-wire relative to the wall is ascertained. It is clear from Fig. 14b and c that the typical measuring accuracy *of this method, which can similarly be used to* determine the relative probe distance of a double hot-wire, is better than $\Delta y_0 = \pm 0.005$ mm.

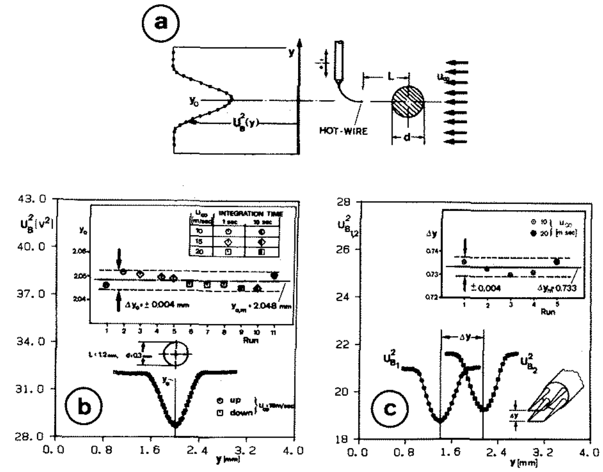


Fig. 14 : Determination of hot-wire positions

4. PRACTICAL APPLICATIONS

After discussing the general principles as well as possible extensions of the investigated measuring methods in the previous section, the applicabilities of these techniques in some practical flow cases should be outlined. The present investigation focuses on shear stress experiments in boundary-layers with additional parameters of influence (pressure gradient, heat flux or changed temperatures), on transition flows, separated and re-attached flows as well as on a discussion of applications in three-dimensional flows.

4.1 Boundary-Layer Flows with Additional Parameters

The investigation on the influence of additional flow parameters has concentrated on equilibrium boundary-layers, whose law of the wall can be formulated mathematically, i.e. the correction functions e.g. for sublayer fences according to Fig. 7 can be considered. In Fig. 15 several experimental results for a turbulent flat plate flow with adverse pressure gradient (inclined plate, $60 < dp/dx\ [N/m^3] < 200$, $0.0113 < p^+ < 0.0166$), strongly non-adiabatic turbulent flow (heated or cooled flat plate, $-4300 < \dot{q}_w\ [W/m^2] < 12100$, $-0.0117 < \beta_q < 0.0464$) as well as adiabatic flat plate flow, however at different flow temperatures, are summarized.

From Figs. 15a and b the failure of the conventional Preston tube method in boundary-layer flows with changed wall laws is evident (different shear stresses obtained from Preston tubes of different diameter). In contrast, Figs. 15a* and b* illustrate the agreement of sublayer fence and computational Preston tube data (two probes) demonstrating the applicability of both methods in such flows.

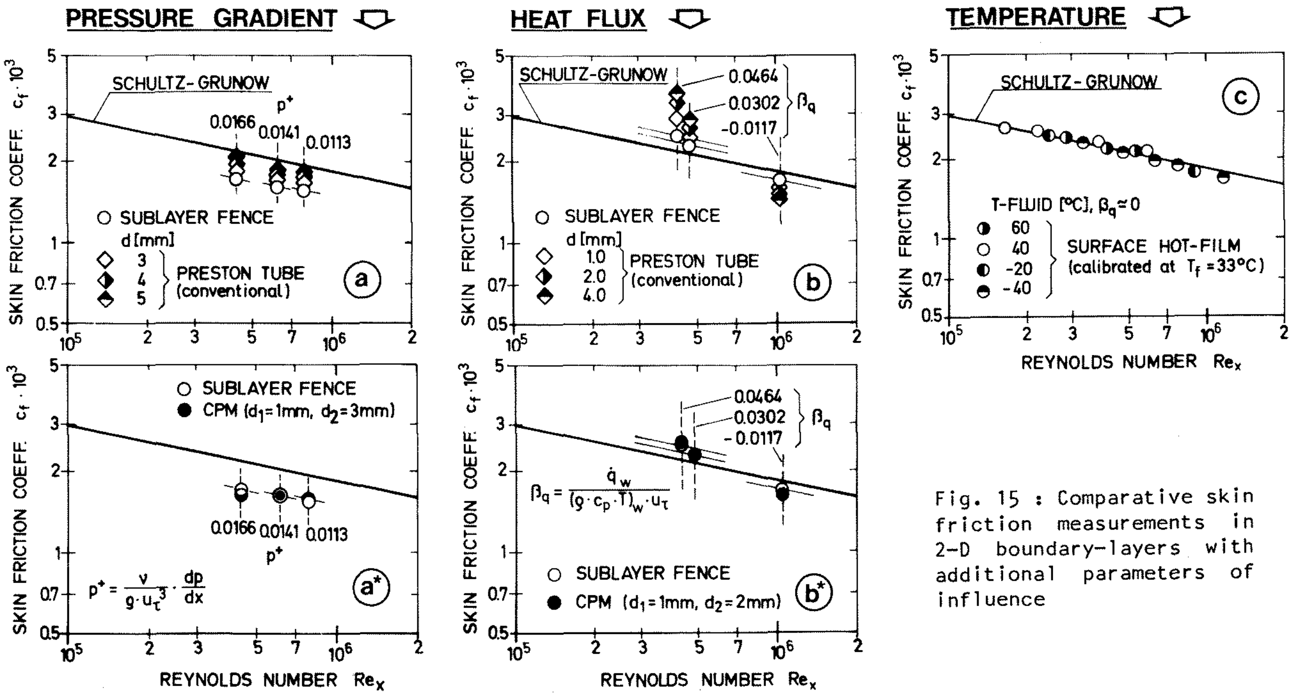


Fig. 15 : Comparative skin friction measurements in 2-D boundary-layers with additional parameters of influence

As a more specific example Fig. 15c depicts the application of the surface hot-film calibration including temperature effects, Fig. 4. For an adiabatic plate flow (insulated wall), however at different flow temperatures approximately within the range of a subsonic free flight test ($-40°C < T_f < 60°C$) the friction coefficients are determined using a calibration curve obtained at $T_f = 33°C$. It is clear from Fig. 15c that the limitations of the surface hot-film technique due to the high temperature sensitivity (Fig.3) can be compensated to a large extent so that this method proves well in variable temperature flows too.

4.2 Transition Flows

Skin friction measurements in transition flows are required not only to determine the friction drag but also to locate transition points or regions e.g. in airfoil testing, Fig. 1a, the latter being a significant test tool in matching full-scale flight conditions through wind tunnel tests.

As the simple law of the wall, Eq. (6), cannot be assumed in transition flows, this consequently leads to principle restrictions when applying measuring techniques based thereof, e.g. the conventi-

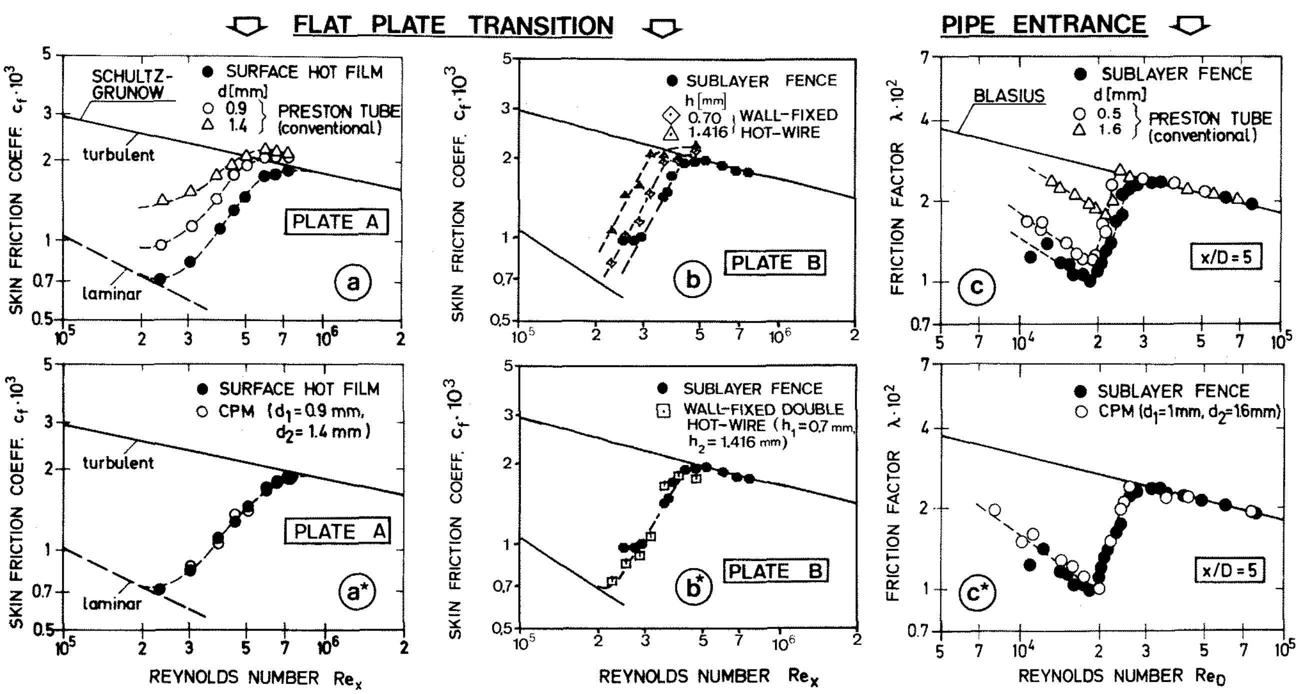


Fig. 16 : Comparative skin friction measurements in transition flows

onal Preston tube method or the wall-fixed hot-wire technique. However, measuring methods that are only based on the law of the viscous sublayer (sublayer fence) or on the analogy between skin friction and heat transfer (surface hot-film) respectively, are applicable as this wall law as well as the analogy remain valid to a large extent. Similarly it can be expected that measuring techniques based on a variable wall law (CPM, wall-fixed double hot-wire) can be applied in transition flows too.

Several experimental results of simple transitional flows on a flat plate and in a pipe entrance demonstrate the capabilities of the respective techniques, Fig.16 . Results of the conventional Preston tube method as well as those of the wall-fixed hot-wire technique are compared in the upper row (Figs. 16a,b,c) from which it becomes clear that the techniques based on the complete wall law break down (different shear stresses obtained for different Preston tube diameters and different wall distances of the hot-wire). However, the data summarized in the lower figures (16a*,b*,c*) show good agreement between the computational Preston tube, wall-fixed double hot-wire, sublayer fence and surface hot-film method, resulting in four techniques out of the six investigated to be well applicable in measuring wall shear stresses in transition flows.

4.3 Separated and Re-attached Flows

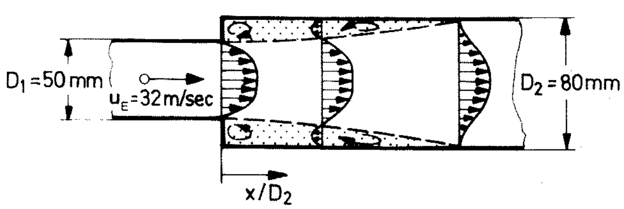
Shear stress measurement techniques to be used in separated flows demand additional capabilities as unlike in attached flows not only the amount but also the sign of the wall shear stress (e.g. negative τ_w in recirculation regions) needs to be measured. This is required to enable dependable wall friction measurements including recirculation regions as well as to specify separation and re-attachment locations.

In the present investigation on a forced separation flow in a pipe with sudden enlargement, Fig. 17, a change in sign of the wall shear stress occurs twice : First, from positive to negative shear stress immediate behind the step ($x/D_2 \simeq 0.3$) and second, the change back to positive τ_w behind the re-attachment point at $x/D_2 \simeq 1.8$.

Among the measuring techniques investigated here, at a fixed orientation of the probes, first of all the sublayer fence offers the capability of registering positive and negative wall shear stresses as the sign of τ_w can be deduced from the sign of the measured pressure difference. Hence, the fence is used as the reference device in the present investigation.

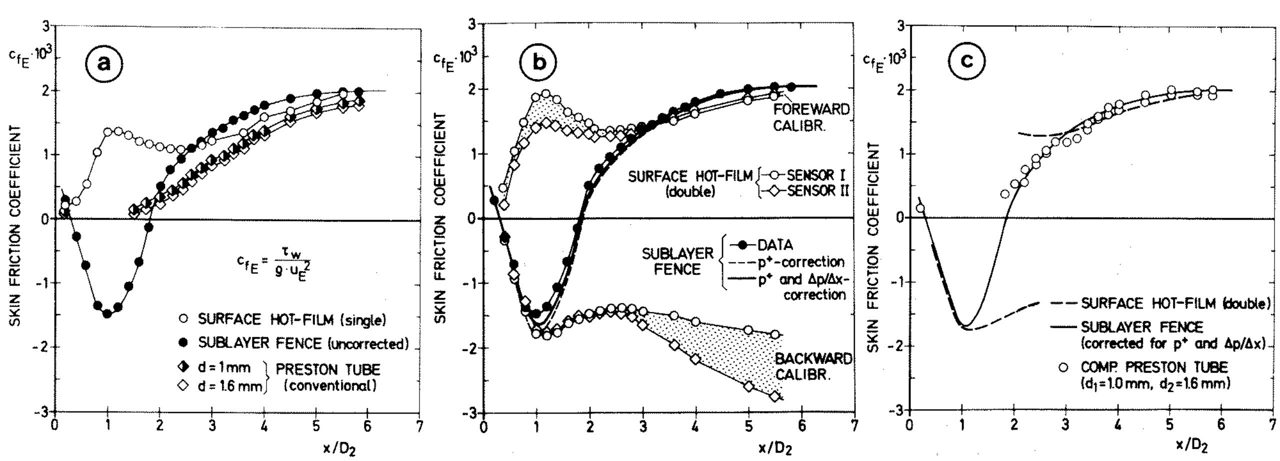
With the aid of the raw data compiled in Fig. 18a, principle restrictions of some of the other techniques are illustrated. For example, a single surface hot-film senses only the amount of its convective heat loss. As this amount is positive under foreward and backward flow conditions, the hot-film signal yields positive shear stresses also in the recirculation region behind the step, and results comparable to the fence data are obtained only downstream of the re-attachment point.

The wall shear stresses measured with different sized Preston tubes as likewise depicted in Fig.18a indicate again the failure of this method due to changes in the boundary-layer law, as already outlined in the previous sections. Besides measuring errors in the shear stress, the Preston tube data underpredict the re-attachment length, as the probes immediate to the re-attachment point due to their comparatively large diameters sense not only the back flow close to the wall but also the foreward flow outside the recirculation region. Thus, one measures positive dynamic pressures and thereby positive shear stresses up to x/D_2 = 1.2 - 1.4, depending on the probe diameter. Further upstream to



◁ Fig. 17 : Pipe flow with a sudden enlargement

Fig. 18 : Skin friction distribution downstream of the pipe step. Raw data (a), sublayer fence and double surface hot-film data (b), double surface hot-film and computational Preston tube data (c)
▽



the pipe step one obtains no results, as negative Preston tube readings cannot be correlated to the shear stress.

For the same test case some special aspects concerning the sublayer fence and surface hot-film technique are outlined in Fig. 18b. As mentioned above, a single hot-film is not able to read the sign of the shear stress. To overcome this disadvantage, a double hot-film probe consisting of two parallel mounted sensors, Fig. 19a, has been tested. By turning the probe about 180 degrees, calibration curves under foreward and backward flow conditions have been determined for each sensor, resulting in alltogether four calibration curves with distinctly smaller increases in the squared bridge voltages for the respective downstream sensor. In practical tests, where the sign of the shear stress cannot be assumed to be known, we now obtain four possible wall shear stresses at each measuring point using both foreward calibration curves (positive τ_w's) as well as both negative calibration curves (negative τ_w's), Fig. 18b. By comparing the shear stresses obtained from sensor I and II, we are able to decide whether the sign is positive or negative as either the foreward or the backward data have to match, indicating the pair of calibration curves proving right. Hence, the amount as well as the sign of the shear stress can be evaluated. However, the results depicted in Fig. 18b clearly show that this improved measuring technique works well only close to the pipe step and downstream of the re-attachment point, but fails completely in the re-attachment region indicating the breakdown of the surface hot-film technique due to violations of the underlying principle : Contrary to the shear stress, the heat transfer in the re-attachment region does not match zero and thus the surface hot-film greatly overestimates the amount of the shear stress.

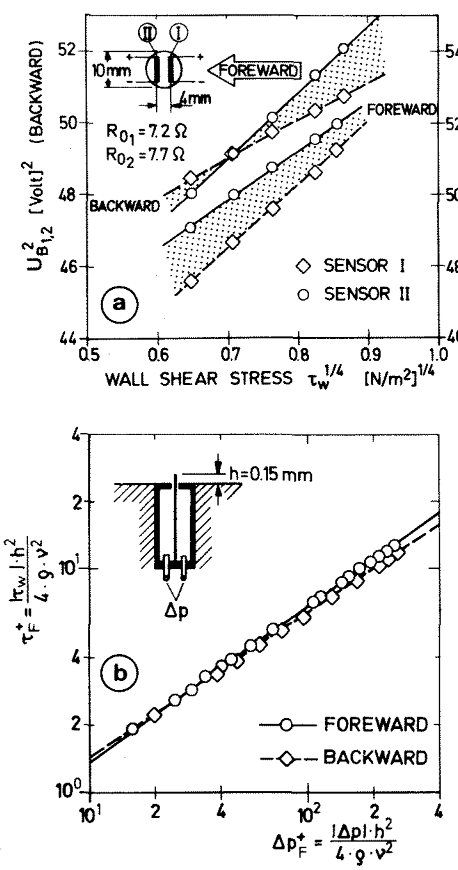


Fig. 19 : Foreward and backward calibrations of double surface hot-film (a) and sublayer fence (b)

In the sublayer fence technique where the sign of the measured pressure difference infers the sign of the shear stress, the slightly different calibration curves for backward and foreward flow conditions (resulting only from the finishing accuracy), Fig. 19b, must be taken into consideration to meet a high precision in positive and negative shear stresses. In Fig. 18b this foreward and backward calibrations and the influence of the boundary-layer pressure parameter p^+ (Fig. 7) as well as of the respective local pressure gradient $\Delta p/\Delta x$ on the fence readings are shown, whereby the comparatively weak influence of the imposed flow conditions on the fence measurements becomes clear.

In Fig. 19c, the shear stress distributions measured definitely by means of the above-mentioned methods are finally compiled and additionally compared with the data obtained from the computational Preston tube method (foreward orientated probes only). It becomes clear from this comparison that the CPM and sublayer fence technique agree well downstream of a re-attachment point while the surface hot-film technique underlies distinctive limitations and therefore should not be employed in separated and re-attached flows. For the methods still not investigated in this flow like the wall-fixed single and double hot-wire we can principally expect results comparable to the conventional and computational Preston tube method respectively, whereby the computational variants can also be employed in the backward flow region by turning the probe tips against the direction of the resulting flow vector.

4.4 Three-Dimensional Flows

To begin with, wall shear stress measurements in 3-D flows are associated with all the problems of 2-D flows as described in the previous sections. Additionally, 3-D measurements require the direction of the wall shear stress vector to be determined. As compared to 2-D flows the direction of the shear stress vector does not coincide with the main flow direction, but depending on flow types, is inclined at an cross flow angle α, as shown in Fig. 20 for a simple 3-D boundary-layer. However, the cross-velocity distribution can be much more complex, e.g. in the form of a S-shaped velocity distribution with alternating sign over the boundary-layer profile. As generally valid formulations of such boundary-layers in the form of similarity

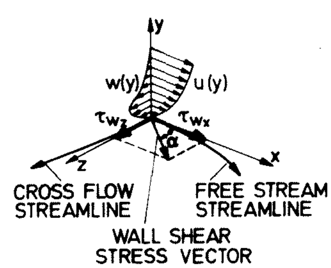


Fig. 20 : 3-D boundary-layer notations

laws are not available, it follows that wall shear stress measuring methods based on a rigid similarity hypothesis of a boundary-layer (Preston tube, wall-fixed hot-wire) are of limited use in 3-D flows and can only be employed for estimated predictions of the shear stress amount excluding the direction.

The preliminary investigations on a 3-D Preston tube method as described in [5], enabling the direction and amount of the shear stress to be determined employing the yaw sensitive two-chamber probe, can be understood as a first step towards a more general applicability in 3-D flows. However, up to now this method, which can also be applied to the wall-fixed hot-wire technique using X-probes, has been tested only for the special 3-D flow case shown in Fig. 20 assuming boundary-layer similarity laws for the main and cross flow velocity distributions. A more general application that aims at including the iterative wall shear stress determination procedure of the computational Preston tube method or wall-fixed double hot-wire technique respectively is currently under investigation at the ILR.

As compared to the methods mentioned above, measuring techniques that are based on a hypothesis of the near-wall flow and consequently sensing only immediate to the surface offer improved capabilities in evaluating the wall shear stress vector in 3-D flows, as these methods are independent of the outer velocity distribution of the boundary-layer.

The surface hot-film technique enables the determination of the amount in sign of the shear stress by means of V-shaped double surface hot-film probes [3] using the yaw-characteristic of the electric power inputs of both probes in the form of simple normalized calibration functions dependent on the yaw angle, whereby separate correlations are to be used for the amount of the shear stress and cross flow angle. Fig. 21a shows the evaluation of some measuring results corresponding to the calibration correlations $F_1(\alpha)$ and $F_2(\alpha)$ according to [3], exemplifying again the main measuring uncertainties of this method due to temperature effects : Similar to the 2-D calibrations shown in Fig. 3 changed thermal conditions lead to distinctive measuring uncertainties in determining the shear stress direction ($F_1(\alpha)$) as well as the amount ($F_2(\alpha)$). However, as in the case of 2-D flows, this temperature influence can be taken into account by extending the calibration correlation on the basis of a heat balance assuming an equilibrium between the convective and conductive heat loss on the one side and the electrical power input on the other [4]. This leads to the new calibration correlation $F_1^*(\alpha)$ and $F_2^*(\alpha)$ shown in Fig. 21b, which are formulated with the ratio between conductive and convective heat losses and the shear stress Reynolds number. It is thus possible to compensate the strong temperature sensitivity of this method as shown in Fig. 21b for different flow temperatures.

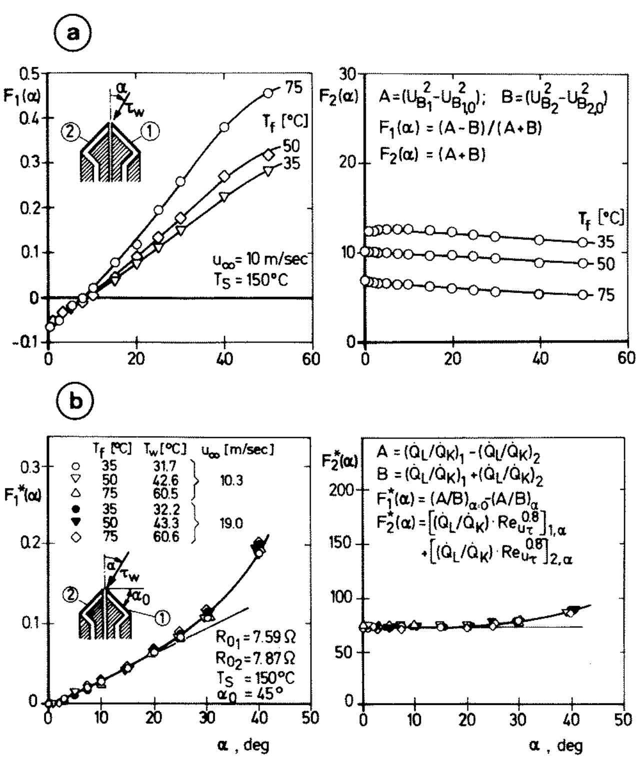


Fig. 21 : Surface hot-film 3-D calibration including temperature effects

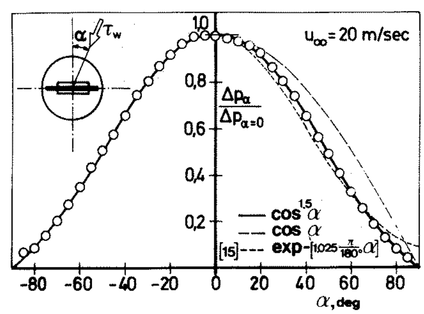


Fig. 22 : Yaw-characteristic of a sublayer fence

Similar to the hot-film surface technique, the sublayer fence is a very useful device, as this method is unsensitive to additional flow parameters to a large extent (see Fig. 7). However, the determination of the direction of the shear stress vector by employing only a single fence requires a relatively high experimental effort due to the following two reasons : The yaw-characteristic of this device, as depicted in Fig. 22 for a fence type according to Fig. 5, abides a cosine power law, i.e. is less pronounced for small yaw angles, leading to the null-seeking method proposed in [15], which however, can be very time consuming in praxis. Secondly, α-determinations even at known yaw-characteristic are only possible by means of turning the probe during the test, and hence, this technique additionally requires a rotating plug. To overcome these restrictions the use of a double-fence consisting of a pair of fences at right angles to each other, which allows the amount and the direction of the shear stress to be determined without rotating, is recommended in [16].

5. PRACTICAL ASPECTS OF USE

The discussion thus far has concentrated on a series of applicabilities without however having considered the handling characteristics of each individual procedure. As such aspects, e.g. the question of measuring effort or free positioning of the device can be of significance in practical investigations, a comparative discussion has to focus on practical aspects too.

TECHNIQUE	– CALIBRATION – specific / standard	restrictions from calibr.	main restrictions	– CAPABILITIES – transition	separation/ re-attachm.	3-D	– HANDLING – variable position (calibr./meas.)	experiment. effort	construct. effort	electron. support
Surface Hot-Film	○ spec.	⊗ middle	○ temperature, $\dot{q}_w \nsim \tau_w$	● yes	○ no	● good	○ no	⊗ middle	⊗ middle	○ high
Sublayer Fence	○ spec.	● low	● pressure grad. (general low)	● yes	● yes	● good	○ no	● low	○ high	● —
Preston Tube	● stand.	○ high	○ deviations from classical law of the wall	○ no	○ no	○ only amount	● yes	● low	● low	● —
Wall-Fixed Hot-Wire	● stand.*	⊗ middle	○	○ no	○ no	○	● yes	⊗ middle	⊗ middle	○ high
Computational Preston Tube	● —	● —	● math. law of the wall	● yes	● yes	⊗ possible (2-chambers)	● yes	⊗ middle**	● low	○ high
Wall-Fixed Double Hot-Wire	● —*	● —	● not applicable (no convergence)	● yes	● yes	⊗ possible (x-wires)	● yes	⊗ middle**	⊗ middle	○ high

* additional hot-wire calibration
** computer aided measuring techniques ● advantage ○ disadvantage

Tab. 1 : Relative merits of indirect shear stress measuring techniques

To support the discussion of the six measuring methods investigated, the relative merits of the various devices are summarized in Tab. 1.

The differences in using standard, special or no calibration curves are collated in the first block of Tab. 1. These peculiarities can be of importance when applying the respective methods in wind tunnel or free flight tests, as defined calibration conditions are only available in exceptional cases (e.g. calibration of surface hot films on a prolate spheroid with the aid of a boundary -layer computer program [17]). Considering this aspect, the methods that operate with standard or no calibrations possess an obvious advantage, which is however partly lowered if we consider the limitations arising from the standard calibration curves, e.g. in the classical Preston tube method.

The applicabilities of the methods listed in the second block result directly from the respective main restrictions indicating the far reaching capabilities of the sublayer fence technique and of the computer aided measuring methods, which are however of limited use in 3-D flows.

Tab. 1 ends in the third block with a compilation of the handling of each individual technique. As made previously clear about the necessity of special calibrations for surface hot-films and sublayer fences these measuring devices are not traversable but fixed-mounted. This is of great disadvantage especially in entire flow field investigations as (if a calibration is possible at all) this requires a multitude of probes and therewith a comparably high electronical support (bridge circuit for each surface hot-film) as well as a manufacturing effort for the sublayer fences. For the computational methods the electronical effort is likewise of significance as besides hot-wire anemometer circuits for the wall-fixed double hot-wire they also need an efficient computer - which is in any case desirable - if the investigations are to be undertaken on-line.

Summing up, the relative merits compiled in Tab. 1 cannot be an absolute and unequivocal recommendation favouring one method against the other, however, the table may be helpful in selecting an appropriate method for a special application.

6. CONCLUSION

The comparative investigations presented in this paper in employing indirect wall shear stress measuring methods in experimental aerodynamics, emphasize the applicabilities of some well known as well as of some newly or recently developed shear stress measuring techniques. The pecularities of the respective methods are discussed for 2-D flows with additional parameters of influence, in transition flows, separated and re-attached as well as 3-D flows. The capabilities as well as some restrictions of the investigated techniques have been outlined, indicating respective advantages and disadvantages for special test conditions. Through these investigations the measuring uncertainties to be expected in employing the methods in practical wind tunnel of free flight testing can be estimated. Hence, in connection with the also discussed experimental and electronical effort this investigation can lead to reasonable applications of the methods according to particular test conditions.

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