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SOME OBSERVATIONS ON THE UNIVERSAL FEATURES OF AN ARRAY OF HEATED FILMS FOR THE SKIN FRICTION MEASUREMENT

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SOME OBSERVATIONS ON THE UNIVERSAL FEATURES OF AN ARRAY OF HEATED FILMS FOR THE SKIN FRICTION MEASUREMENT

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The heat transfer and dynamic behaviour of an array of heated films applied to the common folio in a laminar or at least transitional boundary layer were investigated. The folio with thirty hot-film gauges, gluing it on the flat surface of the experimental body and the primary connections of the film's electrodes with conductors was done in the MTU, Munich. Both construction and production of the experimental body were performed in the Institute of Thermomechanics AS CR, Prague.

In the contribution there are the observed variations of electric resistance, effective time constant and heat transfer for the individual hot-films presented. These characteristics were measured in a laminar or at least transitional boundary layer at the outer stream velocity from 4 m/s to 170 m/s (Mach number 0.52) and with various film overheatings ($T_w/T=1.02$ *up to 1.10).*

Introduction

The application of heated surface gauges of measuring shear stress is based on the similarity between the diffusion of heat and vorticity. The heat diffusion is responsible for the heat transfer and the vorticity diffusion is producing the shear stress and responding to the alterations of flow structure. Due to this and to their extremely low mass, the surface heated sensors are valuable tool for investigation of the phenomena accompanying the flow over solid surfaces; e.g. laminar/turbulent transition, flow-separation, shedding of vortices.

Since the early investigations with surface heated sensors (e.g. FAGE & FALKNER /1930/, LUDWIEG /1949/, LIEPMANN & SKINNER /1954/) many different configurations have been proved. Among them the film-element manifests itself as a well suited device for this application either as a single HF-sensor or as an array of geometrically similar HF-sensors on a common thin flexible substrate. It is well known (e.g. SANDBORN /1972/) that under some simplifying assumptions a response equation between heat-transfer (Q) from the film (temperature T_w) and shear-stress (τ_w) might be derived.

Due to the heat conduction in the wall and in the electrodes and to the individual features of HF-wall sensors, it has been established that the response equation must be assumed in the form (E is the output signal of the anemometer)

$$Q \sim E^2 = a + b\tau_w^{1/N} ; \; N \geq 3 \qquad (1)$$

if the hot-film is operating at a constant temperature T_w in perfect isothermal conditions (temperatures of the wall (T_A) and of the fluid (T) are constant and identical). The coefficients and exponent (a, b and N) must be determined from the individual calibration measurement.

Even small departures from the conditions at calibration cause rapid increase of systematic measurement errors. Therefore a more general - nondimensional form of the HF-response equation should be applied (heat-conduction in the wall is assumed too):

$$\mathrm{Nu} = F(T_A, T_w, T) + G(T_w)\,\mathrm{Re}_\tau^{2/N} \tag{2}$$

where

$$\mathrm{Nu} = \frac{Q}{L\lambda(T_w - T)} \qquad \mathrm{Re}_\tau^2 = \frac{\tau_w}{\rho}\,\frac{L^2\rho^2}{\mu^2} \tag{3}$$

$$F = \frac{A_0 + A_1(T_w - T_A)}{L\lambda(T_w - T)} \qquad G = \frac{C}{L}\left(\frac{C_P.\mu}{\lambda}\right)^{1/3} \tag{4}$$

L is the length of HW-sensor, C_p, λ, μ and ρ are specific heat, heat conductivity, dynamic viscosity and density of fluid; A_0, A_1, C and N are calibration constants.

Because of difficult calibration measurements necessary to determine all calibration constants in the relationship (2) more largely, the response equation is employed:

$$\mathrm{Nu} = A + B.\mathrm{Re}_\tau^{2/N} \tag{5}$$

or contingently

$$\lambda(\tau_w)\mathrm{Nu} = A + B.X^{1/N} \qquad X = \frac{C_P\rho^2L^2\lambda^2}{\mu}\,\frac{\tau_w}{\rho} \tag{6}$$

A, B and N are the calibration constants again.

From a former investigations of this technique for shear stress measuring, it follows: when using the formula (5), small departures from the values at calibration of the flow-, wall and film-temperature and of the stagnation pressure are admissible in the course of measurement. The departures about from 1 up to 3 K or about 500 Pa do not change the measurement accuracy to the worse; at $\tau_w > 0.1$ Pa the relative error retain between 2 and 4 percent. An increase of the assumed departures of the flow parameters causes a great decrease of the measurement accuracy. Some attempts to overwhelm, at least particularly, this problem (e.g. JONÁŠ et al. /1981/, POLYAKOV et al. /1988/) have not been introduced in routine experiments.

No significant problems occur with the preparation and the performance of calibration measurement of a single-wall-hot-film probe (e.g. " DANTEC 55P45 Probe"). They are arranged either in a known shear flow (e.g. fully developed channel or pipe flow) or by measuring the skin-friction τ_w in the given point of wall by other techniques (e.g. a floating element device, Preston probe, fence-probe). The HF-probe is simply built in the wall of the calibration equipment and then in the investigated place of the test facility wall.

Very similarly a calibration and a measurement with an array of hot-film sensors on a common substrate (Fig.1) might be performed in the case if the substrate is mounted on a cut-out of a plane wall. At that time every HF-sensor can be submitted to the individual calibration.

Quite different situation sets in the case of an array of HF-sensors to be mounted (glued) on an airfoil or another curved surface. Then an individual calibration of sensors is impossible as there is no chance to create the flow-conditions with a known skin-friction distribution. It is hard to imagine the possibility to "change" the substrate with hot-films without its damage or at least without fundamental changes of the sensors' features from the calibration surface to the surface of the investigated body. Without any HF-response equation the measured characteristics of the anemometer output signal E give only qualitative information, e.g. SCHRÖDER et al. /1992/:

$$\frac{\bar{E} - E_0}{E_0}\,; \qquad \frac{e_{RMS}}{\bar{E}} \qquad \text{or} \qquad \frac{e_{RMS}}{E_0} \tag{7}$$

where $\bar{E}$ and E_0 are the average values of output signal in the course of fluid flow or in the state of the rest, e_{RMS} is the RMS-value of signal fluctuations.

It should be mentioned that the voltage E_0 corresponds only very roughly with the calibration constants a or A (see (1) or (5)). This is similar to HW-anemometry. The assertion on only qualitative meaning of these simple output-signal characteristics is evident from their comparison with formulas for the mean value $\bar{\tau}_w$ and for the intensity of fluctuations I_τ of the skin-friction:

$$\bar{\tau}_w = \left(\frac{\bar{E}^2 - a}{b}\right)^N ; \qquad y_\tau \equiv \frac{(\tau'_w)_{RMS}}{\bar{\tau}_w} = 2N \frac{\bar{E}^2}{\bar{E}^2 - a} \frac{e_{RMS}}{\bar{E}} \tag{8}$$

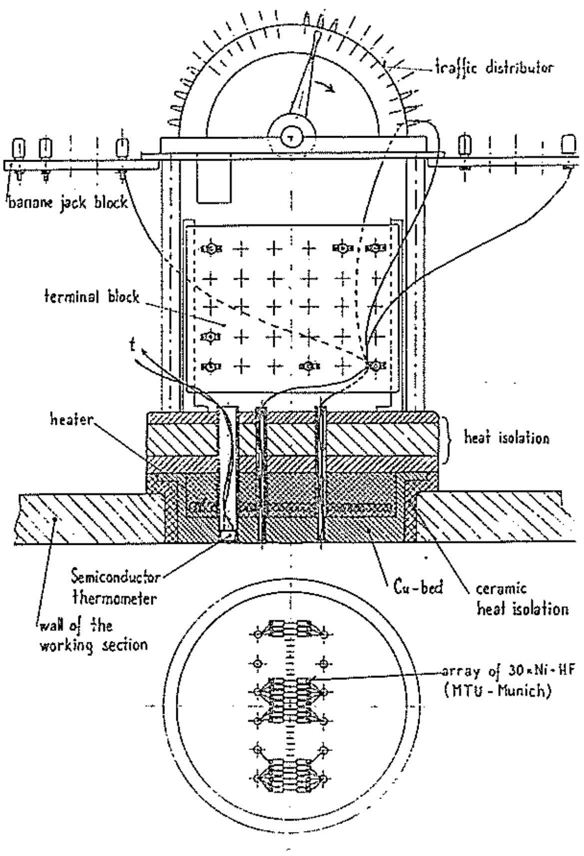
For the seek of simplicity and objectivity, these formulas are derived from the mostly simplified HF-response equation (1).

The aim of this paper is to examine the possibility to find an approximation of the HF-response equation which would at least roughly valid for a given family of a surface-mounted hot-film gauges and to determine the respective statistical estimates of probable errors of the evaluated values $\bar{\tau}_w$ and I_τ.

Experimental set-up

The scheme of the experimental body with an array of heated films for the skin-friction measurement is shown in Fig.1. The array consists of thirty nickel films (0.4 μm thickness; 0.1 mm width; 5 mm length - across the flow; 2.5 mm spacing between sensors). These wall-HF-sensors have been developed in MTU - Motoren- und Turbinen- Union, Munich, GmbH, Germany. In the MTU the substrate with hot-films has been glued on the plane surface of the experimental body. Also the primary connections of the films' electrodes with conductors and the measurement of the films' electrical resistances R_i (i = 1,2,...30) at various temperatures have been done in the MTU. Construction, production and the remaining instrumentation of the experimental body have been done in the Institute of Thermomechanics AS CR, Prague (IT). The electrical heating and the other equipment of the body only at advanced investigations will be utilized.

Figure 1: Experimental body



The plane surface (Φ = 0.1 m) of the experimental body has the shape of cut-outs staggered on the one wall of the intermittent-run wind tunnel. This tunnel is breathing atmospheric air through a dryer and a dust filter into the evacuated volume; galleries of an old gold-ore mine. It has a test-section 0.1x0.1 m and 2,25 m in length. In the upper wall of the test section are staggered circular (Φ = 0.1 m) cut-outs - "windows" with centres in the distances $x_n = 0.107 + 0.15.(n-1)$; n = 1, 2, ... 15 downstream from the entrance section. Due to the great mass of the series of filters, damping screens, high contraction ratio (28:1) and a suitable inlet flow speed control, the flow- and the temperature-fields are reasonably steady and homogeneous in the whole range of velocities; from 0.1 m/s up to Mach number 0.83. At the velocity less then 60 m/s the turbulence level is between 0.1 and 0.2 percent till the distance x = 1.2 m. The presented experiments have been carried out with the experimental body in the position just at the entrance section (n=1) only. Therefore, in the region

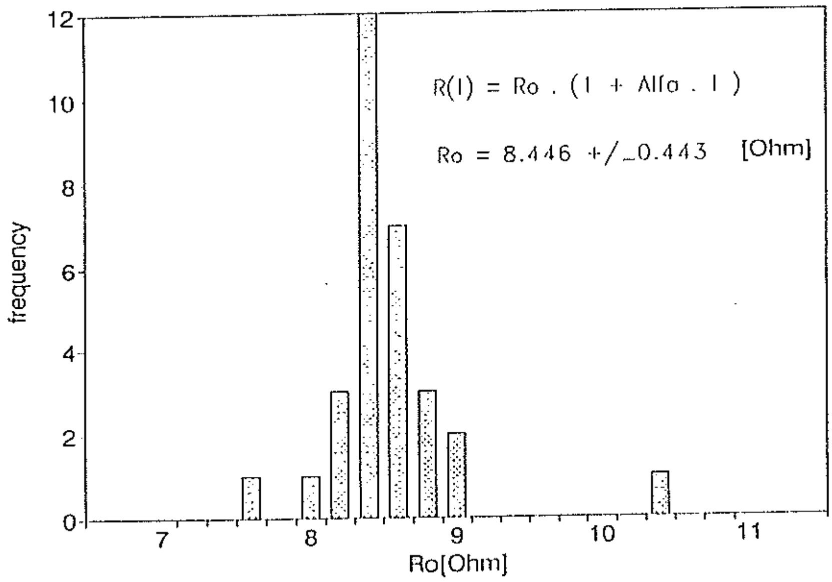
$$0.07\,\mathrm{m} \lesssim x \lesssim 0.14\,\mathrm{m}\,; \qquad (9)$$

at the inflow velocities $3.8\,\mathrm{m/s} \lesssim U_e \lesssim 174\,\mathrm{m/s}$ ($Ma \doteq 0.52$), there has been determined the distribution of the wall-shear friction $\bar{\tau}_w$. This measurement was done by means of a fence-probe (the fence height = 0.179 mm) calibrated towards a floating-element device developed in the IT for direct measurement of wall shear stress (ŘEHÁK et al. /1987/). Thus for every selected value of the inlet flow Reynolds number

$$0.24.10^6 \lesssim Re_l = \frac{\rho U_e}{\mu} < 12.10^6 \qquad (10)$$

the local value $c_f(x_l,Re_l)$ of the skin friction coefficient is known in the region (9).

Figure 2: Histogram Ro



In the course of the calibration measurements of the HF-array the individual heated films have been successively connected to the single channel CTA-System DANTEC (anemometer t.55MO1, Data Acquisition System 56 N). The collection and recording of the measured data have been executed by a PC/AT 486 computer.

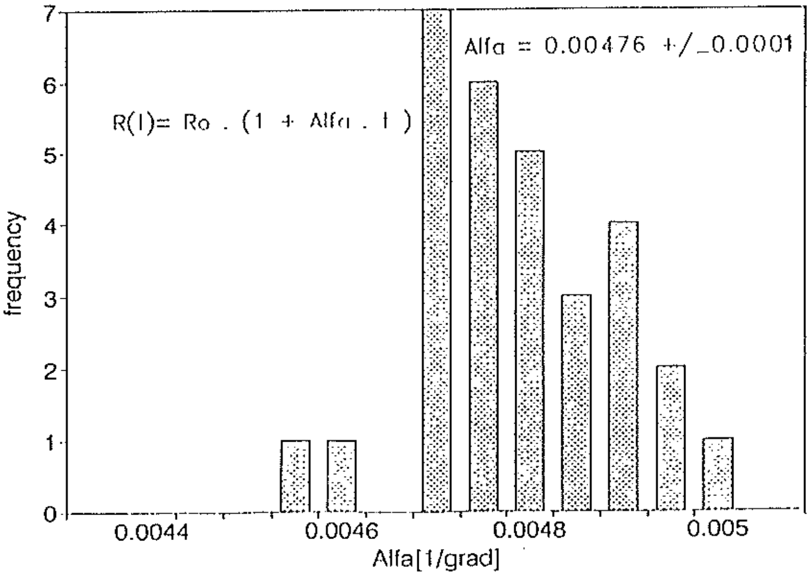
The investigation of the heat-transfer from individual heated film was performed at the heat ratios $T_w/T = 1.02$; 1.04; 1.06; 1.08 and 1.10 and in the region of Reynolds number Re_τ

$$1 < Re_\tau = \frac{\rho . l . u_\tau}{\mu} < 80 \qquad (11)$$

where $l = 0.1$ mm is the length of a hot-film in the flow direction and $u_\tau = \sqrt{\tau_w/\rho}$ is the wall-friction velocity.

The accuracy estimate of the measured data is based on the experience gained previously (JONÁŠ et al. /1981/ and ŘEHÁK et al. /1987/) and on the comparison of repeated measurements. The estimates of the probable errors of the fundamental quantities are following: mean velocity: (0.5 ÷ 1.0) %, skin friction coefficient: (3 ÷ 6) %, temperature difference (T_w-T): (0.5 ÷ 1.0) K, Nusselt number (15 ÷ 3.0) % - indirect proportional to heating ratio T_w/T.

Figure 3: Histogram ALFA



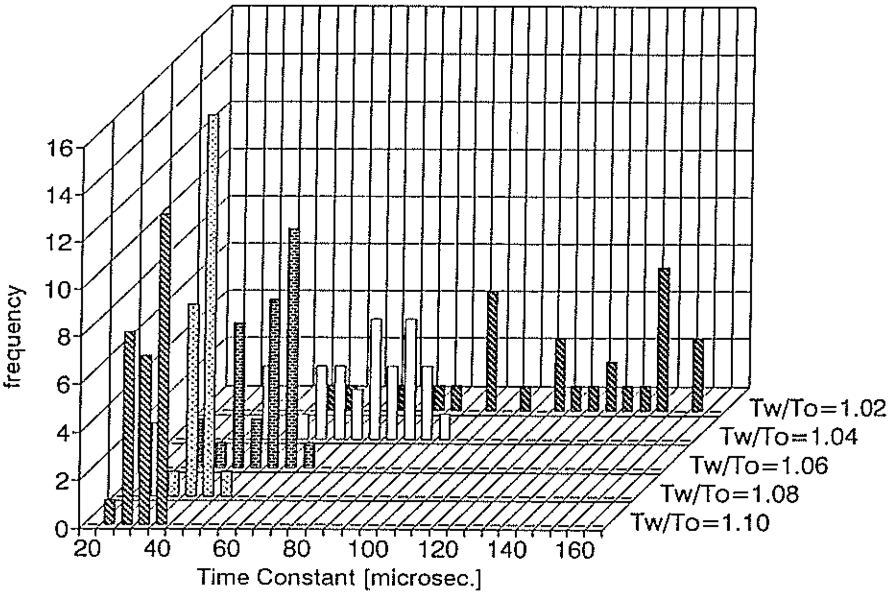
Results and preliminary conclusions

The received results enable us for following conclusions:

The individual HF-sensors in the investigated array have the resistance- temperature characteristics satisfactory similar (Fig.2 and Fig.3); the standard deviation of the individual "cold" resistances R_0 (at 0°) is about 5% of the average (computed from 30 values) resistance $\bar{R}_e = 8.446\ \Omega$ and the standard deviation of the temperature coefficient α is about 2% of its average value $\bar{\alpha} = 0.00476\ \mathrm{deg}^{-1}$.

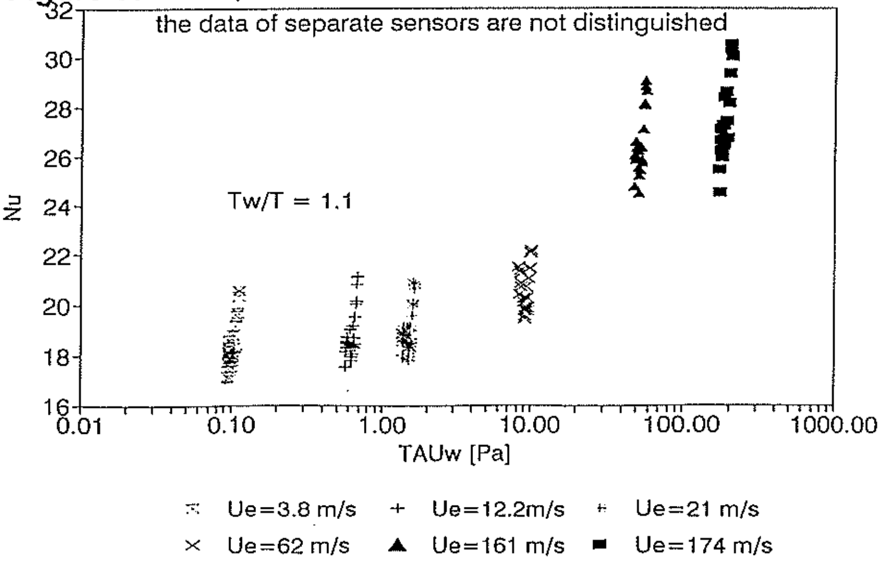
The design and the manufacture of the element with the surface-mounted array of HF-sensors (Fig.1) as well as the connections to the CT-Anemometer bridge are of a good quality; e.g. a perfect smooth surface has been preserved; the effective time-constant of the individual HF-sensors are quite small enough $\tau_{ef} < 50\ \mu s$ at $T_w/T = 1.06$ and $\tau_{ef} \doteq 30\ \mu s$ at $T_w/T = 1.10$; in both cases $Re_T \doteq 6$; Fig.4) although the balancing of the CTA-bridge has been performed as common for the whole array of sensors and with regard to the worst configurations at $T_w/T = 1.02$ up to 1.10.

Figure 4: Effective Time Constant



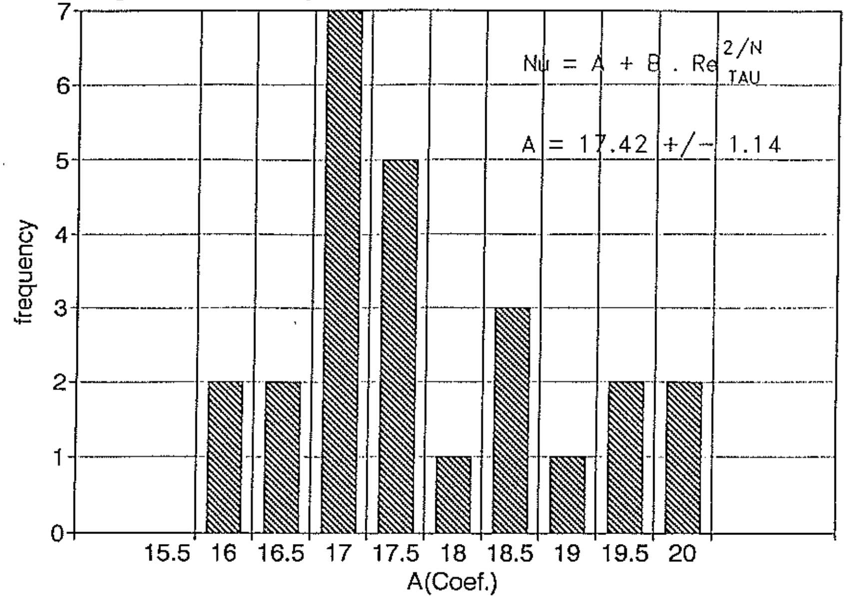
The dependence of the Nusselt number Nu on the skin friction τ_w at a constant temperature ratio $T_w/T = 1.1$ presented in Fig.5 indicates a great scatter between the data from individual sensors. The scatter is comparable with the difference of the Nu-values at $\tau_w = 0.1$ Pa and 10 Pa. Probably it is not only the result of relatively high errors in the evaluation of Nusselt number but also because of some distinctions in heat conduction from the individual heated film to its electrodes and into the wall. Also laminar or at least transitional structure of boundary layer in the course of measurement contributes to the increase of measurement errors (high sensitivity to surface misalignments).

Figure 5: The dependence of the Nusselt number on the skin-friction; the data of separate sensors are not distinguished



At a given Reynolds number and the ratio are the measured values of Nusselt number of an individual HF-sensor the same and repeatable in the limits of the measurement accuracy. It is surprising and not still elucidated

Figure 6: Histogram A



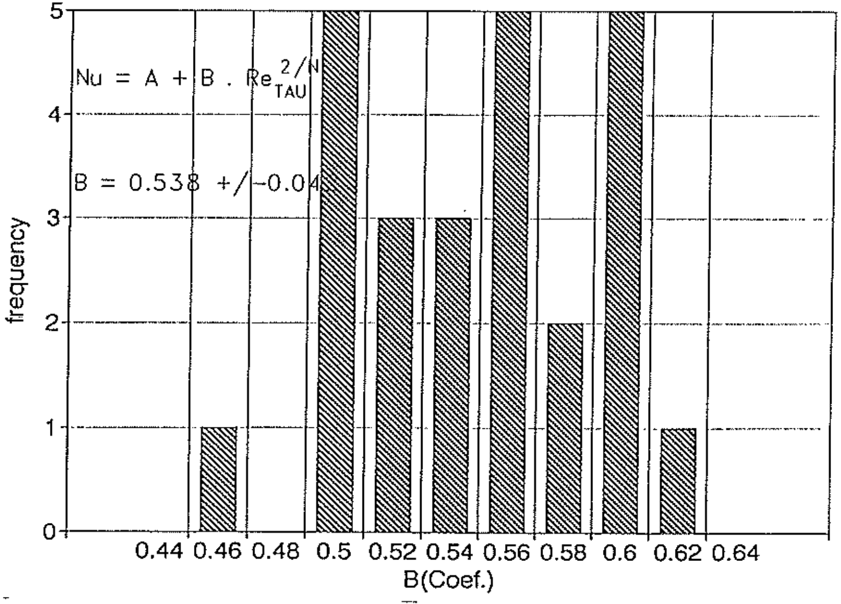
that a part of the tested sensors shows the tendency to decrease Nu with increasing ratio T_w/T and an another group of sensors shows an opposite tendency.

A simple statistical analyse of the estimated coefficients A_i, B_i (i=1,2..30) from the relation (5) has been done; index i denotes the number of a HF-sensor in the array on the common substrate. Histograms of the coefficients (Fig.6 and Fig.7) and statistical estimates of mean values and standard deviations (computed on the ensemble of all HF-sensors)

$$A = 17.42\,(1 \pm 0.065); \quad B = 0.538\,(1 \pm 0.078)$$

display (Fig.8) that we are still far from derivation of an universal form of the cooling-law (5) for all HF-sensors on the common substrate; e.g. in the region of the Re_τ values during the performed experiments. From the above presented std. values follows the estimate of relative errors in computation of Re_τ from 170% to 43%.

Figure 7: Histogram B



In contrast with this, from the individual interpolation of (5) (Fig.9), the relative errors follow about:

$$\frac{s(A)}{A} \doteq 0.015 \text{ and } \frac{s(B)}{B} \doteq 0.025$$

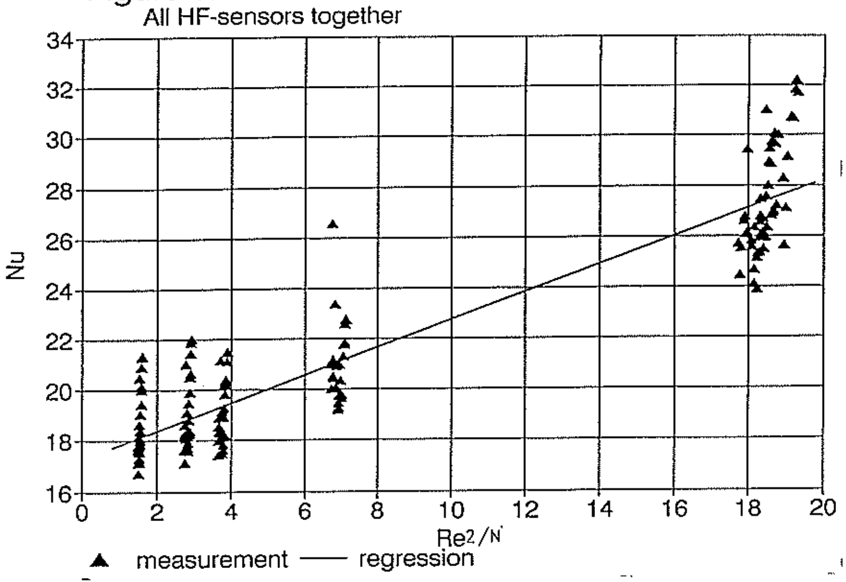
and thus the estimated relative error of measurement of Re_τ is between 38% (at $Re_\tau \doteq 1$) and 3.8% (at $Re_\tau = 80$). This is still more than has been achieved before. However, we must point out to extremely wide interval of calibration here presented.

Perspective

According to our former experiences, calibration of HF-gauges for the wall-friction measurements performed in narrower intervals of Re_τ give significant higher accuracy of the determination of the coefficients in the cooling-law (5).

Also a moderate increase of the heat ratio $T_w/T \geq 1.06$, a shift of the lower limit of Re_τ and a control of the wall temperature (especially at higher outer stream Mach number) may help to get more optimistic view on the way how to find an "universal" HF-response

Figure 8: Nusselt number



equation for the tested configuration. This research will continue if further finds will be available.

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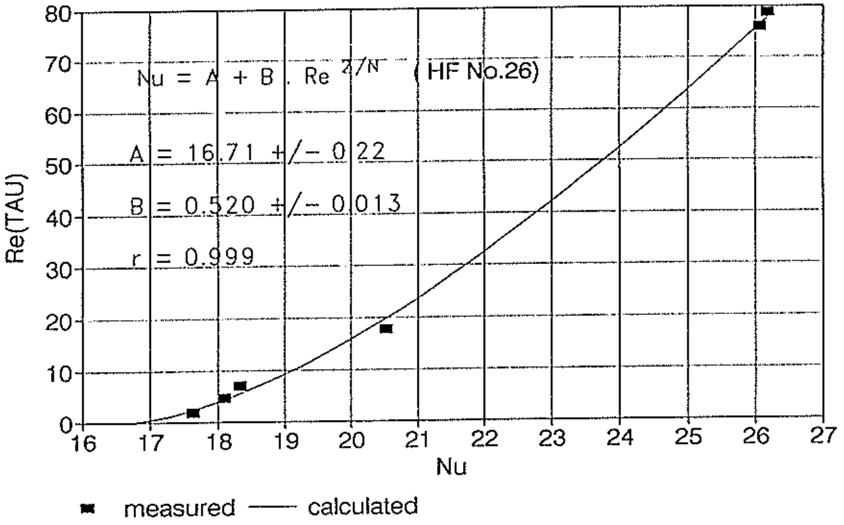
Figure 9: Individual calibration



References

FAGE A., FALKNER V.M. /1930/: An experimental determination of the intensity of friction on the surface of an aerofoil. Proc.Roy.Soc.(A), Vol.129, p.378

JONÁŠ P., PLAČEK V., PURR D. /1981/: Zur Wandschubspannungsmessung mit Heissfoliengebern unter nicht-isothermen Bedingungen. "Turbulenzmesstechnik", I. Mech. A. d. W. der DDR, R-MECH-02/81, Berlin, 90-10

LIEPMANN H.W., SKINNER G.T. /1954/: Shearing-stress measurements by use of a heated element. NACA TN 3268

LUDWIEG H. /1949/: Ein Gerät zur Messung der Wandschubspannungen turbulenter Reibungsschichten. Ing.-Arch., Bd.17, 207-218

POLYAKOV A.F., TROITSKY V.V., SHEHTER Ju.L., JØRGENSEN F.E. /1988/: Shear stress measurements on heat transfer surfaces. DANTEC Information 06, 12-15

ŘEHÁK V., VANĚK F., JONÁŠ P. /1987/: A method of the wall-shear measurement in a boundary layer. Proc. of the 1st Conference on Mechanics. Pt.8, ČSAV, Prague, 237-240

SANDBORN V.A. /1972/: Resistance Temperature Transducers. Metrology Press, Ft.Collins, Colorado

SCHRÖDER T., BAIER R.D., BROICHHAUSEN K. /1992/: Laminar flow and unsteady phenomena in boundary layers of turbomachinery blades. Proc. 1st European Forum on Laminar Flow Technology, DGLR-Bericht 92-06, 201-211