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poświęcone są publikacjom naukowym z zakresu teorii i badań doświadczalnych w dziedzinie mechaniki i termodynamiki przepływów, ze szczególnym uwzględnieniem problematyki maszyn przepływowych

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Dresden*)

Characteristic Fields of the Natural Transitional Boundary Layer**)

In order to investigate the laminar-turbulent transition, calculated by means of boundary layer method, in a sufficiently exact manner, theoretical results on turbulent spot formation have been compared with experimental data obtained by means of the soot removal method on a flat plate and with various other results obtained by measuring the local heat transfer and by hot-wire anemometry. Furthermore, an experimentally founded model concept has been developed explaining the formation and development of the turbulent spot within the transitional boundary layer. As a result of these investigations, characteristic correlations between momentum thickness, Reynolds number and free-stream turbulence level with the intermittency factor as a parameter of the flat plate without pressure gradient have been obtained. A characteristic showing the pressure gradient influence on the laminar-turbulent transition has been established as well. The reliability of those fields of characteristics can be verified experimentally by means of the sample method.

1. Introduction

To design flow systems suitable to transform efficiently kinetic flow energy into pressure energy, a sufficiently exact calculation of the boundary layer upstream of the diffuser is generally necessary. This is especially the case for flat blade profiles showing in the nominal operation point, a uniform velocity distribution over a wide range of their suction side which results in the boundary layer transition (see [6] and [22]). In most cases the turbulence observed in the cascade channel is relatively intense. In order to obtain under these conditions a detachment-free flow within the outflow space of the cascade channel, the cascade was designed in such a way that the separation criteria, recommended for turbulent boundary layers, were taken as the upper bound values. It follows from the above that design limitations are unknown up to now. This unsatisfactory situation requires development of a calculation method for transitional boundary layers.

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**) Part 1 of the paper 9P6 "Natural boundary layer transition on the basis of theoretical and various experimental results obtained from the flat plate without and with pressure gradient", read to the 2. Symposium on Laminar/Turbulent Transition of the IUTAM in Novosibirsk, USSR, July 9—13, 1984. Extended abstract entitled "Characteristic Fields of the Natural Transitional Boundary Layer" published in the Conference Proceedings by Springer-Verlag GmbH and Co, Berlin-Heidelberg.

Since detection of coherent structures in turbulent boundary layers by S. I. Kline [17] a thorough investigation of existing flow phenomena began, so that the findings known up to now permit already a sufficiently exact calculation of transitional boundary layers. The questions tackled in this report are as follows:

1. Determination of the dependence of the Reynolds number corresponding to the laminar/turbulent transition inception and end on the flat plate in case of zero pressure gradient on the free stream turbulence level.

2. Turbulence anisotropy influence of free stream and pressure gradient on start and end of transitional region.

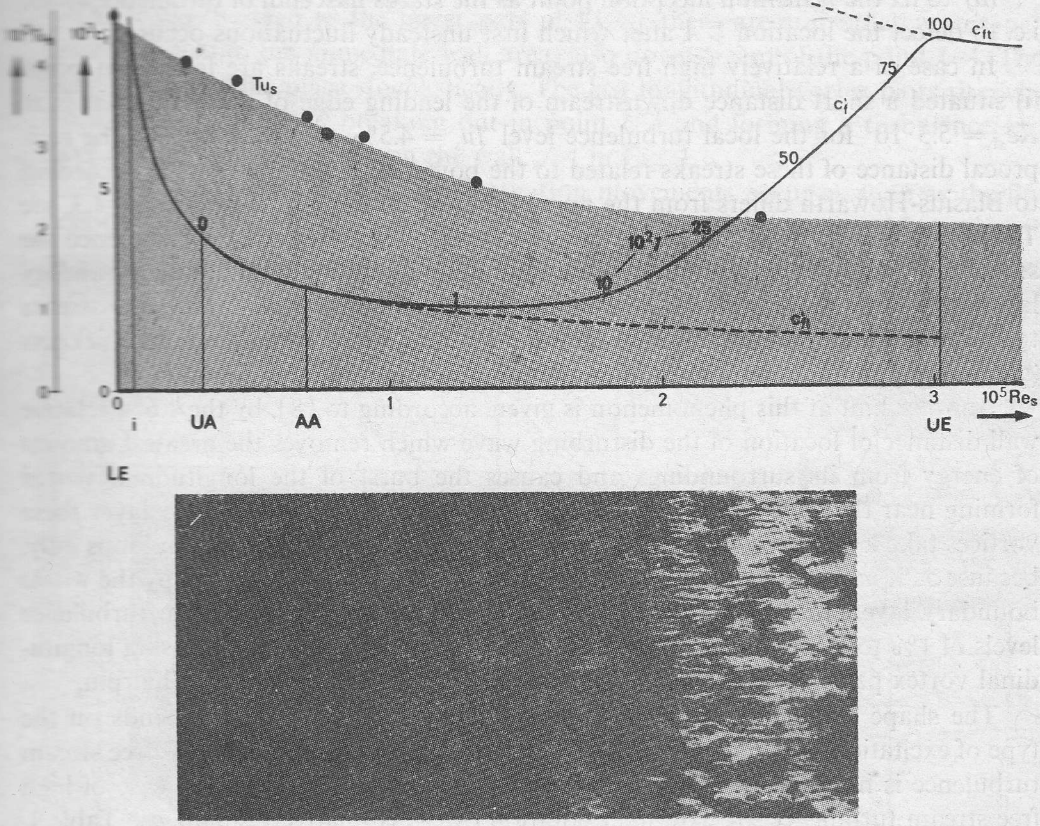
Verification of the characteristic fields developed to describe the laminar/turbulent transition, is made using the measurement results of R. Herbst [13] obtained by means of the sample method, in which an intermittent inflow on the flat plate with pressure gradient is assumed.

In future it will be necessary to illuminate the flow mechanism leading to formation of turbulence spots so that it will be possible to formulate experimentally founded hypotheses on its structure and then to develop and test mathematical models. W. Albring [2] and M. T. Landahl [18, 19], for instance, point out promising approaches.

2. Transition Initiation in Case of Zero Pressure Gradient

Measurement results on the transition initiation on a flat plate, positioned parallel to the main flow direction, which are obtained by different methods, i.e. hot wire anemometry, heat transfer measurement and soot-oil-petroleum erosion, differ so much that the transition inception points reported cover approximately half of the whole transitional region (see [7] and [10]). This applies first of all to free stream turbulence level values of 2% and more. Therefore experimental and theoretical investigations of the flow structure near the wall leading to the formation of turbulence spots have been carried out especially in this incidence area (see [22] and [8]). A result of these investigations is given in Fig. 1 showing the local skin-friction drag coefficient, i.e. the wall shear stress related to the dynamic pressure of the undisturbed free stream, versus the streamwise length Reynolds number with the intermittency factor γ as a parameter in the transitional boundary layer region. Measurement results show a statistical distribution which may be approximated by means of the Gaussian distribution in case of turbulence level values less than 0.1% (see [9]). In the present case the free stream turbulence level measured by means of a hot wire anemometer amounts up to 4.6% at the leading edge and is reduced to about 2% at the end of the transitional region.

The lower part of Fig. 1 gives an insight into the structure of the transitional boundary layer near the wall. It has been obtained by means of the soot-oil-petroleum erosion technique. The erosion pattern to be seen at the right side and in the middle of the figure, results from the different times of turbulence spot formation and consequently, it cannot be a spanwise measure of the intermittency factor. In the first half of the transitional region this factor is very small (see Fig. 1).



$$Tu_s = \frac{\sqrt{\overline{u'^2}}}{u_\delta}, \quad Re_s = \frac{u_\delta s}{\nu}, \quad c_{fl}' = 2\,\frac{d\delta_2}{ds}$$

$$c_{fl}' = 0.66412\, Re_s^{-1/2}, \quad c_{ft}' = 0.1(Re_s - Re_{sUA})^{-1/5}$$

$$c_f' = c_{fl}' + \gamma(c_{ft}' - c_{fl}'), \quad \gamma = 1 - \exp(-5\eta^9)$$

$$\eta = (Re_s - Re_{sUA})/(Re_{sUE} - Re_{sUA})$$

Fig. 1. above: Relationship between local skin-friction drag coefficient c_f' and streamwise length Reynolds number Re_s with intermittency factor γ as a parameter of the flat plate for high isotropic free stream turbulence and zero pressure gradient; *LE* — leading edge, *AA* — start of spot prints, *UA* — transition inception point, *i* — start of the streaks

below: Use of soot-oil-petroleum erosion to show the streaks (left) in the unstable laminar boundary layer and the turbulent spots (centre and right hand side of the figure) in the first half of transitional boundary layer region. The photograph shows the streaks according to the values on the abscissa lying in the area of the streamwise length Reynolds number between $Re_s = 0.25 \cdot 10^5$ and $Re_s = 1.94 \cdot 10^5$

The aim of investigations was

(i) to assess the magnitude of streaks (left side of the figure) observed in the unstable laminar boundary layer upstream and immediately downstream of the transition inception point and

(ii) to fix the transition inception point as the status nascendi of turbulence spots, i.e. to detect the location UA after which first unsteady fluctuations occur.

In case of a relatively high free stream turbulence, streaks are formed at point (i) situated a short distance downstream of the leading edge of the plate, that is at $Re_{si} = 5.3 \cdot 10^3$ for the local turbulence level $Tu_s = 4.5\%$. At the point UA the reciprocal distance of these streaks related to the boundary layer thickness δ_l according to Blasius-Howarth differs from the approximate value $\lambda_n/\delta_l = 1$ to become 1.3, see Table 1. It follows from the above that in case of intense free stream turbulence the secondary flows in the unstable laminar boundary layer cover the whole boundary layer between points (*i*) and UA, whereas in case of no and very poor free stream turbulences these secondary flows cover only 1 to 2% of the boundary layer thickness (see [24]).

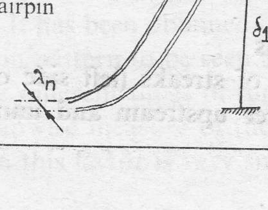
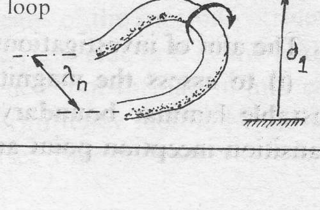
Another hint at this phenomenon is given, according to [8], by the 1.6% relative wall distance of location of the disturbing wave which removes the greatest amount of energy from its surroundings and causes the burst of the longitudinal vortex forming near the wall. In case of self-excitation in the laminar boundary layer these vortices take a hairpin shape. In case of external excitation they can from loops only, because as it has been said above, the longitudinal vortices already occupy the whole boundary layer. In areas of mixed excitation, i.e. in case of free stream turbulence levels of 1% to 0.1% and turbulence levels falling down, the shape of rising longitudinal vortex pairs changes from a loop to a horseshoe and finally to a hairpin.

The shape of the vortex pairs bursting the layer near the wall depends on the type of excitation, i.e. whether the transition inception in case of very low free stream turbulence is induced by self-excitation (Re_{sUA} is relatively large) or, in case of high free stream turbulence, by external excitation (Re_{sUA} is relatively small), see Table 1.

The structural phenomena of fully developed turbulent boundary layers as by M. R. Head and P. Bandyopadhyay [12] may in a certain sense be also used to the status nascendi of turbulence spots, i.e. to transition inception.

Table 1

Characteristic differences of formation of longitudinal vortex systems near the wall at the transition inception point

Kind of excitation:	Self-excitation	External excitation
$10^2 Tu_s$	< 0.1	> 1
λ_n/δ_1	≈ 0.016	≈ 1 before UA ≈ 1.3 after UA
Re_{sUA}	$= 2.82 \cdot 10^6$	$= 177 \cdot 1\,(kTu)^{-1.606}$
Effect of Reynolds number on features of longitudinal vortex pairs at the transition inception point	hairpin 	loop 

As it can be seen in the lower part of Fig. 1 there are still other vortex pairs remaining within the immediate wall area, also downstream of the point UA. Their burst seems to take place stochastically. The last longitudinal vortex pairs rise when the first ones, i.e. those breaking out in point UA and forming a turbulence spot, have already left their print on the wall: AA in Fig. 1.

Due to the fact that unsteady fluctuation movements occur as soon as the fluid near the wall bursts for the first time in the direction of the boundary layer edge, the

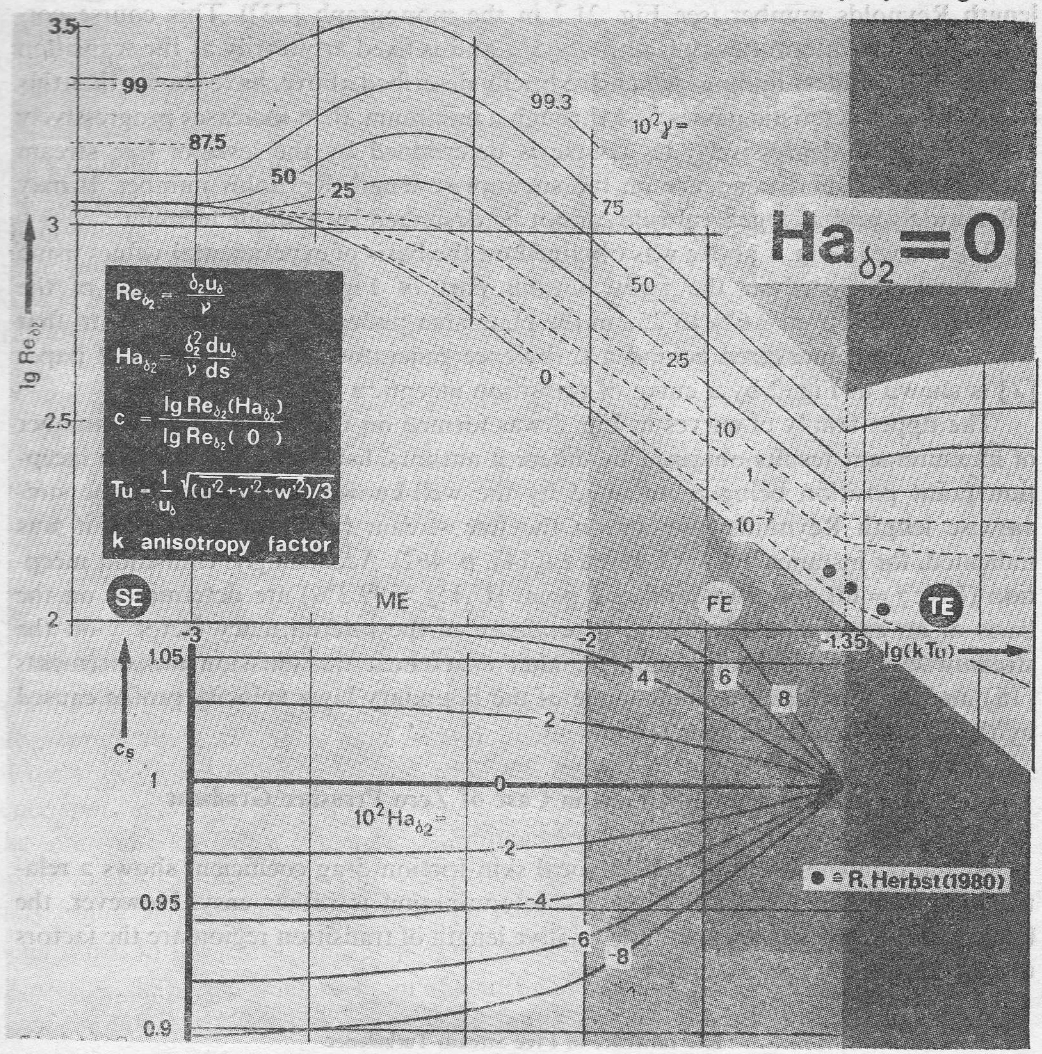


Fig. 2. above: Relationship between momentum thickness Reynolds number and free stream turbulence level for transitional boundary layer at zero pressure gradient with the intermittency factor as a parameter below: Effect of pressure gradient for an intermittency factor of 5%

SE — region of self-excitation, ME — region of mixed excitation, FE — region of external excitation, TE — turbulence energy in the free stream is greater than or equal to the maximum of turbulence energy in the boundary layer; anisotropy factor: $k = \sqrt{3/(1+(\overline{v'^2}+\overline{w'^2})/\overline{u'^2})}$; momentum thickness factor: $k_{2t} = \delta_{2t}(0)/\delta_{2t}(kTu)$

transition inception is fixed, although it is not possible to note a marked deviation of the skin-friction drag coefficient behaviour because of the infinitely small intermittency factor, cf. upper part of Fig. 1. Exact evaluations of heat transfer measurements carried out by J. Kestin, P. F. Maeder and H. E. Wang [15] showed, however, that the transition inception point UA may be clearly fixed in the external excitation region (see [7]). Up to now a degressively increasing course was given for the transition region of the skin-friction drag coefficient depending on the streamwise length Reynolds number (see Fig. 21.2 in the monograph [23]). This course corresponds to an intermittency factor $\gamma > 5\%$ and is fixed arbitrarily as the transition inception. The latest findings which are briefly described above, have shown that this transition characteristic passes first through a minimum, then increases progressively and afterwards degressively. Its course is determined by the level of free stream turbulence and its dependence on the streamwise length Reynolds number. It may differ widely and as a general rule cannot be described by a single formula.

The curve in Fig. 1 above was obtained on the basis of experimental values using the equations listed in the right bottom part of Fig. 1. The decrease of the turbulence level from 4.6% to 2% in the plate area under study corresponds to that which has been measured behind a turbulence generator [22]. The result of paper [7] is shown in Fig. 2 by a curve of transition inception at $\gamma = 0$.

The upper family of curves in Fig. 2 was formed on the basis of a great number of measurement results obtained by different authors, listed in [7, 9, 10], the inception point position being represented by the well-known dependence of the streamwise length Reynolds number on the free stream turbulence level, as it was indicated, for instance, by J. O. Hinze ([14], p. 462). Accordingly, transition inception ($UA: \gamma = \emptyset$) and transition end point ($UA: \gamma \approx 99.3\%$) are determined on the basis of an experimentally found dependence of the intermittency factor γ on the streamwise length Reynolds number, after exact heat transmission measurements [15] and in consideration of a change of the boundary layer velocity profile caused by the free stream turbulence level.

3. Transition End of Flow in Case of Zero Pressure Gradient

At the transition region end the local skin-friction drag coefficient shows a relative maximum (see Fig. 1) so that its determination is rather easy. However, the free stream turbulence level and the relative length of transition region are the factors to be taken under consideration.

3.1. Influence of Free Stream Turbulence

The external turbulence deforms the boundary layer velocity profile in such a way that displacement and momentum thickness become greater as compared with the external turbulence-free state. In the turbulence level region FE (external excitation region) the momentum thickness factor $1/k_{2t} = 1/0.68$, i.e. 1.47 (see Fig. 2, bottom part). In the turbulence level region ME of mixed excitation, the above factor depends on the turbulence level and in region SE of self-excitation it equals 1 according to the definition, [10]. The corresponding numerical value of displacement thickness in the FE region is $1/0.75 = 1.34$.

3.2. Relative Length of Transition Region

In case of the free stream turbulence level values less than about 4.5% the minimum turbulence level value in the boundary layer preponderates over that of external turbulence. In the case of free stream turbulence levels greater than about 4.5% the relations are inverted, i.e. within the boundary layer the turbulence is smaller than outside. Hence, one can distinguish a state of turbulence energy homogeneity dividing the external excitation turbulence level region of the transition end according to the diagram in Fig. 2 above into two subareas, i.e. the actual region FE in which the Reynolds number of the transition end depends of the free stream turbulence level and the region TE being independent of the turbulence level due to $Re_{UE} = 9.75 \cdot 10^4$ (see Fig. 2). Accordingly, the relative and absolute streamwise transition length relationships were obtained and listed in Table 2.

Table 2

Relative length of the transitional region on the flat plate for zero pressure gradient

Region of	kTu	$(s_{UE}-s_{UA})/s_{UA}$	$Re_{sUE}-Re_{sUA}$
SE self-excitation	$< 0.1\%$	0.374	$1.07 \cdot 10^6$
ME mixed excitation	0.1%...	$8.41(kTu)^{0.262}-1$	
FE external excitation	4.5%		
TE turbulence energy homogeneity	$= 4.5\%$ $> 4.5\%$	2.721 $550.53(kTu)^{1.606}-1$	$0.92 \cdot 10^5$

At the transition end the intermittency factor $\gamma = 0.993$ to 1. For this factor the relationship $\gamma = (\overline{F} - \overline{F}_1)/(\overline{F}_t - \overline{F}_1)$ holds where $\overline{F}$ stands for displacement thickness, momentum thickness, local skin friction coefficient or any other shape parameter of the transitional boundary layer, while the subscripts t and l refer to the turbulence spot region and the ambient laminar flow, respectively. As it is generally known, the intermittency factor γ can be determined from the fluctuation diagrams which are obtained by means of a hot wire probe. According to this, from the experimentally found value of factor γ, the shape parameters of the boundary layer may be determined in the transitional region using the formula $\overline{F} = \gamma(F_t - F_l) + F_l$, with the respective shape parameters $\overline{F}_t$ of the turbulence spots as well as the parameters F_l of the laminarly flowing surrounding found either experimentally or by computation.

4. Turbulence Anisotropy and Pressure Gradient

When discussing the test results in the field of cnaracteristics demonstrating the laminar/turbulent transition in case of zero pressure gradient (Fig. 2 above) attention should be paid to external turbulence anisotropy and pressure gradient. In most experimental cases neither turbulence isotropy nor flowing states with zero pressure gradient prevail so that the measuring values must be adjusted to be able to make sufficiently exact statements of the transition region beginning and end in the case of zero pressure gradient.

4.1. Turbulence Anisotropy

The transition field of characteristics shown in Fig. 2 above is taken from measurement results obtained on the flat plate with zero pressure gradient and from considerations of similarity theory under assumption of, strictly speaking, only isotropic free stream turbulence (produced by screens). In case of external turbulence not excessively anisotropic, i.e. nearly isotropic, this field of characteristics may, however, also be applied if the product of turbulence energy level Tu and an anisotropy factor k is used as an independent quantity instead of the turbulence level which only regards the longitudinal fluctuation component [9]. Although this product corresponds formally to the usual turbulence level, i.e. that which is formed only by means of the longitudinal fluctuation component, the factor k gives a practicable measure of accuracy which must be reckoned with if this transition field of characteristics is applied to anisotropic external turbulence.

4.2. Pressure Gradient

As a similarity number describing the pressure force to viscous force ratio within the fluid, the Hagen number $Ha_{\delta 2}$ introduced in 1961 by W. Albring must be taken. Relatively reliable measurement results concerning this Hagen number influence may be obtained for the region SE of the low-turbulence free stream (see Fig. 2 bottom left). As a dependent quantity one can use the ratio of the logarithms of the momentum thickness Reynolds number of the flow without zero pressure gradient to that in the flow state with zero pressure gradient (see Appendix 3).

Furthermore, the relevant test results suggest that in the TE region in which the turbulence of the boundary layer is less than that of the free stream, the pressure gradient is of no influence. In case of the equivalent level $kTu = 4.5\%$ the field of characteristics of the exponent c shows a pole. The asymptotes of the $Ha_{\delta 2} = \text{const}$ lines in this pole and those in the SE region intersect each other approximately at the boundary of the turbulence level regions ME and FE, i.e. in case of an equivalent turbulence level of about $kTu = 1\%$. The field of characteristics shown in Fig. 2 was plotted on the basis of measurement results corresponding to the intermittency factor $\gamma = 5\%$ (index S) [10], i.e. according to Fig. 1 this field is approximately true to the transition region centre. With increasing intermittency factor the expression $(c-1)$ becomes smaller. At the transition and the exponent c is less than c_S by about a power of ten so that by way of approximation the relative difference may be set $(c-c_{\mathrm{UA}})/(c_{\mathrm{UE}}-c_{\mathrm{UA}}) = \gamma$ with $c_{\mathrm{UE}} \approx 1$ (see Appendix 3).

5. Verification by Means of the Sample Technique

For reliability tests of the characteristic transition inception line shown in Fig. 2 measurement results of R. Herbst [13] were taken. The results have been obtained from the flat plate experiments by means of the sample technique independently of the tests made by R. Rössler [21, 22] (Fig. 1 below). In this connection it should be stated that two different methods are applied: on the one hand the sample method, in which certain time periods are taken from the hot wire probe fluctuation diagram for evaluation purposes, and on the other hand the soot-oil-petroleum erosion method. These two methods are used to find the transition inception point UA for intermittency factor values of $\gamma < 0.1\%$, which in contrast to former results obtained by other measurement and evaluation methods, are a good proof of their precision. In this respect compare the VITA (variable-interval-time-averaging) technique to R. F. Blackwelder and R. E. Kaplan [3]. In order to simulate the unsteady flow conditions at the cascade inlet in multi-stage flow machines R. Herbst generated, by means of a spoked roll, an unsteady flow upstream of the flat plate with different pressure gradients (the angles of incidence ranging between -2° and -10°) so that accelerated transitional boundary layers formed. In our case the wakes behind the 90 spokes of the fluctuation generator have already grown together at the transition start so that there was a continuous turbulence field in the free stream.

The Hagen number varied from $Ha_{\delta 2} = 0.01$ to 0.03, the momentum thickness Reynolds number at the transtion inception point — between $Re_{\delta 2}$ $(Ha_{\delta 2}) = 110$ and 150 while the free stream turbulence level was $Tu_s = 3$ to 4% (see Appendix 1). This turbulence level $Tu_s = \sqrt{u'^2}/u_\delta$ covers only the fluctuation velocity u' which seems to vary irregularly.

After revaluation, the momentum thickness Reynolds number $Re_{\delta 2}(0)$ corresponding to the flow state with zero pressure gradient ranges between 107 and 140 according to the field of characteristics shown in Fig. 2 and the free stream turbulence levels $Tu_s(0)$ amounting between 5.8% and 4.1%. In the field of characteristics the three values determined in this way nearly lie on an isoline of the constant intermittency factor which on its part is very small. By means of the sample technique it is not possible to find the transition inception point UA with the intermittency factor equal exactly zero, but obviously it is possible if the γ value is rather small.

Although the external turbulence, according to A. C. Ginevski et al. [15], tends to show isotropy already after a shorter streamwise length behind non-stationary cylindrical bars than in the case of the same bars in a stationary state, an eventual turbulence anisotropy at the transition start should not be excluded (see [9] and Appendix 2).

6. Conclusions and Prospects

As a result of the above investigations the following conclusions may be drawn:

1. Due to the dependence of the momentum thickness Reynolds number and the Hagen number on the turbulence level and the intermittency factor according to

Fig. 2, the dependence of the skin-friction drag coefficient on the streamwise length Reynolds number may be computed in a sufficiently exact way for any turbulence level courses.

2. The transition fields of characteristics shown in Fig. 2 apply to isotropic and nearly isotropic free stream turbulence.

3. Both anisotropic turbulence in a steady free stream and that in an inermittent--unsteady free stream can be considered a nearly isotropic turbulence so far there exists a coherent turbulence field.

4. The anisotropy factor k is suitable as a measure of nearly isotropic turbulence.

5. In case of distinct anisotropic free stream turbulence, anisotropy ratios in each of the three coordinate directions (see [16]) must be introduced as independent quantities instead of the anisotropy factor k.

6. In case of an intermittent non-stationary free stream, the relative amplitude of velocity change Δu_δ and the Strouhal number of periodically arranged wakes must be introduced as further influential parameters. According to [20] one can distinguish a critical value of the $(\Delta u_\delta u_\delta)/(\omega \nu)$ similarity number below which no relationship of such a kind exists and turbulent spots are formed in an aperiodic way. Above this number turbulence spots are formed periodically with the free stream frequency; but the Reynolds number Re_{sUA} corresponding to the transition inception is not dependent on velocity change $\Delta u_\delta/\bar{u}_\delta$.

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Appendix 1

Revaluation of field data of transition characteristics with regard to pressure gradient

The data on transition inception on a flat plate with different pressure gradient given by R. Herbst [13] are stated in the columns 1 and 2 of Table 3. For a revaluation required to get a flow state with zero pressure gradient four equations shown in this table are taken. Equation (4) is true only in the

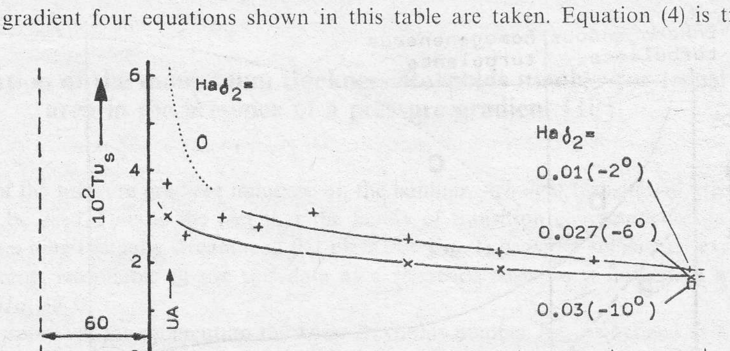

Fig. 3. Turbulence level above the flat plate with pressure gradient behind a fluctuation generator T in the form of a wheel with pitch diameter 0.6 m and 90 nylon strings of 2 m diameter arranged according to R. Herbst (rotational frequency: 400 min^{-1}); LE — leading edge of the plate. Hagen number is used as a parameter while the number in parantheses denotes the angle of incidence

Table 3

Revaluation of transition inception data obtained by R. Herbst in case of accelerated flow ($Ha_{\delta 2} > 0$) onto the zero pressure gradient conditions ($Ha_{\delta 2} = 0$)

$\lambda = Ha_{\delta 2}$	$Re_{\delta 2}$	c_S	c_{UA}	$Re_{\delta 2}(0)$	$10^{-4} Re_s$	$10^2 Tu_s$	$10^2 kTu(0)$
1	2	3	4	5	6	7	8
0.01	110	1.005	1.005	107	1.734	4.1	5.8
0.027	130	1.012	1.013	122	2.252		4.6
0.03	150	1.013	1.014	140	2.957	3.0	4.1

(1) $c_{UA} = 1.05(c_S - 0.05 c_S^{-1})$; (2) $c = \lg Re_{\delta 2}(Ha_{\delta 2}) / \lg Re_{\delta 2}(0)$;

(3) $Re_{\delta 2} = 0.66412\sqrt{Re_s}$; (4) $Re_{sUA}\Big|_{FE,\ TE} = 177.1(kTu)^{-1.606}$

region of externally excited turbulence. The free stream turbulence level values obtained for the flow state of zero pressure gradient (O) listed in column 8 of Table 3 are taken to plot the dotted line in Fig. 3. This line is expected to be the proper extrapolation of the measured values of R. Herbst.

Appendix 2

The anisotropy factor k behind non-stationary and stationary cylindrical bar cascade

The change of turbulence level and anisotropy factor k in the wake depends substantially on the kind of the turbulence generator. Generally, the turbulence level can be approximated by the equation $Tu_s = k_1 (s/t)_T^{-k_2}$. In case of cylindrical bar cascades two characteristic values of the relative streamwise length $(s/t)_T$ marked by (H) and (I) in Fig. 4 — can be distinguished. The values given in Table 4 represent the validity ranges of k_1 and k_2 coefficients. According to F. Klatt [16] the point H of the individual stationary cylindrical bar cascade separates the region of inhomogeneous turbulence from that of homogeneous turbulence. Behind the non-stationary cylindrical bar chain the region of apparently isotropic turbulence $k = 1$ begins at point H according to measurements made by A. S. Ginevskij et al. [5].

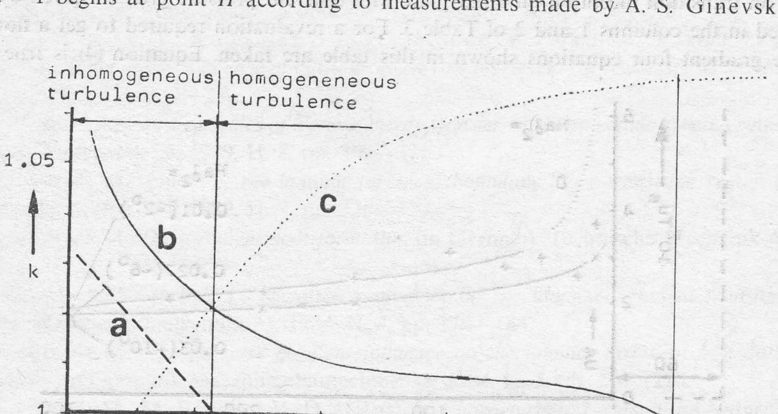

Fig. 4. Correlation between anisotropy factor k and relative streamwise length behind the turbulence generator being: a) a non-stationary cylindrical bar chain, b) a stationary cylindrical bar chain consisting of 2 stationary cylindrical bar screens, c) individual stationary cylindrical bar cascades

Table 4

Correlation between turbulence level and relative streamwise length as measured downstream of the turbulence generator (*T*) representing non-stationary and stationary cylindrical bar chains, the screen and the individual cylindrical bar screen

Flow system	Relative streamwise length range	k_1	k_2	According to the measurement results obtained by
Non-stationary cylindrical bar chain	$3 < (s/t)_T \leq 24$ $24 \leq (s/t)_T$	0.269 0.150	0.240 0.075	A. S. Ginevskij et al. [5]
Stationary chain (2 cylindrical bar screens situated one after another)	$3 < (s/t)_T \leq 48$	0.232	0.642	A. S. Ginevskij et al. [5]
Screen		0.3	0.63	A. S. Ginevskij et al. [5]
Cylindrical bar screen	$5.7 < ((s/t)_T + 0.9)$	0.42	0.71	F. Klatt [16]

In case of a stationary cylindrical bar chain, i. e. if 2 stationary cylindrical bar cascades are arranged one after another, an anisotropic turbulence can be observed up to the point (*I*) at which a changed regularity of the turbulence level relationship may be observed behind the non-stationary cylindrical bar chain. As regards the exponent k_2, the non-stationary cylindrical bar chains differ substantially from the stationary cylindrical bar chain, the screen and the individual stationary cylindrical bar cascade. In the latter case, however, the anisotropy factor *k* increases degressively with the streamwise length (Fig. 4). As far as inflow conditions in flow machines are concerned the cylindrical bar chain device described by W. H. Gibson [4] is representative. Here the object to be studied is exposed to turbulence behind a single non-stationary cylindrical bar cascade so that thinkable interference phenomena of the wakes behind two cylindrical bar cascades moving anti-clockwise are excluded. The spoked wheel used by R. Herbst [13] will presumably approach turbulent conditions of the individual non-stationary cylindrical bar cascade, but it does not exclude, nevertheless, the existence of interference phenomena of low intensity so that here an external turbulence anisotropy up to the point (*I*) of Fig. 4 should be regarded possible.

Appendix 3

Standardization of the momentum thickness Reynolds number for transitional area in the presence of a pressure gradient [10]

For detection of the pressure gradient influence on the laminar/turbulent transitional area the Hagen number $Ha_{\delta 2}$ can be used. Due to the fact that the family of transition characteristics describing the boundary layer on a longitudinally streamlined flat plate (see Fig. 1) provides sufficiently exact information material, it seems reasonable to use this data as a reference basis for a flow state without zero pressure gradient $Ha_{\delta 2} \neq 0$.

Following this approach the momentum thickness Reynolds number $Re_{\delta 2}$ is defined as a multiple of that corresponding to the flow state with zero pressure gradient, that is:

$$K_{Ha} = \frac{Re_{\delta 2}(Ha_{\delta 2})}{Re_{\delta 2}(0)} \quad \text{or} \quad c = \frac{\lg Re_{\delta 2}(Ha_{\delta 2})}{\lg Re_{\delta 2}(0)} \tag{1}$$

Due to the fact that the measurement results available have been obtained by means of hot wire anemometry with an intermittency factor of $\gamma = 5\%$, they are marked with the subscript *S*, i.e.

$$C_s = 1 + 1.01(C_{SI} - 1)\,\mathrm{th}\,\frac{\lg(kTu) + 1.3516}{\Delta_{III}} \tag{2}$$

with a special relation for the turbulence level area $I = SE$ (Fig. 2):

$$C_{SI} = 1 + 1.5113\,Ha_{\delta 2} + 2.875\,Ha_{\delta 2}^2 \tag{3}$$

and another relation for the turbulence level area $\mathrm{III} = FE$ (Fig. 2):

$$\Delta_{III} = (C_{SI} - 4.6854)0.5358 + 1.3516. \tag{4}$$

The correlation between the quantities c of equation (1) and C_S of equation (2) is given by the approximate relation [11]:

$$C \approx \gamma(1 - C_S) + C_S. \tag{5}$$

Charakterystyki warstwy przyściennej w strefie turbulizacji

Streszczenie

Celem wystarczająco dokładnego zbadania przejścia laminarno-turbulentnego wyznaczonego metodą warstwy przyściennej, wyniki teoretyczne dotyczące pojawiania się turbulencji porównano z danymi doświadczalnymi, uzyskanymi techniką usuwania sadzy na płaskiej płytce oraz z różnymi innymi wynikami uzyskanymi przez pomiar lokalnego przekazu ciepła i zastosowanie anemometru z gorącym drutem. Co więcej, opracowano eksperymentalnie uzasadnioną koncepcję modelu wyjaśniającego formowanie się i rozwój obszarów turbulencji w ulegającej turbulizacji warstwie przyściennej. W wyniku tych badań uzyskano charakterystyczne związki między liniową miarą straty pędu, liczbą Reynoldsa i poziomem turbulencji w strudze swobodnej ze współczynnikiem przejścia jako parametr płaskiej płytki opływanej bez gradientu ciśnienia. Ustalono również przebieg charakterystyk wskazujących na wpływ gradientu ciśnienia na turbulizację. Wiarygodność uzyskanych pól charakterystyk może być zweryfikowana doświadczalnie, stosując metodę próbkowania.

Характеристики пограничного слоя в зоне турбулизации

Резюме

Целью достаточно точного изучения ламинарно-турбулентного перехода, определённого методом пограничного слоя, теоретические результаты относящиеся к появлению турбуленции сравниваются с экспериментальными данными, полученными техникой устранения сажи на плоской пластинке, а также с различными другими результатами достигнутыми путём измерения местной теплопередачи и применения анемометра с горячей проволокой. Что больше, разработана, экспериментально обоснованная идея модели выясняющей формирования и развитие турбулентных зон в подвергающемся турбулизации пограничном слое. В результате этих исследований получены характеристические зависимости между линейной мерой потери импульса, числом Рейнольдса и уровнем турбуленции в свободной струе с коэффициентом перехода в качестве параметра плоской пластинки обтекаемой без градиента давления. Определён также ход характеристик указывающих на влияние градиента давления на турбулизацию. Достоверность полученных полей характеристик может быть проверена экспериментально, пользуясь методом дискретизации.