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# Thermal boundary layer development in transonic and/or separated turbulent flows past surfaces

L. M. ZYSINA-MOLOZHEN, L. S. PETUKHOV and A. A. MALKOV
Polzunov Scientific–Industrial Association for the Research and Development of Power Engineering Equipment, Leningrad, U.S.S.R.

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**Abstract**—Results are presented from an experimental investigation of the boundary layer development and of local heat transfer coefficients on the surface of a blade in transonic and separated flow over blade cascades with different degrees of turbulence. The influence of the longitudinal pressure gradient and of the free-stream turbulence on the boundary layer development for two typical blade cascades is shown. Shadowgraphs and distributions of local heat transfer coefficients and of density gradient fluctuations along the contour of a blade in these cascades are analysed. It is shown that, just like in non-separated flow, the influence of the initial flow turbulence on heat transfer in the separation zone depends on the mode of flow in a boundary layer. In the zone of transonic flow the enhancement of heat transfer is observed only in the case of boundary layer separation due to its interaction with shock waves.

## INTRODUCTION

THE SOLUTION of a wide variety of practical problems of flows with local transonic and separated zones requires the calculation of boundary layers that develop in curvilinear channels. In particular, such problems are encountered in variable-power turbines and during the start-up and stoppage of turbines. Few publications available in the existing literature on these flows show that local variations in heat transfer coefficients in the separation zone can evoke local superheating or supercooling of metal over the blade cross-section and exert considerable influence on the temperature and stress states of the blade that govern the reliable operation of a turbine. The nonuniformity in the distribution of local heat transfer coefficients along the blade contour is aggravated in those cases when the flow in a cascade becomes transonic. Up to the present time, the complex character of transonic and separated flows in a blade cascade has precluded the development of the method for calculating local heat transfer under these conditions. In order to understand the mechanism of heat transfer in such flows, which is a prerequisite for developing the theoretical method of calculation, it is very important that systematic experimental data be accumulated.

This paper reports some results of a computational–experimental investigation of local heat transfer in the separation zone in sub- and transonic flows along cascades of nozzle blades and blades of a variable-power turbine characterized by varying Mach number $M$ and angle $\beta_i$. A great number of blade cascades with such flow patterns have been investigated at the Polzunov Boiler and Turbine Institute.

## EXPERIMENTAL RESULTS

The experiments were carried out on an optical rig at the Physics and Technology Department of the Polzunov Institute. Different blade cascades were investigated in sub- and transonic flows at different incidence angles and turbulence intensities. The flow pattern and the boundary layer structure were observed visually with the aid of an IAB-451 shadowgraph. The flow density gradient fluctuations along the blade contour and at the cascade inlet were measured using shadow photography with photoelectric recording of signals. The method being non-contact allowed measurements to be carried out directly in the zones of separated and transonic flows. In thermal experiments the local heat transfer coefficients were measured along the blade contour. The experimental procedure, instrumentation and the rigs are described in refs. [1, 2] and therefore will not be repeated here.

In earlier experiments on subsonic non-separated flows over blade cascades it was found (see e.g. ref. [3]) that, depending on the mode of boundary layer flow on the blade surface, the free-stream turbulence can exert a different effect on the local heat transfer coefficients—it is very pronounced in a laminar boundary layer and virtually not manifested in a turbulent one when $\varepsilon \leqslant 9\%$. For the laminar boundary layer the flow correlations were obtained yielding a relative change in the local values of Nusselt numbers $Nu_x$ with variation of $\varepsilon$ [3].

Based on the analysis of experimental data, pertaining to separated transonic flows, and their comparison with predictions, some general estimates were obtained and the semi-empirical method of cal-

## NOMENCLATURE

$a_*$ speed of sound in the critical cross-section [m s$^{-1}$]
$L$ blade contour perimeter [m]
$\bar{S}$ relative coordinate along blade contour, $S/L$.

Greek symbols
$\varepsilon$ flow turbulence level (%), $100\sqrt{((u')^2)}/u$
$\lambda$ relative stream velocity at boundary layer outlet, $u/a_*$.

Subscripts
$x$ variable value along blade profile
1 value at cascade inlet
2 value at cascade outlet.

culating local heat transfer coefficients along the blade contour was refined, thus allowing approximate calculations of heat transfer also in the separated region [4].

Two examples are given below that show specific features of boundary layer development under the above-mentioned conditions.

### *Example 1*

Figure 1 shows the distribution of heat transfer coefficients along the blade contour of one of the blade cascades investigated at the exit Mach numbers $M_2 \cong 0.603$ (Fig. 1(a)) and $M_2 \cong 0.845$ (Fig. 1(b)) and turbulence levels $\varepsilon = 0.3$, 3.5, and 8%. The distribution of the relative velocity $\lambda_x$ is presented schematically in the right-hand inset at the bottom of the figure. It is seen that the characteristic feature of this velocity diagram is a smooth, predominantly confusor-like, distribution of $\lambda_x$ along the suction face of the blade (the left-hand side of the figure), a sharp velocity peak at the leading edge on the pressure face (the right-hand side of the figure) followed by an abrupt decrease in the velocity, which then, at $\bar{S} \approx 0.70$, is replaced by a confusor-like flow. As can be seen from the shadowgraphs presented in Figs. 2 and 3, this distribution of velocities leads to a smooth flow along the suction face and to boundary layer separation starting almost from the leading edge on the pressure face with subsequent reattachment at $\bar{S} \approx 0.80$–$0.85$.

When $M_2 \approx 0.845$, a series of shock waves originate at the trailing edge on the suction side that pulsate along the blade surface not causing boundary layer separation. A relative change in the normal, $\bar{U}$ (Fig. 4(a)), and tangential, $\bar{V}$ (Fig. 4(b)), components of the density gradient fluctuation intensity along the blade contour corresponds quite well to the shadowgraph pattern. When $M_2 \approx 0.603$ (solid line), there are low values of $\bar{U}$ and $\bar{V}$ which are close to those in the free stream; on the pressure face (the right-hand side of Fig. 4) the values of $\bar{U}$ and $\bar{V}$ increase in the separation region up to the point of flow reattachment ($\bar{S} \approx 0.80$–$0.85$) where almost a five-fold increase in the fluctuation intensity is observed. After the reattachment, the intensity of oscillations in the boundary layer gradually decreases. When $M_2 \approx 0.845$, the character of the distribution of $\bar{U}(\bar{S})$ is preserved, whereas the pattern of the change in $\bar{V}(\bar{S})$ is disturbed: there is a sharp increase in $\bar{V}$ on the suction side in the region of the trailing edge, which appears to be due to shock wave longitudinal fluctuations visible on the shadow-

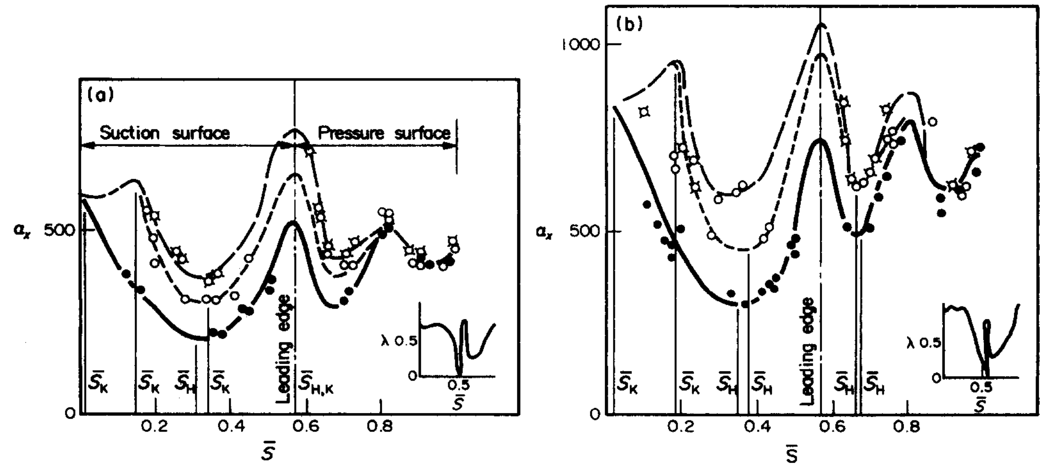

FIG. 1. Distribution of heat transfer along the blade surface in cascade No. 1: (a) $M_2 = 0.639$; (b) $M_2 = 0.849$. ———, calculated [4], ● experimental ($\varepsilon \approx 0.3\%$); ----, calculated [4], ○ experimental ($\varepsilon \approx 3.5\%$); — — —, calculated [4], ¤ experimental ($\varepsilon \approx 8\%$).

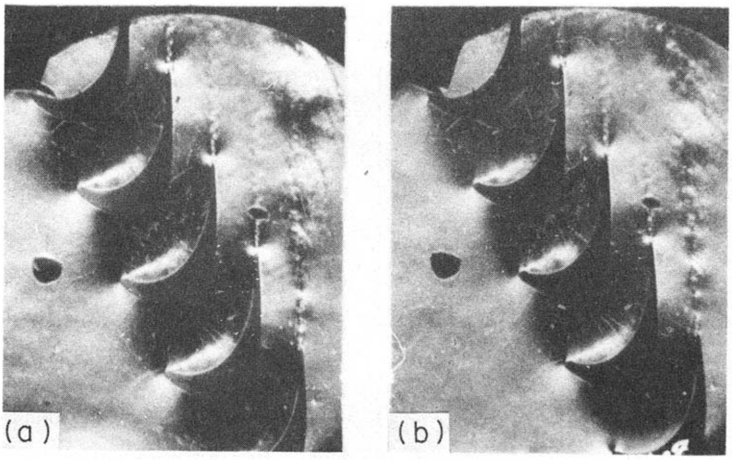

FIG. 2. Shadowgraphs for cascade No. 1 ($M_2 = 0.63$). (a) $\varepsilon \approx 1.0\%$; (b) $\varepsilon \approx 3.2\%$.

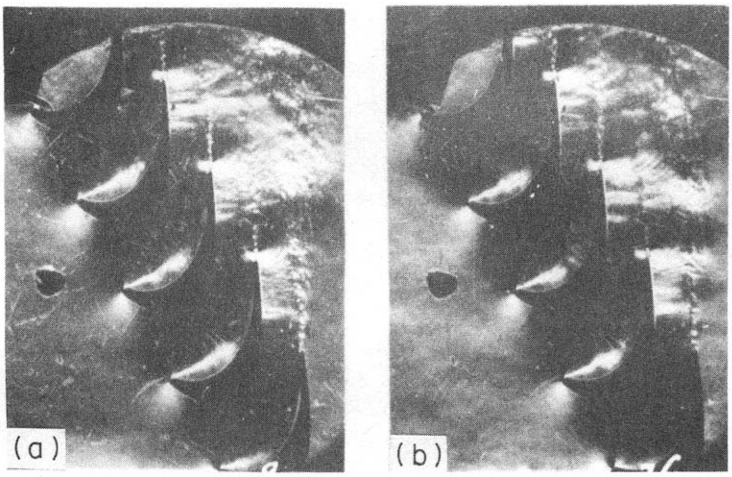

FIG. 3. Shadowgraphs for cascade No. 1 ($M_2 = 0.845$). (a) $\varepsilon \approx 0.5\%$; (b) $\varepsilon \approx 4.0\%$.

graph. This phenomenon does not influence the value of $\bar{U}$.

The curves $\alpha_x(\bar{S})$, given in Fig. 1 for this blade cascade, reveal that their behaviour is in accord with the available physical concepts regarding the character of blade cascade flow. When $M_2 \approx 0.603$ (Fig. 1(a)), a distinct influence of $\varepsilon$ on $\alpha_x$ can be seen on the suction side in the region of laminar and transitional boundary layer flows. For laminar boundary layer flows this effect checks well with correlations suggested in ref. [3] and employed in ref. [4]. It is also consistent with the recommendations of ref. [4] for transitional and turbulent boundary layer flows.

An analogous result was also obtained for $M_2 = 0.845$, i.e. shock waves at the trailing edge and their longitudinal fluctuations did not influence $\alpha_x$. This result is not surprising, since it is known from a number of publications (e.g. ref. [5]) that the correlation between the transverse velocity and temperature fluctuations ($v^\circ T^\circ$) do influence the heat transfer rate.

On the pressure side, where at $\varepsilon = 0.5\%$, the separation of the laminar and, at higher values of $\varepsilon$, of the transitional boundary layer takes place, the influence of $\varepsilon$ becomes imperceptible only in the vicinity of the reattachment point where the boundary layer develops into a turbulent one.

In the separation region the values of $\alpha_x$ increase (see Fig. 1), with the maximum increase (by about a factor of 1.5–2) being attained in the reattachment region. With the development of a turbulent flow in the reattached boundary layer, the values of $\alpha_x$ decrease and approach those typical of a non-separated turbulent flow. In Fig. 1 the experimental data are shown by different symbols, the results calculated according to ref. [4] are presented by lines. There is a satisfactory coincidence for the separated and non-separated flows.

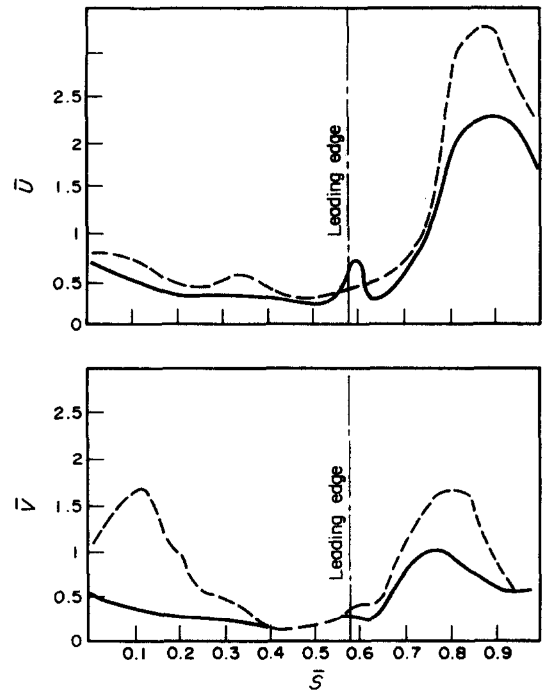

FIG. 4. Distribution of the fluctuation intensity along the blade surface for $\varepsilon \approx 1\%$. ———, $M_2 = 0.603$; — — —, $M_2 = 0.845$: (a) transverse component; (b) longitudinal component.

*Example 2*

Figure 5 presents the distribution of $\alpha_x$ along the blade surface of another type of blade cascade the flow along which (as seen from the velocity diagram in the right-hand inset at the bottom of the figure) is characterized on the suction side by the presence of the convergent flow segment at the inlet followed by almost a non-gradient flow in the interblade passage and at the trailng side. When $M_2 \approx 0.845$, a local transonic region with $\lambda_x \approx 1.05$–$1.10$ develops over this length. At $M_2 \approx 0.60$ and 0.845 a steep velocity peak is observed on the pressure side in the region of the leading edge followed by almost a non-gradient flow. The shadowgraphs presented in Figs. 6 and 7 show that this distribution of velocities results in boundary layer separation on the pressure side near the leading edge of the blade, with separation developing downstream without subsequent boundary layer reattachment. When $M_2 \approx 0.60$, the flow along the suction face is smooth and separationless. As can be seen from Fig. 5(a) at $M_2 \approx 0.60$ the experimental values of $\alpha_x$ (points) correspond satisfactorily to those calculated according to ref. [4] (lines) in both the non-separated and separated flow regions. In laminar and transitional boundary layer flows a distinct splitting of experimental data is observed that corresponds to different values of $\varepsilon$; for a developed turbulent boundary layer flow all the experimental points for different values of $\varepsilon$ cluster around a single line. This trend is characteristic for both the non-separated (left-hand side of Fig. 5) and separated (right-hand side of Fig. 5) flow regions. Comparison of Figs. 6(a) and (b) shows that the character of blade cascade flow does not change with variation of the free-stream turbulence.

When $M_2 \approx 0.80$, the pattern of blade cascade flow alters: a series of $\lambda$-shaped shock waves appear on the suction surface in the region of $\lambda_x \geqslant 1$ (when $\bar{S} < 0.3$) that interact with the suction side boundary layer and cause its separation which develops downstream. As is seen from the shadowgraphs of Fig. 7, in the second half of the interblade passage there is a complex interaction between the shock waves and separated bound-

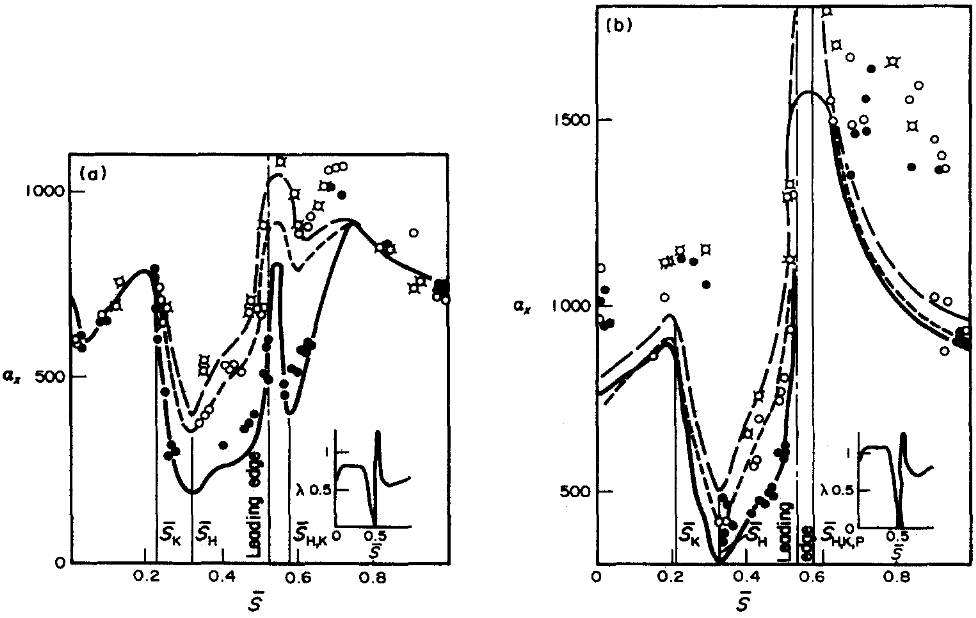

FIG. 5. Distribution of heat transfer coefficients along the blade surface for cascade No. 2: (a) $M_2 = 0.639$; (b) $M_2 = 0.849$. Notation is the same as in Fig. 1.

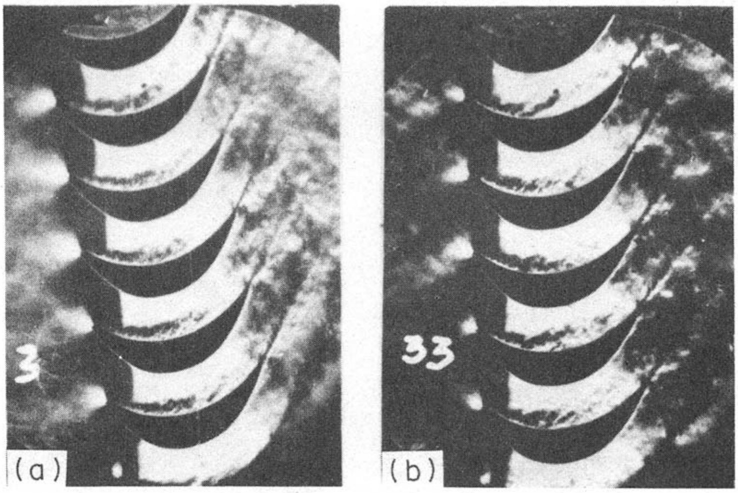

FIG. 6. Shadowgraphs for cascade No. 2 at $M_2 \approx 0.6$: (a) $\varepsilon \approx 0.5\%$; (b) $\varepsilon \approx 8\%$.

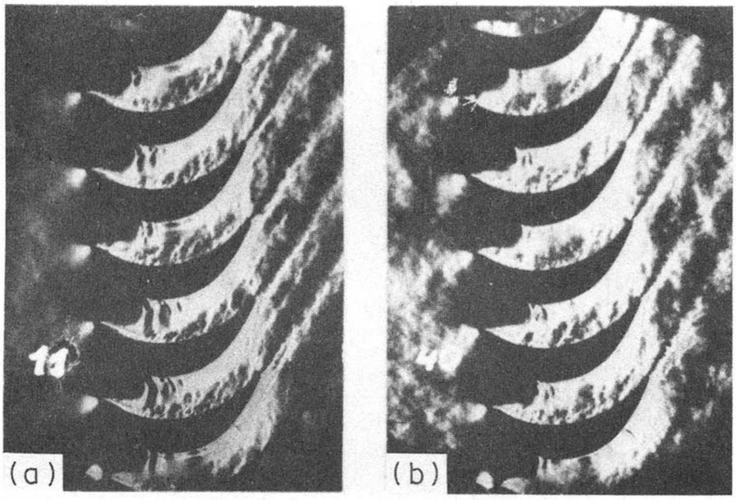

FIG. 7. Shadowgraphs for cascade No. 2 at $M_2 \approx 0.80$: (a) $\varepsilon \approx 0.5\%$; (b) $\varepsilon \approx 9\%$.

ary layers on the suction and pressure sides. To this complex flow pattern there corresponds a substantial increase in the heat transfer rate, the experimental values of $\alpha_x$ become unstable and begin to exceed the results calculated according to ref. [4], being quite natural since the computational method for a plane flow cannot incorporate the interaction of the separated boundary layers. Comparison of Figs. 7(a) and (b) shows that in this case the flow pattern does not change with variation of the free-stream turbulence. The values of $\alpha_x$, while being very unstable in this region, virtually coincide for all the values of $\varepsilon$ investigated. Measurements indicate that to this flow region there corresponds a considerable (nearly 7–10-fold) increase in the intensity of pressure gradient fluctuations.

## CONCLUSIONS

Analysis and generalization of the results pertaining to flows over blade cascades of the aforegoing and other types allowed the following conclusions to be drawn.

(1) Depending on the velocity distribution along the blade contour in a cascade and on the free-stream turbulence level, the boundary layer separated from the blade surface can either reattach or develop downstream without reattachment. The reattached boundary layer is always turbulent and has higher intensity of fluctuations. In the separation zone the heat transfer coefficients $\alpha_x$ exceed the corresponding values for the non-separated flow. The maximum enhancement of heat transfer and growth of the fluctuation intensity

occur in the zone of boundary layer reattachment.

(2) In the separation zone, just as in the case of non-separated flow, the free-stream turbulence effect on heat transfer depends on the mode of flow in the boundary layer. It is the greatest in laminar flow and virtually imperceptible in the turbulent mode of flow. In the transitional boundary layer there is a varying effect: from an appreciable effect at the beginning of the zone to a vanishing effect at the end. This trend is also typical of the intensity of pressure gradient fluctuations in the wall portion of the boundary layer.

(3) In the region of transonic flows, an increase in heat transfer occurs on boundary layer separation under the action of shock waves. In this case, if a laminar boundary layer is separated, then a change in the free-stream turbulence exerts an influence on the increase in heat transfer by suppressing the separation altogether or delaying it. In the case of turbulent boundary layer separation, the increase in the free-stream turbulence level does not influence either the shock picture of the flow, or the heat transfer enhancement. The increase in the fluctuation intensity in the transonic region is also independent in this case of the external flow turbulence.

(4) With the presence of shock waves in the transonic region which does not cause the separation of a boundary layer, but which pulsate along the blade surface, only an increase in the longitudinal component of the flow density gradient fluctuation intensity takes place without an increase in heat transfer. The pattern of shock waves and fluctuations under these conditions is independent of the free-stream turbulence level.

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## DEVELOPPEMENT DE COUCHE LIMITE THERMIQUE DANS DES ECOULEMENTS TURBULENTS TRANSONIQUES ET/OU SEPARES DERRIERE DES SURFACES

**Résumé**—On présente des résultats expérimentaux sur le développement de couche limite et de coefficient de transfert thermique local sur la surface d'une ailette en écoulement transonique et séparé sur des cascades d'ailettes, avec différents degrés de turbulence. On montre l'influence du gradient longitudinal de pression et de la turbulence de l'écoulement libre sur le développement de couche limite pour deux types de cascades. On analyse des clichés d'ombre et les distributions des coefficients de transfert thermique local et des fluctuations de gradient de densité le long du contour de l'ailette dans ces cascades. On montre que, comme dans l'écoulement non séparé, l'influence de la turbulence de l'écoulement incident sur le transfert de chaleur, dans la zone de séparation, dépend du mode d'écoulement dans une couche limite. Dans la zone transonique, on observe l'accroissement du transfert thermique seulement dans le cas de la séparation de couche limite due à son interaction avec des ondes de choc.

## ENTWICKLUNG DER THERMISCHEN GRENZSCHICHT BEI SCHALLNAHEN UND/ODER ABGELÖSTEN TURBULENTEN STRÖMUNGEN HINTER SCHAUFELN

**Zusammenfassung**—Die Entwicklung der Grenzschicht sowie die örtlichen Wärmeübergangskoeffizienten an der Oberfläche einer Schaufel wurde bei schallnaher abgelöster Strömung in Schaufelgittern bei unterschiedlichen Turbulenzgraden experimentell untersucht. Der Einfluß des Druckgradienten in Strömungsrichtung sowie des Turbulenzgrades der ungestörten Anströmung auf die Entwicklung der Grenzschicht wird für zwei typische Schaufelgitter gezeigt. Schattenaufnahmen sowie die Verteilung des örtlichen Wärmeübergangskoeffizienten und der Schwankungen der Dichtegradienten entlang der Kontur der Schaufel in diesen Gittern wird ausgewertet. Es zeigt sich, daß, wie bei nicht abgelöster Strömung, der Einfluß des anfänglichen Turbulenzgrades auf den Wärmeübergang in der Ablösungszone von der Art der Grenzschichtströmung abhängt. Im Gebiet schallnaher Strömung wird eine Verbesserung des Wärmeübergangskoeffizienten nur im Fall der Grenzschicht-Ablösung beobachtet, was auf ein Zusammenwirken mit Stoßwellen zurückzuführen ist.

# РАЗВИТИЕ ТЕПЛОВОГО ПОГРАНИЧНОГО СЛОЯ В ТУРБУЛЕНТНОМ ПОТОКЕ ПРИ ТРАНСЗВУКОВЫХ И ОТРЫВНЫХ ОБТЕКАНИЯХ ПОВЕРХНОСТЕЙ

**Аннотация**—Приведены результаты исследования развития пограничного слоя и локальных значений коэффициентов теплоотдачи на поверхности профиля при трансзвуковых и отрывных обтеканиях решеток профилей в потоках различной турбулентности. Показано влияние продольного градиента давления и турбулентности набегающего потока на развитие пограничного слоя для двух характерных типов решеток профилей. Анализируются тенеграммы и распределения вдоль контура профиля локальных значений коэффициентов теплоотдачи и пульсаций градиента плотности для этих решеток. Показано, что в зоне отрыва, также как и при безотрывном обтекании, влияние начальной турбулентности потока на теплоотдачу зависит от режима течения в пограничном слое. В зоне трансзвукового обтекания теплоотдача интенсифицируется только в том случае, когда в результате взаимодействия скачков уплотнения с пограничным слоем возникает отрыв последнего.