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HEAT TRANSFER IN THE PRESENCE OF TRANSITION INDUCED BY WAKES OF HESITATING CYLINDER

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Experimental investigations of a flat plate heat transfer in the presence of transition induced by wakes after still and hesitating cylinder were carried out. Analysis of distributions of local heat transfer coefficients, temperature and velocity profiles, their fluctuations and other characteristics of boundary layers permits to determine the length of wake-induced transition and its location. On the basis of study of wakes characteristics in the free-stream the reason of heat transfer intensification in pre-transitional boundary layer was determined. Under influence of periodic unsteady wakes transition region shits upstream in comparison with the case of steady wake.

Keywords: *heat transfer, laminar-turbulent transition, wakes, hesitating cylinder, dynamic and thermal boundary layers*

Introduction

Unsteady flows after moving and still obstructions are widely spread in various technical applications such as turbomachinery, thermal power installations, and internal flow in technological equipment. Unsteady flow initiates special type of laminar-turbulent boundary layer transition: wake-induced transition. Successful prediction of transition induced by wakes would help in designing efficient equipment. It concerns first of all gas turbine engines. The aerodynamic performance of turbines is dependent on the nature of boundary layer development on the blades. It is known that a considerable area of the blade surface can be covered by transitional boundary layer (BL). This is especially true at the low Reynolds numbers typical for the low-pressure stages in gas turbines. The blade boundary layers are subjected to a combination of variables including free-stream turbulence, pressure gradient, unsteady periodic wakes of the upstream blade rows. These conditions have a significant influence on the BL transition process.

During the last years many researchers experimentally and theoretically investigated the effect of unsteady wakes on the characteristics of thermal and dynamic BL transition. The unsteady wake exhibits mean velocity defect with a high level of turbulence intensity. Just the last is primarily responsible for transition under the influence of periodic unsteady wakes [1, 2]. So such transition has common features with bypass transition at Tu >0 as noted in [3].

The present investigation focuses on the effect of periodic unsteady wakes on heat transfer and internal structure of the thermal and dynamic boundary layers in the presence of laminar-turbulent transition. In order to study the influence of periodic instability experimental investigation with still cylinder situated on the distance from the plate equal to the amplitude of hesitating cylinder was conducted.

1. Experimental technique

The experiments were carried out at velocity 9 m/s in a wind tunnel T-5 of IET NASU with working section 120x120x800 mm. A heated flat plate (2) was mounted in working section (3) asymmetrically at h =90 mm from top wall (Fig.1). For generating periodic unsteady wakes single hesitating at f =4.4 Hz cylinder (1) d =3 mm was located upstream of the plate at x =-15 mm. The amplitude of cylinder motion was 20 mm from the axis of the leading edge of the plate. Steady wake was produced by the same still cylinder which is situated also at x=-15 mm and y_c=20 mm.

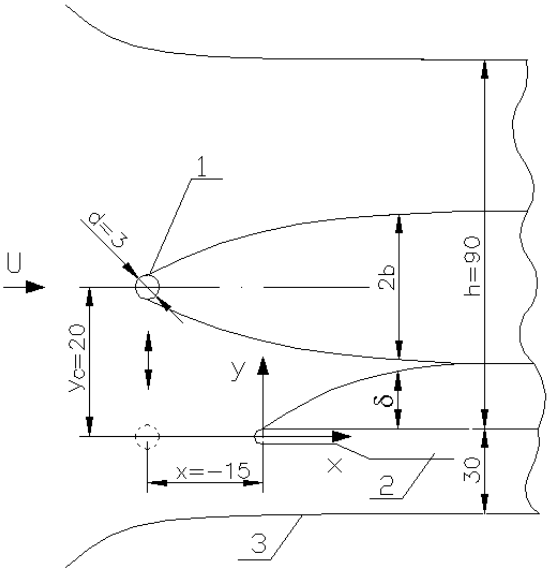


Fig. 1. Sketch of the experimental installation

Heat transfer was explored by electrocalorimetry. The parameters of the internal structure of the dynamic and thermal boundary layers and external flow were measured by DISA-55M hot-wire system with 5μ and 1μ probes. It is necessary to remark that in periodically disturbed flow total turbulence intensity was measured including periodic and turbulent fluctuating components.

2. RESULTS AND DISCUSSION

Heat transfer

For estimating the influence of the wakes on the characteristics of the thermal transition the results of heat transfer investigation without cylinder with natural transition at Tu=0.2-0.4% were used (Fig.2, symbol 3). In case of steady wake generation after still cylinder (Fig.2, symbol 4) the distribution of local heat transfer coefficients along the plate is changed: the start of wake-induced transition is shifted upstream relatively natural transition which occurred without wakes and heat transfer in the pre-transition boundary layer is increased.

In the presence of hesitating cylinder (Fig.2, symbol 5) the distribution $St = f(\mathrm{Re}_x)$ became smoother than in previous case but remained non-monotone. Intensification of heat transfer in the pre-transition boundary layer in cases of steady and periodic wakes was correspondingly ~20% and 38% at $\mathrm{Re}_x = 4 \cdot 10^4$ relatively laminar boundary layer (Fig.2, line 1).

The increase of heat transfer in the pre-transition boundary layer allows one to treat the latter as an analog of the pseudolaminar boundary layer [4]. The reason of pseudolaminar boundary layer origin consists in the presence of elevated free-stream turbulence. As shown in [5] under influence of other moving obstructions organised by still and rotating “squirrel cage” the distribution of local heat transfer coefficients along the plate is also changed relatively natural transition: the start of wake-induced transition is shifted upstream which occurred without wakes and heat transfer in the pre-transition boundary layer is also increased. But after still and rotating “squirrel cage” the distribution $St = f(\mathrm{Re}_x)$ became monotone and approach to the turbulent BL from “above”. In this case the existence of wake-induced laminar-turbulent transition of upper type is confirmed.

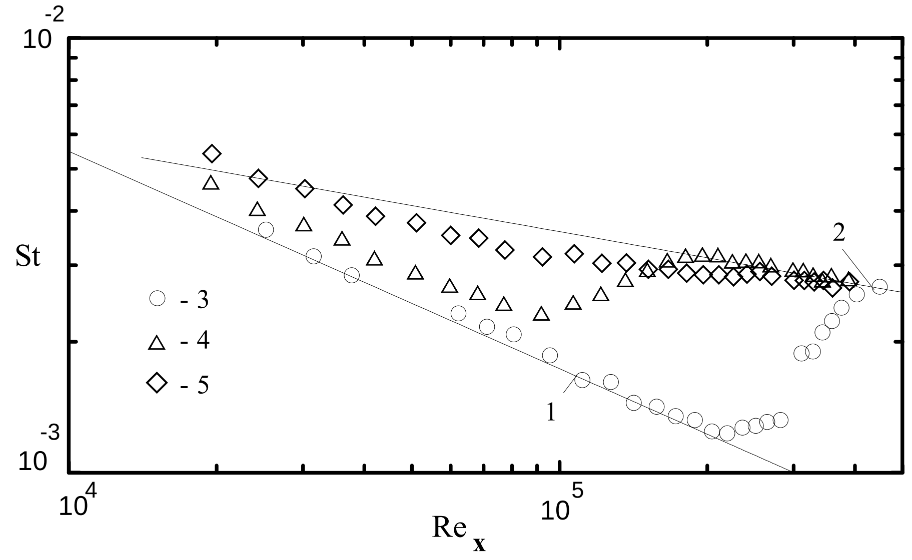
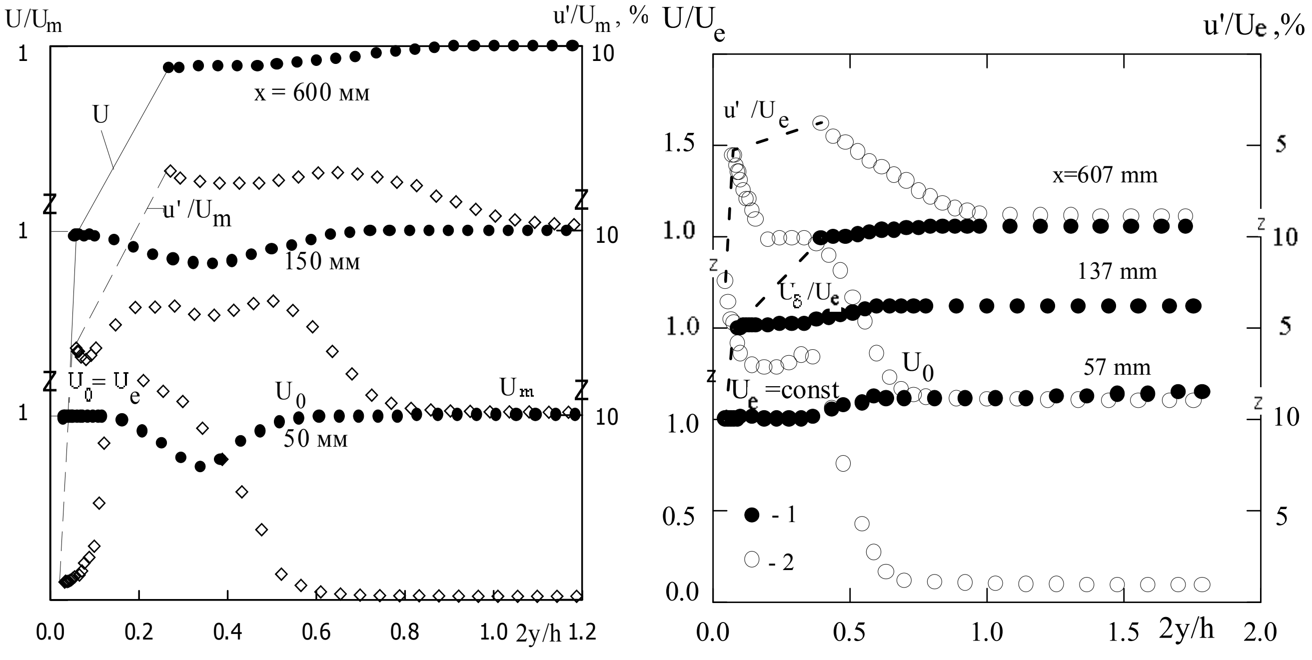


Fig.2. Heat transfer distribution: 1- $St = 0.55\,\mathrm{Re}_x^{-0.5}$; 2 - $St = 0.036\,\mathrm{Re}_x^{-0.2}$;
3 – without cylinder; 4 - still cylinder; 5 - hesitating cylinder

Characteristics of wakes

The analysis of distributions of time-averaged velocity (Fig.3a, 3b, symbol 1) and its longitudinal fluctuation (Fig.3a, 3b, symbol 2) in the free-stream ($y > \delta$) showed that wakes change the uniformity of the velocity distribution because of the presence of defect and generate a nonuniform turbulence field.



a) b)

Fig.3. Characteristics of wakes after still (a) and hesitating (b) cylinder

However the interaction between shearing motion in the wake and boundary layer leads to formation the region close to BL with the uniform field of the velocity U_e=const in cases of still (Fig.3a) and hesitating cylinder (Fig.3b). The value U_e is taking as a velocity of free-stream at forming of BL. In the region U_e=const at x<150 mm longitudinal fluctuations of velocity changed substantially (for example, from u'_δ / U_m=1% up to 8.5% (Fig.3a, x=50 mm) and from u'_δ / U_e=15.8% up to 12% (Fig.3b, x=57 mm), where U_m - maximal velocity out of the wake. As seen from Fig.3a and 3b, total intensity of turbulence in case of hesitating cylinder is higher than for still one. Such increased level of turbulence in free-stream causes the increase of the local heat transfer and friction coefficients in pre-transitional boundary layer.

Features of dynamic and thermal boundary layers

The analysis of dynamic and thermal boundary layers characteristics in the presence of still and hesitating cylinder confirmed the origin of pseudolaminar boundary layer before wake-induced transition. The profiles of velocity and temperature in BL that precedes wake-induced transition are characterized by the elevated gradients at the wall. At the same time the BL thicknesses δ and δ^{**} increase at conservative displacement thickness δ^{**}, what leads to reduction of shape parameter H in comparison with laminar BL. Distinguishing feature of pseudolaminar BL is also the appearance of maximum of turbulence kinetic energy at y/δ=0.2-0.3. Distributions of the longitudinal velocity fluctuations in BL disturbed by the wake of still cylinder (Fig.4a) demonstrated such peak at x=50 and 150 mm. This peak shifts in direction of the wall in the process of transition.

One of the important features of longitudinal velocity fluctuations in BL disturbed by the wakes of hesitating cylinder is appearance of two peaks (Fig.4b). The amplitude and the location of these peaks vary with the development of transition.

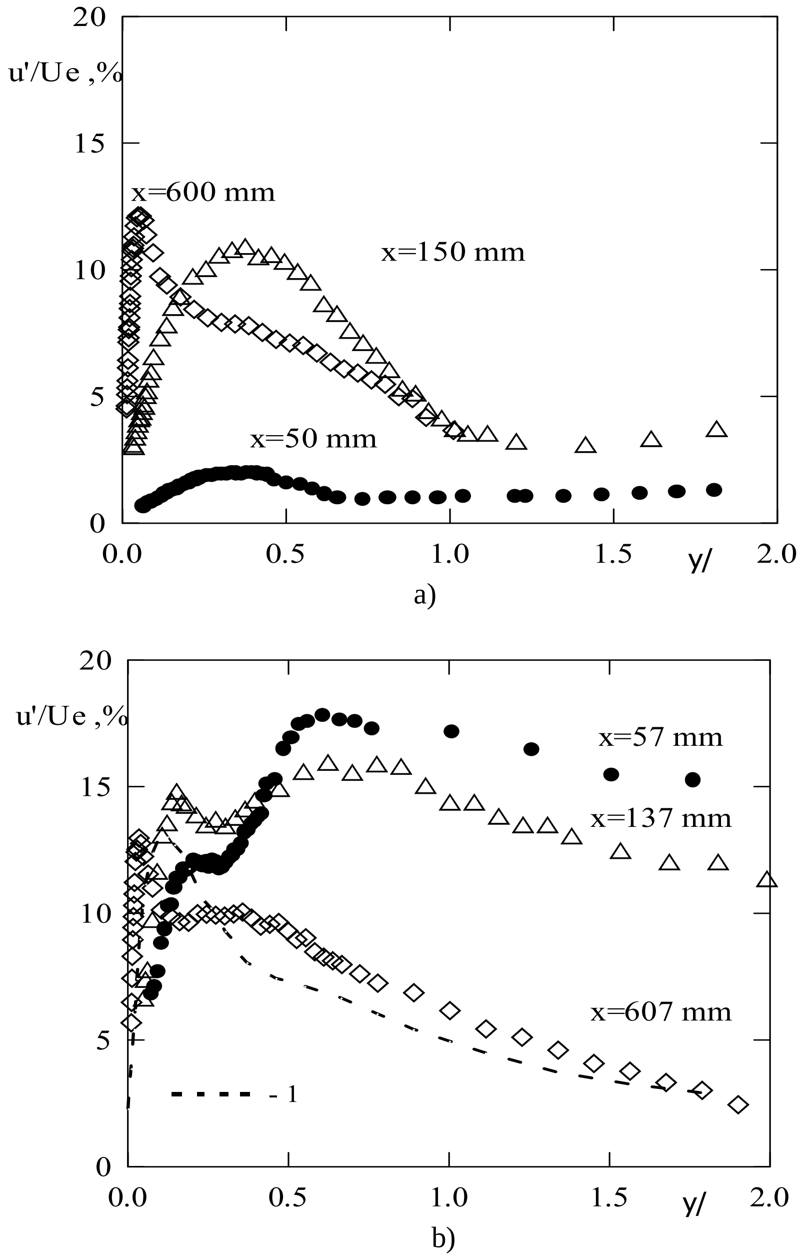
Thus, the amplitude of the first near the wall peak increases upon approaching the transition and its location is shifted to the wall. The location and amplification of this peak is similar to that observed in bypass transition. The second peak located closer to the outer edge of the boundary layer arises as a result of wakes interaction. The energy of secondary peak decreases with distance from the wake generator. The observed features of velocity fluctuation profiles are in good agreement with results of investigation carried out in Institute of Fluid-Flow Machinery PASci. (Gdansk), when boundary layer affected by the wakes of two different wake generators: single moving cylinder [3, 6] and rotating “squirrel cage”.

At the same time profiles of temperature fluctuation have only one peak near the wall (Fig.4b, dashed line 1) like the first peak in velocity fluctuation profiles but located closer to the wall.

Coordinates of wake-induced transition

The analysis of mentioned above specific features of pseudolaminar BL and bypass transition permitted to determine coordinates of wake-induced transition using special diagnostics methods developed in IET NASU [7]. At presence of still cylinder the start and the end of transition are located at $\mathrm{Re}_{xst}=9\cdot10^4$ and $\mathrm{Re}_{xend}=2.65\cdot10^5$ correspondingly; for hesitating cylinder $\mathrm{Re}_{xst}=8.5\cdot10^4$ and $\mathrm{Re}_{xend}=2.4\cdot10^5$. In both cases wake-induced transition transformed into turbulent boundary layer (Fig.2, line 2). Thus the start and the end of wake-induced transition were shifted upstream relatively natural transition which occurred without wakes ($\mathrm{Re}_{xst}=2\cdot10^5$, $\mathrm{Re}_{xend}=4.5\cdot10^5$).

As mentioned above total turbulence level in free-stream for hesitating cylinder was higher than for still one (Fig.3a and 3b). So comparison of heat transfer distributions in cases of steady and periodic unsteady wakes showed that when total turbulence intensity increases intensification of heat transfer in the pre-transition BL also increases. Region of transition induced by hesitating cylinder shifts upstream relatively steady case.



a)

b)

Fig.4. Distributions of the longitudinal velocity fluctuations in the presence of still (a) and hesitating (b) cylinder: 1 - $t'/(t_w - t_e)\% = f(y/\delta_t)$ at x =50 mm

Comparative length of transition ($\mathrm{Re}_{xend}/\mathrm{Re}_{xst}$) in both cases is practically constant ($\pm$5%). At the same time the absolute length of wake-induced transition ($\mathrm{Re}_{xend} - \mathrm{Re}_{xst}$) for periodic unsteady wakes decreases in comparison with the steady ones.

Conclusion

Experimental investigations of a flat plate heat transfer in the presence of laminar-turbulent transition induced by wakes after still and hesitating cylinder were carried out.

It has been shown that wake-induced transition shifts upstream relatively natural transition without wakes. In both cases of wake-induced transition pre-transitional BL was pseudolaminar and characterized by substantial heat transfer growth in comparison with laminar boundary layer. Taking into account that under influence of hesitating cylinder total turbulence intensity of free-stream is higher than in the presence of steady wakes, intensification of heat transfer in pre-transitional BL at $\mathrm{Re}_x = 4 \cdot 10^4$ increased from ~20% for steady wakes to 38% for periodic ones. Due to increasing turbulence intensity wake-induced transition shifts to lower Reynolds numbers, its comparative length ($\mathrm{Re}_{xend}/\mathrm{Re}_{xst}$) remains unvarying and absolute length ($\mathrm{Re}_{xend} - \mathrm{Re}_{xst}$) decreases.

Obtained results of experimental study of thermal transition induced by wakes should provide test cases for improving the heat transfer modelling and enhancing the accuracy of thermal load prediction.

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