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Experimental Investigation of the Boundary Layer State Hysteresis and its Influence on the Starting of the Streamline-Traced Intake

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Abstract

The results of thermal testing of high-speed aircraft model with the streamline-traced dorsal intake and internal power engine duct in the super/hypersonic TsAGI T-116 wind tunnel are presented. Boundary layer state on the compression intake surface was found to depend on a flight regime and particular type of turbulence stimulators. In addition to mass flow rate hysteresis found earlier, the boundary layer state hysteresis was discovered to accompany forward and reversed angle-of-attack change for definite types of turbulence stimulators. This and other factors influenced the intake start, are discussed.

Keywords: experimental investigation, TsAGI T-116 wind tunnel, boundary layer state hysteresis, Busemann diffuser, intake start.

Nomenclature

Latin
BL – boundary layer
M – Mach number
MFR, f – mass flow rate
Re – Reynolds number
St – Stanton number
TS - turbulence stimulator
WT – wind tunnel
W/TS – without TS
Greek
α – angle-of-attack
δ – BL outer edge

The testing model configuration for experimental exploration represents the aerodynamic shape of high-speed experimental flight test vehicle EFTV investigating within the HEXAFLY-INT International Project as described in Refs. [1–3]. The interior of the dorsal intake is composed of streamlines of the Busemann diffuser compression conical flow. Experimental values of heat transfer coefficients were obtained in accordance with the methodology of Ref. [4] using wall temperature measurements by thermocouples and using the regular regime thermal method of Ref. [5]. Location of thermocouples in the symmetry plane on lower (no. 1-14) and upper (no. 15-17) surfaces is shown in Fig. 1.

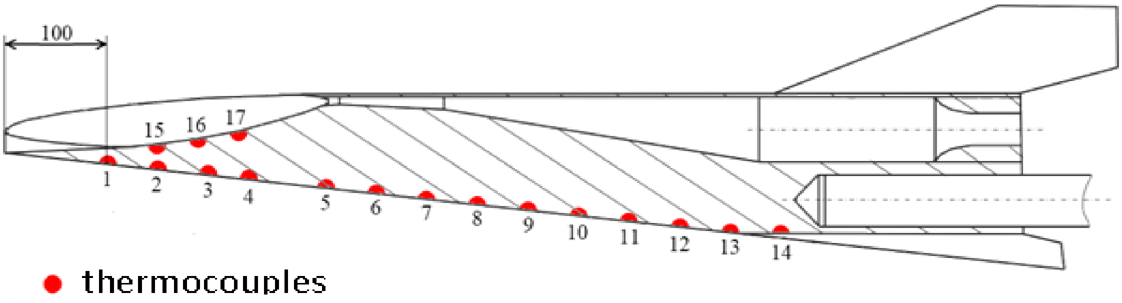

Fig. 1. Location of thermocouples

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To identify the boundary layer state on the model surface, the experimental values of Stanton numbers based on experimental heat transfer coefficients were compared with empirical correlation dependencies St (Re) for laminar and turbulent BL according to Refs. [6, 7] (see Fig. 2 for M=7).

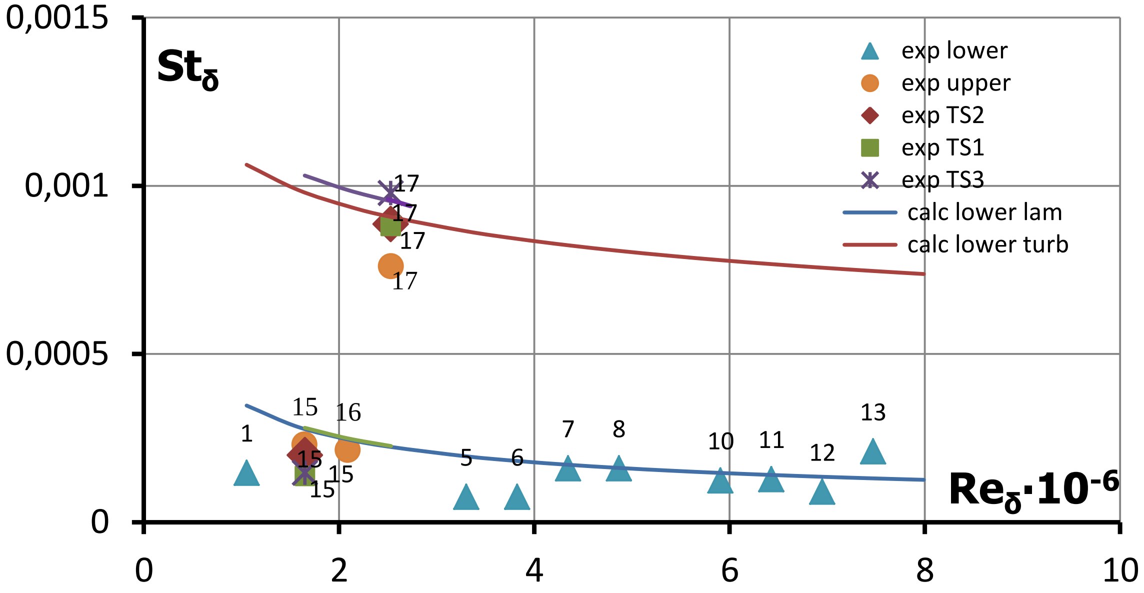

Fig. 2. Comparison of experimental Stanton numbers with and without TS, and empirical curves

As Fig. 2 shows, at M=7, α=0 the BL was purely laminar near the lower surface, while on the intake compression (upper) surface initially laminar BL became transitional near the intake throat. The artificial BL flow turbulization on the intake compression surface was performed by using turbulence stimulators (TS) of different kinds installed near the intake leading edge, in particular, 10 and 3 screw heads with 1.2 mm height above the model surface for the stimulators TS1 and TS4 respectively. Turbulence stimulators TS2 and TS3 were formed by adding wires to the screw heads of TS1 obliquely for TS2 and parallel to the intake leading edge for TS3 (see Fig. 3). The effects of TS1 – TS3 were to make BL near the intake throat turbulent, as also shown in Fig. 2.

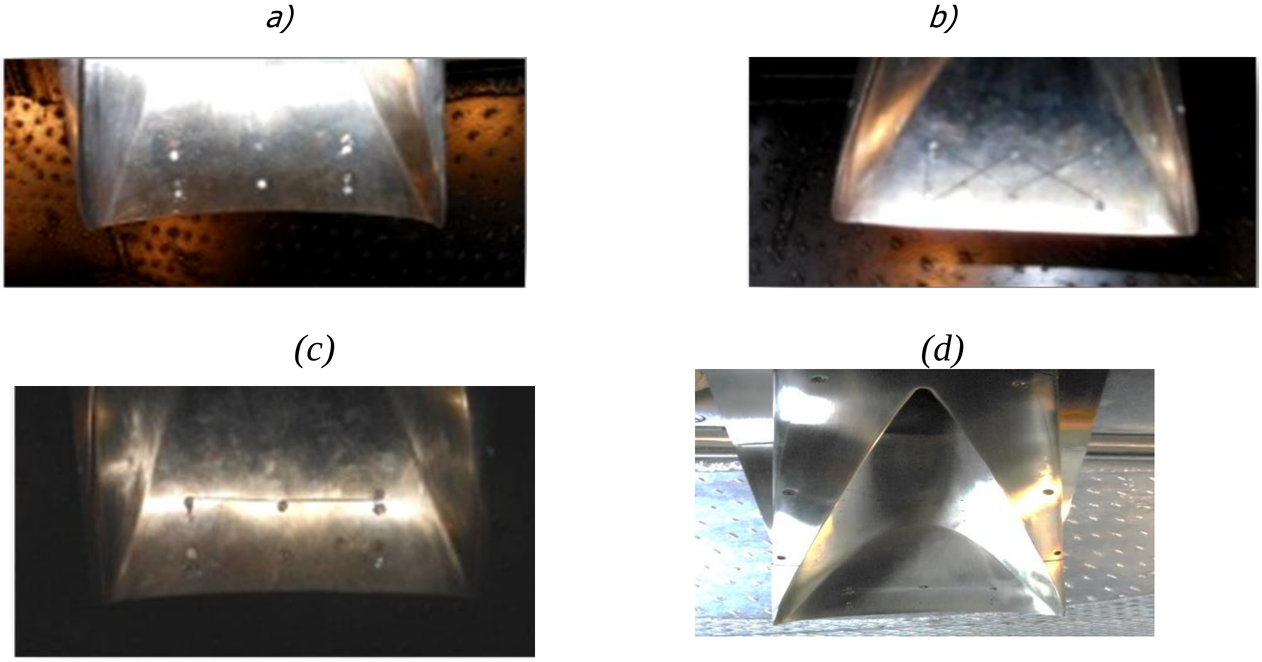

Fig. 3. Turbulence stimulators *(a)* TS1, *(b)* TS2, *(c)* TS3, *(d)* TS4

The experimental exploration had shown that the use of turbulence stimulators may broaden the area of design flow regime where the intake starts in comparison with smooth compression surface. Or simply they are capable to produce intake start, which is absent without them (see Fig. 4). The high level of mass flow rate (f≥0.6÷0.8) demonstrating start of intake is received when using TS1-TS3.

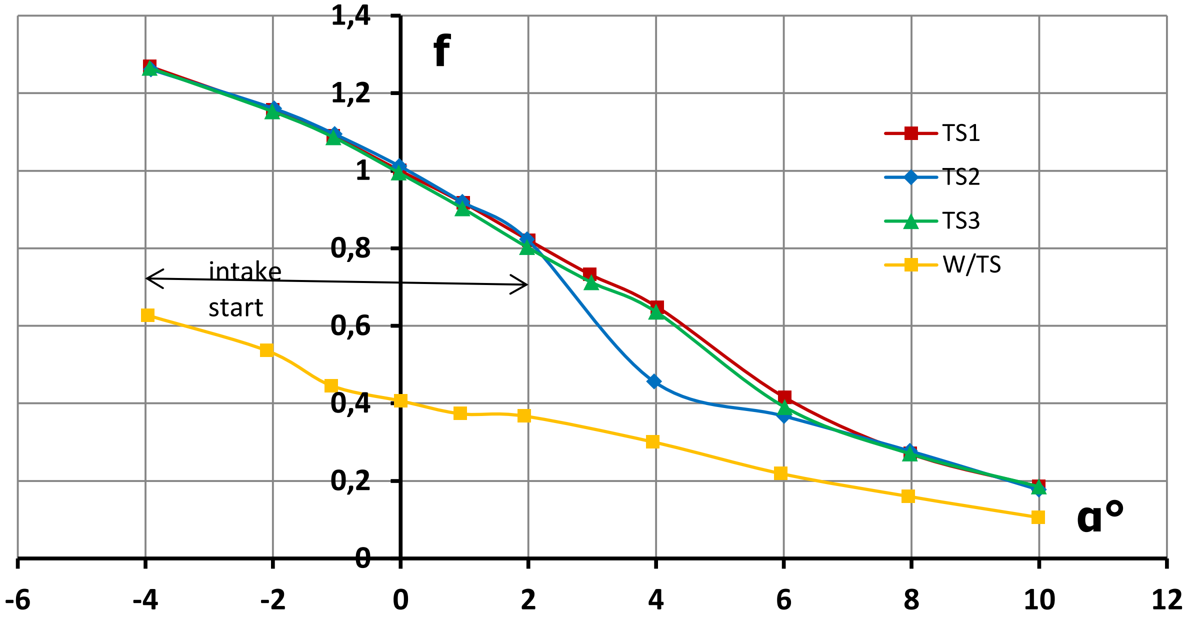

Fig. 4. Intake MFR with TS1-TS3 and without TS (W/TS) at M=7

Further tests provided with different histories of angles-of-attack change have exhibited the important phenomenon of hysteresis behavior of intake mass flow rate mentioned earlier in Refs. [4, 8]. Such hysteresis behavior of mass flow rate versus angle of attack was observed with TS1 only and is obvious in Fig. 5 as the visible discrepancy of red and blue curves at α =0÷5º for different ways of incidence change.

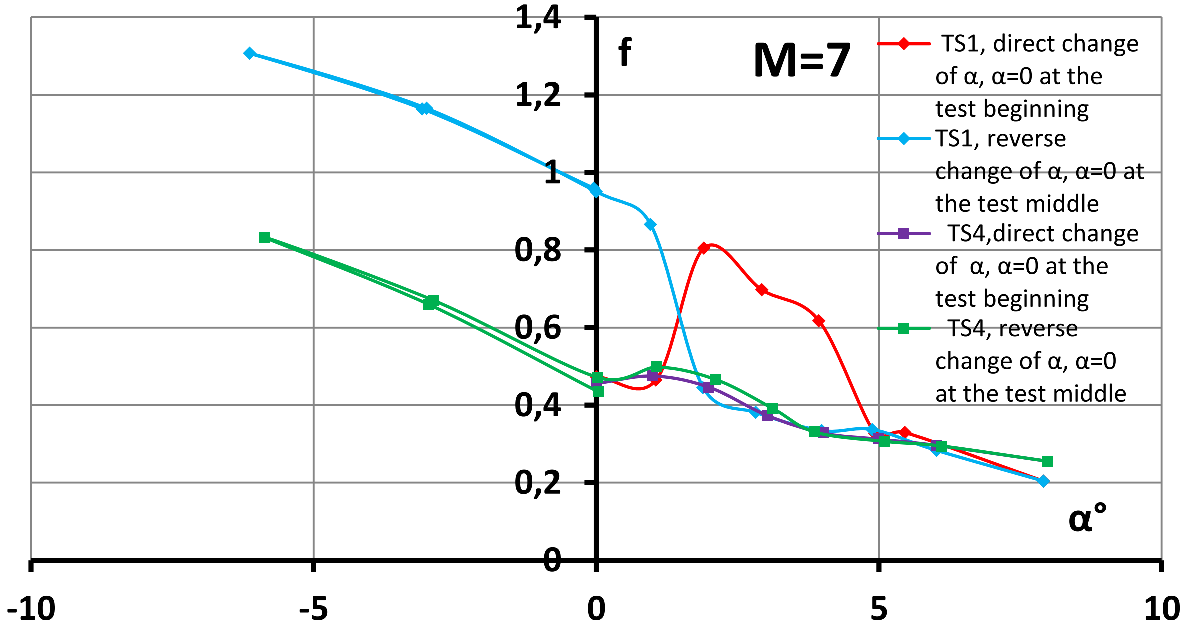

Fig. 5. Intake mass flow rate versus angle of attack. TS1and TS4 influence on the intake start

This phenomenon is of importance because it influences the intake start. Apparently from Fig. 5, during angle of attack direct change (a red curve), intake start is noted in the range of positive angles of attack 2º ≤ α ≤ 4º, and throughout reverse motion (a blue curve) start begins with α=1°, steadily remains to α= -6 ° (including directly unstarted region 0÷ 2º) and at final return to α = 0. In Fig. 5 curves for both TS1 and TS4 merge, after α=5 ° that, obviously, is connected with the fact that model has begun shadowing the dorsal intake.

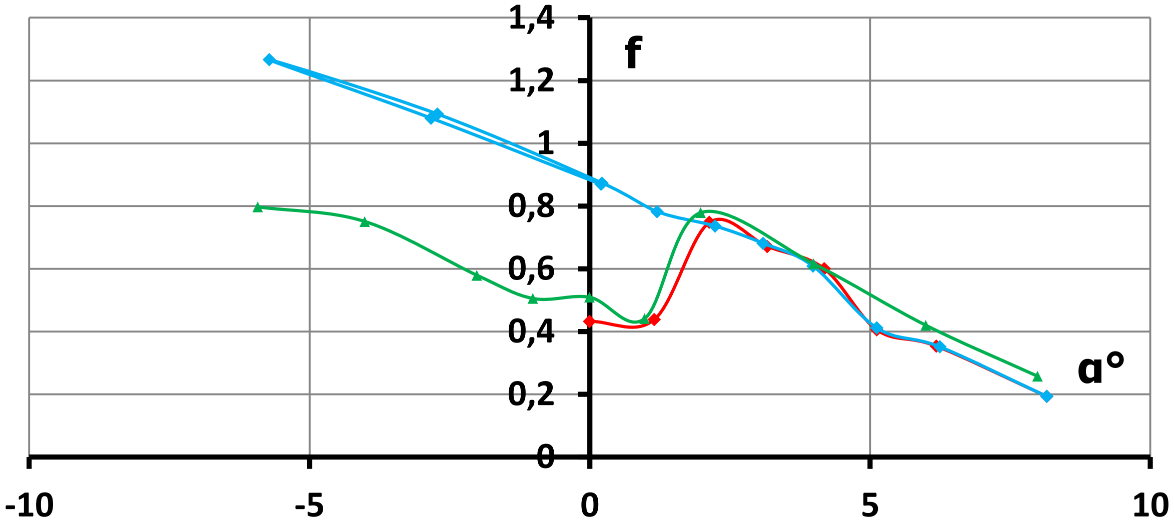

Fig. 6. Intake MFR versus angle of attack. TS1 influence on the intake start at M=6
α = 0 ÷ 8° ÷ **0** ÷ - 6°÷ 0**;** **α =** -6° ÷ **0** ÷ 8°

However, the MFR hysteresis didn't occur with TS4 at M = 7 (see Fig. 5 where violet and green lines coincide) and is less pronounced with TS1 at M=6 (see Fig. 6) being visible at α=0÷2° only.

Particular emphasis has been given to the state of BL on the intake compression surface. Here in addition to the MFR hysteresis the evidences of **the boundary layer state hysteresis** were found to accompany the direct (**0** – 8º) and reversed (8º – **0**) angle of attack changes. Experimental values of Stanton number versus Reynolds number for Mach number 7 and different TS's are shown in Fig. 7 together with calculated curves for laminar and turbulent BL.

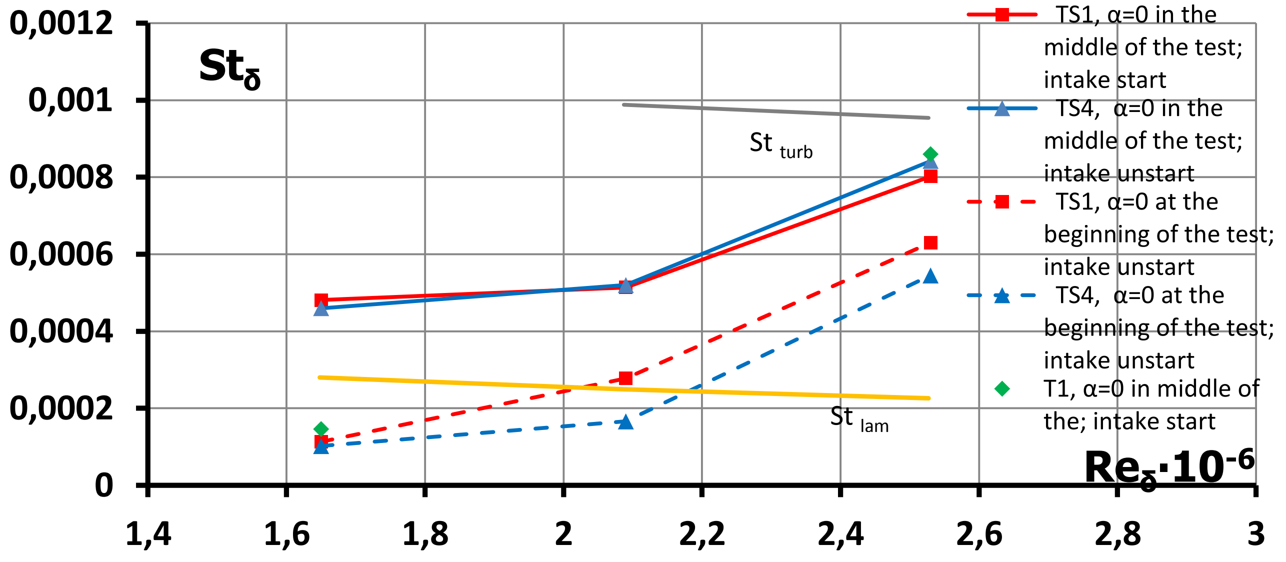

Fig. 7. Boundary layer state hysteresis at M=7:
α = 0 ÷ 8° ÷ **0÷ -6° ÷ 0, α = 0 ÷ 8° ÷0 ÷ -6° ÷ 0, α = -6° ÷ 0 ÷ 8°**

Why does such a hysteresis occur and what are its peculiarities? The case is that possible temperature changes of a surface owing to the model heating during wind tunnel tests (1-2 min.) are small and can't serve as an explanation of so noticeable distinctions inherent to the hysteresis. The hysteresis reason, probably, is as follows. According to Fig. 7 (dashed lines) and to Fig. 2, at $\alpha=0$ at the beginning of the test even in the presence of TS the laminar BL state on the most part of a compression surface is replaced by transitional one when approaching to a throat. Influence of rarefaction of a stream on the upper surface at positive angles of attack (to 8º) leads to additional BL turbulization, therefore on the most part of compression surface BL state becomes transitional, and near a throat – turbulent (solid lines in Fig. 7). At the subsequent incidence reduction to zero, this BL state doesn't change any more, as leads to a BL state hysteresis on the intake compression surface. From Fig. 7 we see that at the specified angle of attack change, the BL state hysteresis occurs practically on the whole compression surface and causes significant increase of the wall heat transfer. In the same drawing two green points taken from Fig. 2 correspond to $\alpha=0$ in the middle of the test at incidence change in the opposite sequence: $\alpha=0$ … –6 ° … 0 … 8 ° … 0. In this case it is visible that the hysteresis occurs only at the end of intake compression surface (thermocouple No. 17).

Further, is there any connection between two types of hysteresis mentioned and intake start? The answer is "yes" but their relationship is not simple. Really in Fig. 7 dashed lines correspond to the absence of intake start, when BL at the beginning of the test was laminar on the main part of compression surface, despite of the TS presence. On the contrary, the solid lines correspond to BL hysteresis with almost turbulent BL for both TS1 and TS4 at the middle of the test. However, the start of intake was obtained for TS1 only, together with the hysteresis of MFR. Thus, it is established that TS1 has bigger efficiency in ensuring intake start in comparison with TS4, and that particular BL state as far as its hysteresis not obligatory lead to intake start. In other words, it is possible to conclude that the state of BL is not the only factor influencing intake start. Apparently, by 3 times the bigger number of screws in TS1, besides turbulization of BL, leads also to formation of vortex bundles outside of viscous BL which local thickness near the forward row of screws arrangement is equal to their height. Certainly, all this in addition to emergence of shock waves at blunted leading and side edges and other factors, including, specified in Ref. [9], causes difference of the real flow field in the entrance highway of intake from an ideal pattern of an axisymmetric conical flow in the Busemann's diffuser. Certainly of the influencing factors it is also necessary to refer emergence of the interacting shocks from the leading and side edges even if they are sharp, but there is an angle of attack, which are also absent at classical internal flow in the Busemann's diffuser.

The drawn conclusion fully belongs also to flow at $M = 6$. The corresponding tests were carried out with TS1 only. The mass flow rate versus angle of attack which changes similarly to Fig. 5 is shown in Fig. 6. It is visible that for the initial basic value $\alpha=0$, intake start isn't observed at the beginning, but at a direct way to $\alpha=8$ ° (a red curve) also occurs in the range $\alpha=2\div4$° and remains in the course of reverse motion to $\alpha= -6$ ° and final return to 0. At reverse motion the same $f(\alpha)$ values are registered, as at direct, excepting the narrow range of angles of attack $\alpha=0\div2$ ° in which there is also the mass flow rate hysteresis. It is also absent for negative angles of attack. Schedules in Fig. 8 similar to ones in Fig. 7, allow to conclude about BL state at $\alpha=0$ at the beginning (the dashed line) and in the middle of the test (solid line) in the course of which the angle of attack changed in the direct and reverse directions: even with TS1 in both cases on the main part of intake compression surface the BL is almost laminar, and corresponds laminar-turbulent transition at the end. Unlike the previous option ($M = 7$), in this case the hysteresis and distinction of BL state are expressed slightly more weakly. However, its one more qualitative feature is visible: on a forward (bigger) part of compression surface at a hysteresis the BL comes nearer to turbulent (the solid curve is located above dashed one), whereas on a back quarter there is an opposite picture – the hysteresis leads to BL laminarization and lower heat transfer (the solid curve is located below dashed one).

Here the BL hysteresis accompanies the hysteresis of MFR and together they lead to intake start at the middle of the test. Really, according to Fig. 6 there is mass flow rate hysteresis which is also accompanying the intake start in the narrow range $0 \le \alpha \le 2$ °. At the same time, at reverse motion start begins with $\alpha = 4$º and to $\alpha = 2$º happens at coincidence of the reverse and direct $f(\alpha)$ curves, i.e. in the absence of a hysteresis. Besides, in the course of monotonous increase in an angle of attack from -6° to 8° (green curve) intake is started also in an interval α=2÷4 ° without start at α =0.

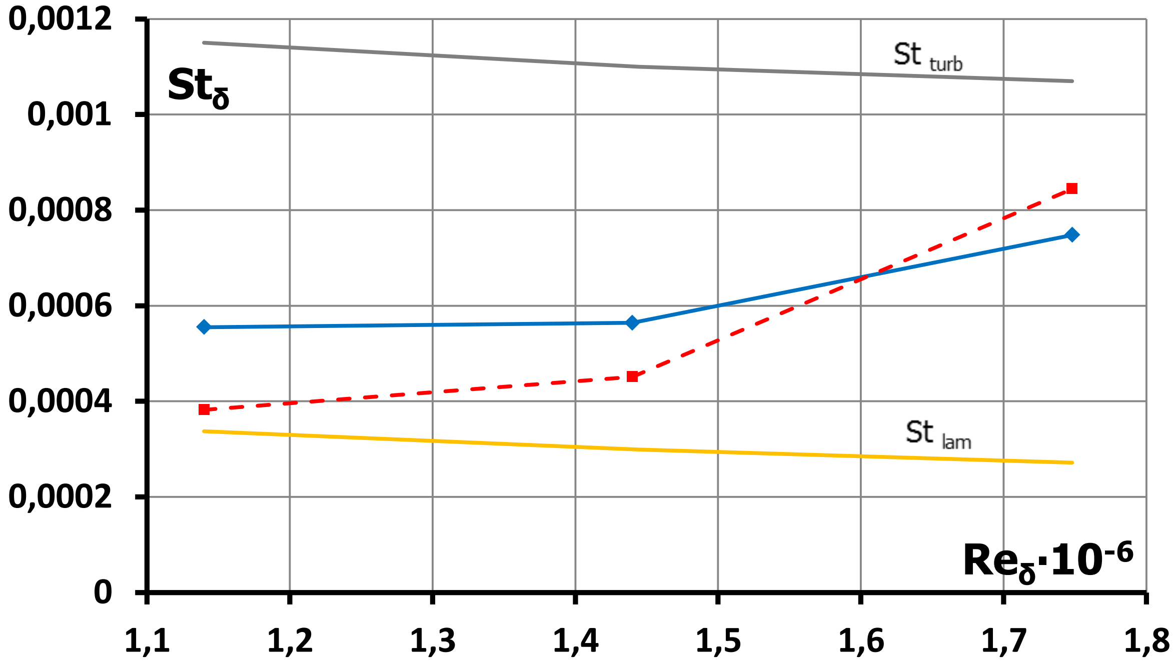

Fig. 8. Boundary layer state hysteresis at M=6
α = 0 ÷ 8° ÷ 0÷ -6° ÷ 0

Conclusions

As the result of analysis numerous experiments in T-116 WT together with theoretical calculations:

- The use of particular turbulence stimulators was found to broaden the domain of hypersonic aircraft convergent intake design condition, when it starts or simply makes start to be possible in comparison to the case of its smooth internal surface.

- The experimental evidences of hysteresis behavior the intake compression surface boundary layer state were found to exist for angle of attack direct and reverse changes at some Mach numbers and TS types.

- It was established that BL hysteresis may took part on the whole intake compression surface or only on its back portion near the throat. Due to the hysteresis, boundary layer became more turbulent as a rule, however the possibility of its laminarization was also observed.

- The BL state does accompany or not the intake start, depending on above mentioned as far as some other factors. Thus, the BL state including those formed as a result of BL state hysteresis, cannot be considered as the unique reason of the intake start. Indeed, the appearance and interaction of shock waves from the intake blunted leading/side edges with each other and with vortex structures produced by some TS types beyond the viscous boundary layer should be taken into account. Similar to the cross flow factors mentioned earlier in Ref. [9], these will generate significant difference between the real internal flow and design inviscid conical compression flow in the Busemann diffuser, particularly at nonzero angle-of-attack. The case here is analogous to Ref. [10], where the real flow pattern of bow shock wave reflection from the side fence installed on pyramidal wing in supersonic flow, is in cardinal difference in comparison to the ideal gas prediction.

- Depending on the level of disturbances mentioned, the hysteresis of intake mass flow rate may accompany BL state hysteresis, but for particular turbulence stimulator types only.

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