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STUDY OF THE EFFECTS OF GAP SUCTION ON TURBULENT SEPARATED FLOWS AT SUPERSONIC SPEEDS

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An experimental investigation was made to determine the effects of suction on supersonic turbulent boundary-layer seperation induced by a spoiler an a flat plate. The test model was the flat plate and the spoilers with and without a gap. It was shown that the length of separation region for spoiler with a gap expressed in normalized form by means of the spoiler height depend only upon ratio of gap and spoiler height. It was found that the seperation pressure is independent of suction. This study has indicated that the separation process induced by the spoiler with gap is free interaction type. The normalized pressure distribution in the fore region of the spoilers without and with a gap were found. The ratio of gap and spoiler heights was correlated with the normal force induced by the spoiler with a gap.

NOTATION

- F normal force resulting from flow separation ahead the spoiler,
- $\bar{F}$ dimensionlless normal force $\bar{F} \equiv F/p_\infty h_i$,
- g spoiler thickness,
- h_i spoiler height,
- h_g gap height,
- L distance measured along chord of the flat plat from leading edge,
- M_∞ Mach number of undisturbed flow,
- p pressure,
- p_∞ pressure of undisturbed flow,
- p_s separation pressure, see Fig. 4,
- p_u plateau pressure, see Fig. 4,
- $\bar{p}$ dimensionlless pressure $\equiv p/p_\infty$,
- x distance measured along chord of the flat plat from start of pressure rise,
- Δx length of the region between the beginning of the pressure disturbance and the separation point,
- δ_i' theoretical boundary-layer thickness in point of spoiler location,
- x_{od} length of the region between the separation point and spoiler.

1. INTRODUCTION

The phenomenon of the separation of the two-dimensional boundary-layer has been extensively studied both experimentally and theoretically. These studies were designed primarily to determine such effects as the geometric parameters of models, the location of the transition boundary-layer relative to the reattachment flow, heat-transfer, and the Mach number and Reynolds number on the flow separation characteristics. But less attention has been paid to the subject of reducing or controlling flow separation. The suction in a region of separated flow is the method that appears adequate for reducing separations. The effect of suction on the separated flows has been the object of some investigations in recent years [1–4]. BALL and KORKEGI [1, 2] determined the quantitative effect of natural suction through a gap in the compression corner on laminar boundary-layer separation in the hypersonic speeds regime. It was shown that the extent of separation is extremely sensitive to suction. Suction of a small percentage of boundary-layer mass flow is sufficient to cause the collapse of the region of separated laminar boundary-layer in the compression corner. PATE [3] determined the effectivenes of distributed suction for controlling transitional flow separation on a cylinder-flare model witht the Mach number ranging from 2.5 to 3.5. It was found that the separated flow region is very responsive to distributed suction. TANNER [4] quantitatively showed that suction brings about increasing pressure and decreasing length of the region of the separated turbulent boundary-layer in a compression corner with a Mach number of 1.93.

The present investigation was conducted to determine the quantitative effect of mass flow suction on the characteristic features of two-dimensional turbulent boundary-layer separation induced by a spoiler on a flat plate at supersonic speeds. Suction was obtained by means of a gap of variable height, allowing controlled natural flow from the high-pressure region upstream of the spoiler to the low-pressure region downstream.

2. MODEL AND TEST CONDITIONS

The experiments were performed in an 0.15×0.15 m supersonic wind-tunnel. Details of this tunnel, of the blow-down type, and the tunnel flow characteristics are described in the report [6].

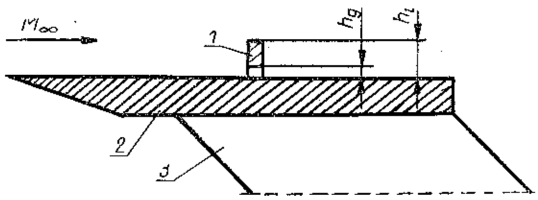

Fig. 1. Sketch of test model;
1 – spoiler with gap; 2 – flat plate; 3 – sting.

The test model consists of a flat plate with different spoilers with and without a gap as shown in Fig. 1. The span of the flat plate and of the spoilers was 150 mm. The length of the flat plate was 120 mm. The spoiler heights ranges from 3 to 6 mm and the gap heights ranged from 0 to 4 mm. The designations of the spoilers would be in the form:

$$h_t - h_g - g,$$

where h_t — spoiler height [mm], h_g — gap height [mm], g — spoiler thickness [mm].

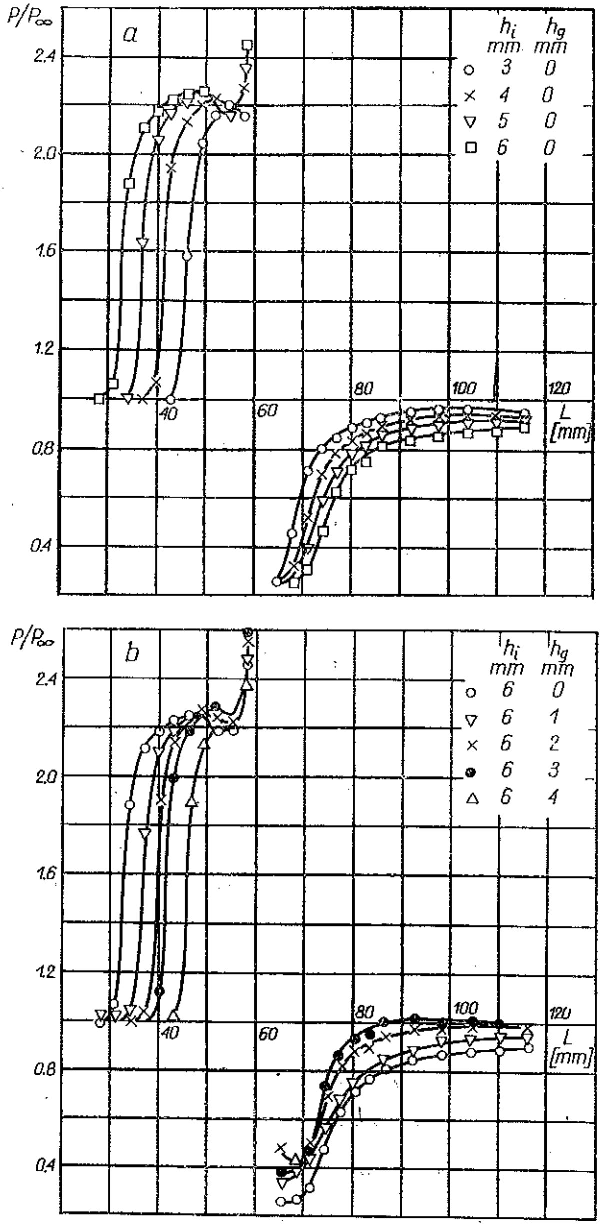

Fig. 2. Streamwise pressure distributions for spoilers without and with a gap:
a) $M=2.5$, $h_g=0$, without suction, b) $M=2.5$, $h_i=6$ mm, with suction.

The experiments were carried out at nominal freestream Mach numbers of 2 and 2.5 and Reynolds numbers per metre of 29×10^6 and 32×10^6, respectively. Surface pressure distributions and shadowgraph observations (from which points of separation were determined as the points where the boundary-layer noticeably deviated from the surface of the flat plate) were made. The boundary-layer trips

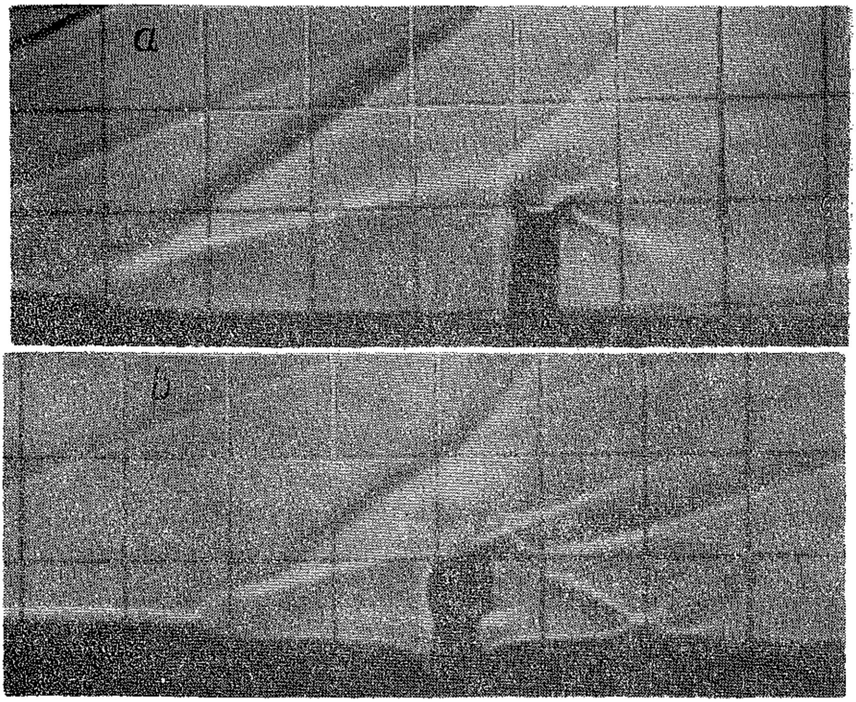

Fig. 3. Shadowgraphs of turbulent separation induced by spoiler for Mach number 2.5. Spoiler height of 6 mm.

a) without suction, b) with suction, gap height of 4 mm.

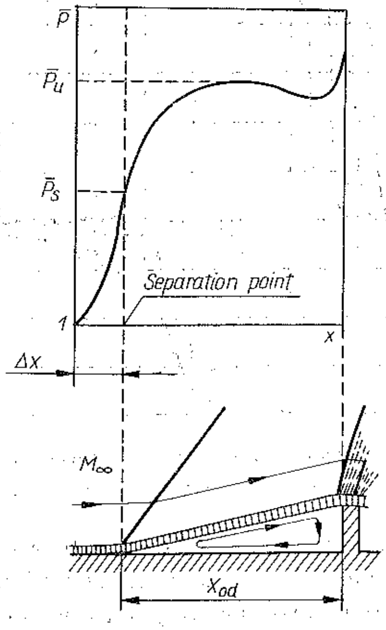

Fig. 4. The characteristic parameters of the separation-flow region upstream of the spoiler

P_s – separation pressure, P_u – plateau pressure.

were fixed on the flat plate at a position 5 mm from the leading edge. Shadowgraph observations and pitot pressure distributions in the boundary-layer indicated that the transition to fully turbulent flow occured upstream of the separation points in all cases.

3. Results and discussion

Typical streamwise pressure distributions in the region of the separation induced by the spoiler with and without suction at a Mach number of 2.5 are shown in Fig. 2. The length of the separation region is noted to decrease with the increase of the gap heights. It is noteworthy that the separated boundary-layer does not collapse even for large gaps which were indicated on the shadowgraph as shown in Fig. 3 ($h_g = 4$ mm)

The characteristic parameters of the separated-flow region, which were considered, are shown in Fig. 4: separation pressure p_s, plateau pressure p_u, the length of the region between the separation point and spoiler x_{od}, the length of the region between the beginning of the pressure disturbance and the separation point Δx.

The values of these parameters for boundary-layer separations induced by the spoiler without suction were found to be in good agreement with the existing correlations obtained by Zukoski [5] for the forward-facing step. The normalized pressure

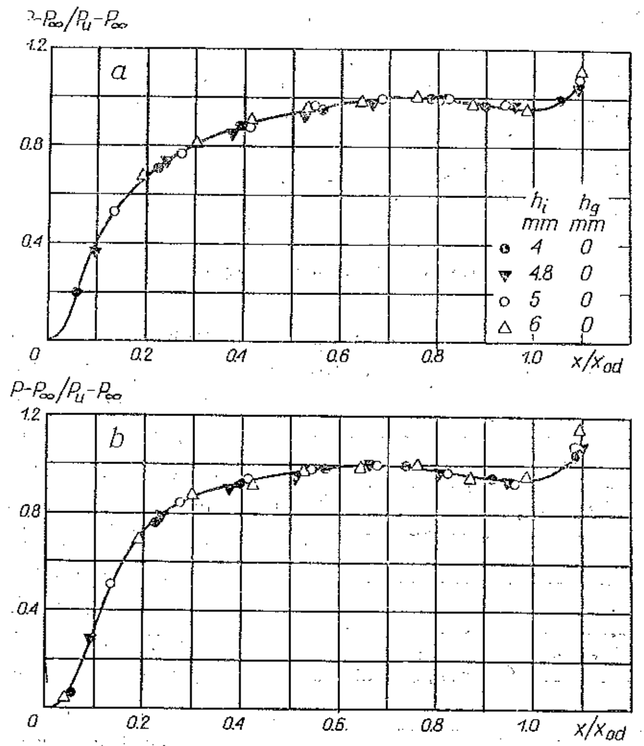

Fig. 5. Normalized pressure distributions in the separation region upstream of spoiler without suction:

a) $M=2.0$, b) $M=2.5$.

distributions in the region of separation upstream of the spoiler without suction were obtained by plotting $(p-p_\infty)/(p_u-p_\infty)$ versus (x/x_{od}) as shown in Fig. 5 for the Mach numbers of 2 and 2.5. The normalized pressure distributions practically coincide

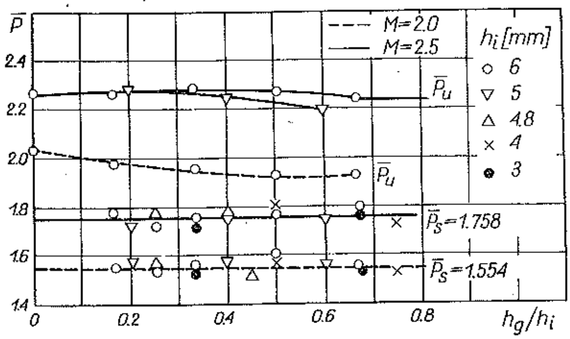

Fig. 6. Effect of suction on the plateau and separation pressure.

up to the immediate neighbourhood of the spoiler. In view of the above correlations it follows that the separation of the turbulent boundary-layer induced by the spoiler is of the free interaction type up to approximately the plateau pressure.

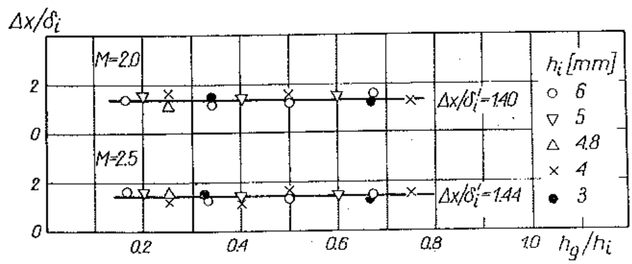

Fig. 7. Effect of suction on the length of region Δx.

The dependence of the separation and plateau pressure on the suction are shown in Fig. 6. The experimental data show that the separation pressure is independent of suction due to the gap and this suction causes a slight decrease of the plateau pressure. The length of the region Δx was normalized by calculating boundary-layer thickness. These normalized values, which are shown in Fig. 7 were roughly independent of the suction and were found to be approximately equal to values for a separation region without suction. As previously, was mentioned suction causes

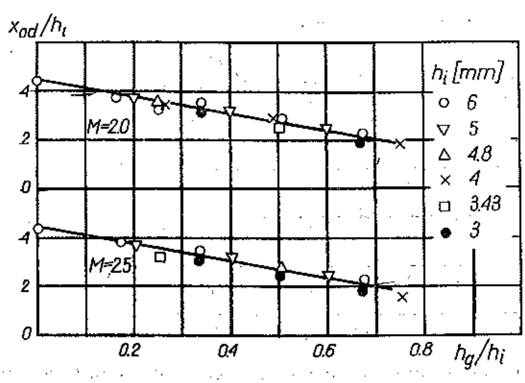

Fig. 8. Correlation of length of separation region with suction.

a decrease of the length of the separation region. It was shown in Fig. 8 that the length of the separation region with normalized suction relative to spoiler height depends only on the ratio of the gap to spoiler height and is independent of the Mach number (Fig. 9) similarly to the length of the separation region without suction. The normalized length of the separation region with suction can be expressed by the empirical relation

(3.1) $x_{od}/h_i = 4.38 - 3.45\,(h_g/h_i)$.

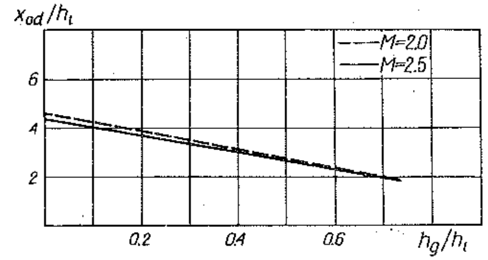

Fig. 9. Comparison of correlation of length of separation region with suction for Mach number of 2 and 2.5.

The normalized pressure distributions in the separation region with suction in the plot of $(p-p_\infty)/(p_u-p_\infty)$ versus (x/x_{od}) were shown in Fig. 10. It is worth noting that these pressure distributions are in good agreement with the data for spoiler without suction throughout the separation region except in the immediate neighbourhood of the spoiler. It appears that suction does not affect the flow in the sepa-

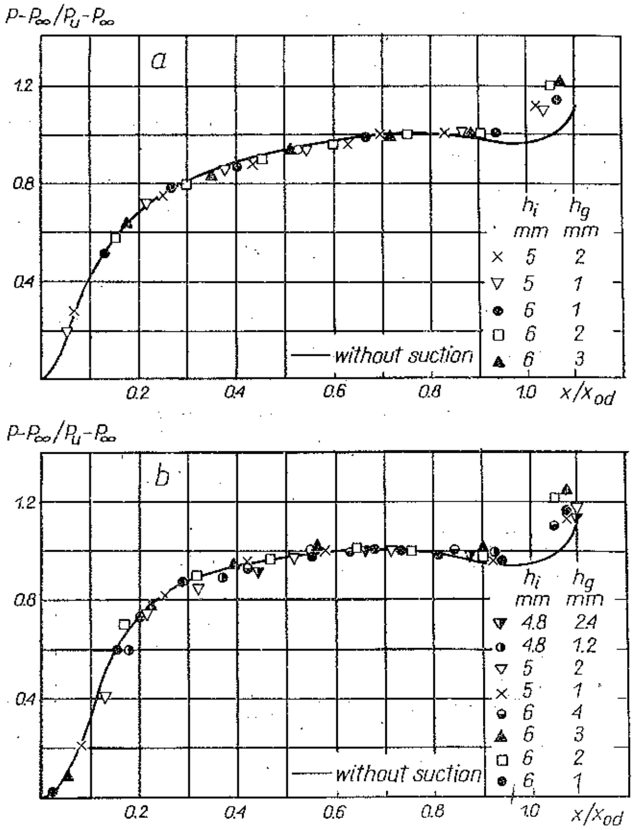

Fig. 10. Normalized pressure distributions in separation region upstream of spoiler with suction: a) M=2.0, b) M=2.5.

ration region up to a point x/x_{od} approximately equal to 0.8 and it can be stated that suction does not change the free interaction process of the turbulent boundary-layer separation induced by the spoiler. Suction affects the flow in the immediate neighbourhood of the spoiler and causes an increase of pressure in this region. The normal force induced by the separation with suction ahead of the spoiler with the gap, can be written as the integral of pressure rise over the high-pressure region,

$$F = \int_0^{x_{od}+\Delta x} (p - p_\infty)\, dx. \tag{3.2}$$

Rearranging the Eq. (3.2) the normalized normal force can be written as

$$\bar{F} = F/p_\infty h_i = \frac{p_u - p_\infty}{p_u} \frac{x_{od}}{h_i} \int_0^{1+\frac{\Delta x}{x_{od}}} \frac{p - p_\infty}{p_u - p_\infty}\, d\left(\frac{x}{x_{od}}\right). \tag{3.3}$$

In accordance with the normalized pressure distribution (see Fig. 10) the value of the integral in the above equation is independent of the geometric parametres of the spoiler and is near unity

$$\bar{F} = \left(\frac{p_u}{p_\infty} - 1\right) \frac{x_{od}}{h_i}. \tag{3.4}$$

The plateau pressure of the separation region with suction agrees approximately with the empirical correlation of the plateau pressure obtained by ZUKOWSKI [5] for the forward-facing step

$$\frac{p_u}{p_\infty} = 1 + 0.5\, M_\infty. \tag{3.5}$$

Introducing (3.1) and (3.5) in the Eq. (3.4), we obtain the dimensionless normal force induced by separation with suction in the form

$$\bar{F} = 2.19 M_\infty - 1.73 M_\infty (h_g/h_i). \tag{3.6}$$

This estimation agrees well with experimental data, see. Fig. 11.

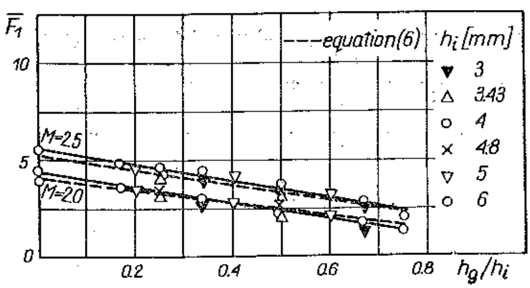

Fig. 11. Correlation of dimensionless normal force induced by separation upstream of spoiler with suction with the ratio of the gap to spoiler heights.

All the above results are valid for the separation region induced by the spoiler with a gap, in which ratio of the gap height to spoiler height is less than 0.7.

In addition it can be stated that the effect of suction on turbulent boundary-layer separation is remarkably smaller than the effect obtained by Ball and Korkegi for laminar separation at a compression corner.

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Streszczenie

BADANIA WPŁYWU ODSYSANIA NA NADDŹWIĘKOWY PRZEPŁYW Z TURBULENTNYM ODERWANIEM

W pracy przedstawiono wyniki badań doświadczalnych dotyczących wpływu odsysania na naddźwiękowe oderwania turbulentnej warstwy przyściennej, spowodowane interceptorem na płaskiej płytce.

Badany model stanowiła płaska płytka i interceptory bez i ze szczeliną. Stwierdzono, że długość obszaru oderwania przed interceptorem ze szczeliną, odniesiona do wysokości interceptora, zależy tylko od stosunku wysokości szczeliny i interceptora oraz że odsysanie nie wpływa na wartość ciśnienia oderwania. W obszarze przed interceptorem bez i ze szczeliną znaleziono znormalizowany rozkład ciśnienia. Wykazano, że proces oderwania, spowodowanego przez interceptor ze szczeliną, jest procesem wzajemnego swobodnego oddziaływania.

Резюме

ИССЛЕДОВАНИЯ ВЛИЯНИЯ ОТСАСЫВАНИЯ НА СВЕРХЗВУКОВОЕ ТЕЧЕНИЕ С ТУРБУЛЕНТНЫМ ОТРЫВОМ

В работе представлены результаты экспериментальных исследований, касающихся влияния отсасывания на сверхзвуковые отрывы турбулентного пограничного слоя, вызванные интерцептором на плоской пластинке.

Исследуемую модель составляли плоская пластинка и интерцепторы без и со щелью. Констатировано, что длина области отрыва перед интерцептором со щелью, отнесенная к высоте интерцептора, зависит только от отношения высоты щели и интерцептора, а также что отсасывание не влияет на значение давления отрыва.

В области перед интерцептором без и со щелью найдено стандартное распределение давления. Доказано, что процесс отрыва, вызванный интерцептором со щелью, является процессом свободного взаимодействия.

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